APPENDIX I

Shell Puget Sound Refinery (PSR) Rail Unloading Facility Dispersion, Fire, and Explosion Analysis

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Shell Puget Sound Refinery (PSR) Anacortes Rail Unloading Facility

Dispersion, Fire, and Explosion Analysis

A Report Prepared By

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On Behalf Of

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Executive Summary

Shell proposes to construct and operate a rail unloading facility at the Shell Puget Sound Refinery (PSR). The proposed project includes building a rail spur from the existing adjacent Anacortes Subdivision onto the Shell PSR property to accommodate trains transporting crude oil from the mid-continent area. One specific concern of the Environmental Impact Statement (EIS) is public safety, in particular, the potential for fire and/or explosion resulting from possible crude-by-rail accidents. This report identifies and evaluates public exposure from fire and/or explosion from potential crude oil releases.

Releases of crude oil are considered high consequence, low probability (HCLP) events. The potential for incidents of this magnitude of frequency and consequence are present at many high-hazard industrial facilities. However, facilities with HCLP risks manage those risks using engineered safeguards and administrative controls to achieve acceptable levels of safety.

The following types of incidents, though very unlikely, could occur and were considered in the analysis:

- **Pool Fire.** This is a fire that burns from a pool of vaporizing fuel. The primary concern associated with pool fires is hazards associated with increased temperatures from thermal radiation (heat). For crude-by-rail trains, a pool fire could occur if there is an incident leading to a release of crude oil that forms a pool and then catches fire.
- **Vapor Cloud Explosion.** A vapor cloud explosion is the result of a flammable material that is released into the atmosphere, at which point the resulting vapor cloud is ignited. The primary concern from a vapor cloud explosion is overpressure (pressure caused by a shockwave). For crude-by-rail trains, such an explosion could occur if oil was released during an incident and evaporated into the air, forming a vapor cloud. This requires that there be no immediate ignition source.
- **Boiling Liquid Expanding Vapor Explosion (BLEVE).** A BLEVE is an explosion that results when a tank of liquefied gas is heated by fire to a point at which the pressure inside has increased and the strength of the tank has been reduced to the point that it ruptures. The concerns of a BLEVE are the generation of overpressure and projectiles from the explosion. A BLEVE may occur if rail cars containing crude oil are exposed to the flames of a pool fire leading to a sudden explosive rupture and ignition.

For this dispersion, fire, and explosion analysis, physical effects modeling was conducted using the PHAST v7.11, an industry-standard tool for evaluating flammable, fire, explosion, and toxic hazards. PHAST is comprised of a comprehensive suite of extensively validated models.

The frequency and return period of these potential events were calculated. The calculated frequency of a pool fire ranged between 0.00044 and 0.0037 pool fires per year, or between one in every 2,300 years to 270 years. The calculated frequency of a vapor cloud explosion ranged between 0.00013 and 0.0011 vapor cloud explosions per year or, between one in every 7,600 years to 910 years. Because no crude-by-rail train accidents involving BLEVEs have taken place, it is not possible to perform a statistical estimate; therefore, the probability of a BLEVE occurring was not calculated.

The potential consequences associated with these events were evaluated at three hypothetical release locations: Swinomish Channel Swing Bridge, Skagit River Crossing, and Edmonds Ferry Terminal. At each hypothetical release location, the analysis included evaluation of two wind conditions (winter high wind, summer medium wind), and two release volumes (5,700 barrels and 20,000 barrels). The evaluation of

the consequences of a pool fire also considered the amount of elapsed time between the release of oil and ignition (early vs. late pool fire).

The potential consequences of a pool fire are measured by the level of exposure to thermal radiation (heat) that people could experience. Since thermal radiation levels decrease as the distance from the center of the pool fire increases, three thermal flux levels were calculated. Table ES-1 presents the maximum distances from the center of a pool fire at which the three different modeled levels of thermal radiation would be experienced at each hypothetical release location.

Table ES-1. Thermal Radiation from a Pool Fire

	Level of Thermal Radiation					
	Pain within 15 to 20 seconds and injury after 30 seconds (4 kW/m^2)		**Extreme pain within 20 seconds of exposure; movement to shelter is instinctive; fatality if escape is not possible (12.5 kW/m^2)**		**Immediate fatality (35 kW/m^2)**	
	Maximum Distance from Pool Fire (meters) under all Scenarios					
	Early Pool Fire	**Late Pool Fire**	**Early Pool Fire**	**Late Pool Fire**	**Early Pool Fire**	**Late Pool Fire**
Swinomish Channel Swing Bridge						
5,700-Barrel Release	136 meters	203 meters	49 meters	74 meters	--	--
20,000-Barrel Release	136 meters	203 meters	49 meters	74 meters	--	--
Skagit River Crossing						
5,700-Barrel Release	136 meters	199 meters	48 meters	72 meters	--	--
20,000-Barrel Release	136 meters	199 meters	48 meters	72 meters	--	--
Edmonds Ferry Terminal (water/land)						
5,700-Barrel Release	67/67 meters	67/67 meters	21/21 meters	21/21 meters	--	--
20,000-Barrel Release	75/75 meters	75/75 meters	23/23 meters	23/23 meters	--	--

Note: The 35 kW/m^2 level of thermal radiation was not reached under any scenario. The modeling at the Edmonds Ferry Terminal includes analysis of land and water.

The potential consequences of a vapor cloud explosion are measured by the overpressure generated by a shockwave and consider the impacts on people and structures from various distances relative to the center of the explosion. Table ES-2 presents the distances and levels of overpressure that would be experienced from the explosion.

Table ES-2. Overpressure from a Vapor Cloud Explosion

	Level of Overpressure		
	Window glass shatters and light injuries from fragments (1 psi)	**Residential structures collapse and serious injuries are common (3.5 psi)**	**Destruction of Buildings and most people are killed (8 psi)**
	Maximum Distance from Vapor Cloud Explosion (meters) under all Scenarios		
Swinomish Channel Swing Bridge			
5,700-Barrel Release	1,164 meters	837 meters	758 meters
20,000-Barrel Release	1,156 meters	834 meters	756 meters
Skagit River Crossing			
5,700-Barrel Release	777 meters	509 meters	444 meters
20,000-Barrel Release	773 meters	508 meters	444 meters
Edmonds Ferry Terminal (water/land)			
5,700-Barrel Release	1,204/317 meters	938/172 meters	729/119 meters
20,000-Barrel Release	1,045/273 meters	790/148 meters	729/119 meters

Note: The modeling at the Edmonds Ferry Terminal includes analysis of land and water.

In the event of a BLEVE, the resulting overpressure from the explosion was analyzed. Table ES-3 presents the distance from the explosion at which different levels of overpressure would be experienced.

Table ES-3. Overpressure from a Potential BLEVE

	Level of Overpressure		
	Window glass shatters and light injuries from fragments (1 psi)	**Residential structures collapse and serious injuries are common (3.5 psi)**	**Destruction of Buildings and most people are killed (8 psi)**
	Maximum Distance from BLEVE (meters)		
1 tank car (650 barrels)	157 meters	74 meters	46 meters
7 tank cars (4,550 barrels)	300 meters	142 meters	88 meters
28 tank cars (18,200 barrels)	476 meters	225 meters	139 meters

1 Introduction

This analysis considers the probability and potential consequences of a fire or explosion resulting from an incident during rail transport of crude oil to the Shell Puget Sound Refinery (PSR). If an incident that resulted in the release of crude oil were to occur along the rail corridor, impacts could include: the direct impacts of crude oil in the terrestrial and marine environment (Horn 2016) and the dispersion of volatile hydrocarbon vapors from the released crude oil, which could result in ignition and combustion.

The following types of incidents, though very unlikely, could occur and were considered in the analysis:

- **Pool Fire.** This is a fire that burns from a pool of vaporizing fuel. The primary concern associated with pool fires is hazards associated with increased temperatures from thermal radiation (heat). For crude-by-rail trains, a pool fire could occur if there is an incident leading to a release of crude oil that forms a pool and then catches fire.
- **Vapor Cloud Explosion.** A vapor cloud explosion is the result of a flammable material that is released into the atmosphere, at which point the resulting vapor cloud is ignited. The primary concern from a vapor cloud explosion is overpressure (pressure caused by a shockwave). For crude-by-rail trains, such an explosion could occur if oil was released during an incident and evaporated into the air, forming a vapor cloud. This requires that there be no immediate ignition source.
- **Boiling Liquid Expanding Vapor Explosion (BLEVE).** A BLEVE is an explosion that results when a tank of liquefied gas is heated by fire to a point at which the pressure inside has increased and the strength of the tank has been reduced to the point that it ruptures. The concerns of a BLEVE are the generation of overpressure and projectiles from the explosion. A BLEVE may occur if rail cars containing crude oil are exposed to the flames of a pool fire leading to a sudden explosive rupture and ignition.

Because the range of locations, conditions, and release quantities for hypothetical scenarios can be an intractable number, specific scenarios were selected through a consultative process with Skagit County and the Washington State Department of Ecology (co-lead agencies) to provide a range of representative consequences of flammable releases.

1.1 Scope of Work and Study Objectives

The scope of work for this project included:

- Perform consequence modeling for potential crude oil releases on three representative locations, using two wind conditions for each
- Determine the extent of flammable vapor dispersion
- Determine the extent of thermal hazard zones derived from proposed pool fires, for both early and late ignition, and for flash fires
- Determine the extent of explosion overpressure for vapor cloud explosions resulting from oil releases
- Determine the extent of explosion overpressure for possible BLEVE events
- Determine the conditional probability of each of the consequence impacts given that a derailment and release occurs

The objective of this analysis is to present the zones affected by dispersion, thermal radiation and explosion overpressure for specified scenarios. Additionally, parametric sensitivity evaluations are also provided to illustrate a range of potential impacts, depending on model assumptions and variabilities from the specified scenario conditions.

2 Analysis Parameters

This section contains the parameters required to evaluate the dispersion, fire, and explosion behavior required for the analysis. Some of the parameters are obtained from project data, others from location-specific environmental data. The remaining data are associated with the specific models or calculations used.

2.1 Project Description

The project proposal is available as described on the project website: http://shellraileis.com/project.

2.2 Selected Sites

Because the range of locations, conditions, and release quantities for proposed scenarios can be an intractable number, certain specific accident scenarios were selected through a consultative process with the co-lead agencies to provide a range of representative consequences of flammable releases. Three sites were:

- Swinomish Channel Swing Bridge
- Skagit River Crossing
- Edmonds Ferry Terminal

2.3 Environmental Parameters

The environmental factors required to perform the dispersion analysis are wind speed, direction, stability class, air temperature, and humidity. These factors can influence various hazard conditions; therefore, the probable conditions at the selected sites were investigated. The data from the following weather stations was collected and analyzed to characterize the environmental factors of interest:

- Station PBFW1 - Padilla Bay Farm, Padilla Bay Reserve, Washington - Owned and maintained by National Estuarine Research Reserve System NERRS Weather Station. This station is located at 48.464 N 122.469 W (48°27'50" N 122°28'9" W), and was used to describe the weather at the ***Swinomish Channel*** and ***Skagit River*** locations.

- Station WPOW1 - West Point, Washington - Owned and maintained by National Data Buoy Center. This station is located at 47.662 N 122.436 W (47°39'44" N 122°26'9" W), and was used to define the weather representative of the ***City of Edmonds***.

The wind speeds considered for predicting vapor dispersion hazards for this analysis comprised the 50th and 95th percentile values for each of the two weather stations. The 50th percentile represented the value below which half of the wind speeds fell that were observed at that site. Similarly, the 95th percentile represented the value below which 95 percent of the wind speeds fell, so this value was exceeded only 5 percent of the time.

In addition to wind speeds, a measure of the effect of turbulence on dispersion was also required for analysis. Turbulence increases the entrainment and mixing of air into the vapor cloud plume and thereby acts to reduce the concentration of vapor the plume (i.e., enhances the plume dispersion). It was therefore important to categorize the amount of atmospheric turbulence present at any given time. According to the Pasquill Stability scale, there are six stability classes: A, B, C, D, E and F, with class A being the most unstable or most turbulent, and class F being the most stable or least turbulent. Stability class F was chosen for analysis at each site to ensure conservative results. Stability class F s specified for

calculation of the dispersion of natural gas accidental releases in the permit approval process governed by the Federal Energy Regulatory Commission (FERC) for liquefied natural gas facilities.

Humid air absorbs / attenuates more thermal radiation than dry air, thereby decreasing the transmissivity of the air and reducing the thermal hazard distance. Air temperature and humidity were also selected to give realistic but conservative estimates. Air temperature was taken from the averages observed at the two weather station data sets, while relative humidity was available only from the PBFW1 Station and taken as the average value.

Table 1: Weather Conditions

Location	Speed 50th m/sec	Speed 95th m/sec	Stability Category	Relative Humidity (%)	Temperature (C)
Swinomish Channel Swing Bridge	2.7	8.2	F	84.5	10.5
Skagit River Crossing	2.7	8.2	F	84.5	10.5
Edmonds Ferry Terminal	4.1	10.4	F	84.5	11.1

2.4 Properties of Crude Oil

The crude oil composition used for this analysis is known as *Conditioned Bakken Crude*. The composition for the Conditioned Bakken Crude was modeled based on the Crude Oil Evaluation data sheet provided by Shell (Shell 2015). The modeling approach of a multi-component mixture is performed by assuming that the composition of the mixture does not change during the different stages in the modeling. During analysis, the composition of the crude oil was assumed to be the same as for the vapor cloud in all stages of dispersion. The properties of the mixture were calculated as a weighted average of each component property, and those averaged properties were used in the modeling in the same way as the properties for a pure component.

The information included on the composition analysis only provided the composition for the light hydrocarbons, which account for only 15 percent of the crude by volume. Therefore, some assumptions had to be made in order to estimate the contribution of the heavy ends to the thermodynamic properties of the mixture, which included the assumption that the remaining hydrocarbon mixture could be represented by n-nonane.

The volatility of the pseudo-component was verified by comparing the calculated Reid Vapor Pressure (RVP) in PHAST against the reported RVP of the Bakken crude. The RVP reported in the Bakken Assay provided by Shell is 5 pounds per square inch (psi), which is lower that the RVP of the pseudo-component mixture calculated in PHAST as 7 psi. This higher value of RVP provided a slight level of conservatism to the consequence modeling results.

2.5 Model Input Data

There are numerous models of physicochemical behavior used in representing the overall consequences of the specified release scenarios:

- Multiphase discharge from a breach and associated flashing of vapor
- Liquid pool spread, heat transfer and evaporation
- Vaporization from liquid pool
- Vapor dispersion

- Combustion
- Attenuation of thermal radiation

All of these models had their own respective input data and parameters that were required. These are summarized in the “Summary Report” output file included as Appendix A.

3 Technical Approach

Liquid releases, pool fires, flash fires, and vapor cloud explosion hazards are possible depending on the timing of the ignition. In some situations, both pool fire and flash fire hazards are possible based on the time of maximum Lower Flammability Limit (LFL) and whether the source pool is still vaporizing. For this study, the hazards were assessed independently and combined to represent the complete consequences of the hazard.

Impacts to safety were limited to the area potentially affected by thermal radiation from fire scenarios, the area potentially affected by a flammable vapor cloud explosion, and the impacts of explosion overpressure resulting from BLEVEs surrounding the proposed project area.

3.1 Scenario Development

This dispersion, fire, and explosion analysis investigated specific—representative— - accidental crude oil release scenarios that were selected based on a range of locations of interest, resources potentially at risk from the consequential impacts of the release, and a statistical analysis of the likelihood of specific release quantities (Etkin 2016).

Scenario specifications are presented in Table 2. The parameters required included:

- Location – Swinomish Channel Swing Bridge, Skagit River Crossing, or Edmonds Ferry Terminal
- Volume Released - 5,700 barrels (7–8 cars) or 20,000 barrels (28–30 cars)
- Pool Surface - Land, River (water surface)
- Dispersion Surface - Land, Water
- Terrain Surface Roughness - low crops, mud flats, open water, city

Finally, BLEVE calculations were conducted assuming 1, 7–8, or 28–30 cars were involved.

Table 2: Scenario Matrix

Case ID PHAST	Site	Volume Released	Pool Surface	Dispersion Surface
SB1	Swinomish Channel Swing Bridge	28–30 cars (20,000 barrels)	River	Land
SB3	Swinomish Channel Swing Bridge	7–8 cars (5,700 barrels)	River	Land
MV3	Skagit River Crossing	28–30 cars (20,000 barrels)	River	Land
MV7	Skagit River Crossing	7–8 cars (5,700 barrels)	River	Land
ED1	Edmonds Ferry Terminal	28–30 cars (20,000 barrels)	Land	Water
ED3	Edmonds Ferry Terminal	28–30 cars (20,000 barrels)	Land	Land
ED5	Edmonds Ferry Terminal	7–8 cars (5,700 barrels)	Land	Water
ED7	Edmonds Ferry Terminal	7–8 cars (5,700 barrels)	Land	Land
BLEVE - 1 car	All (applicable for any site)	1 car	N/A	N/A
BLEVE - 7 car	All (applicable for any site)	7 cars	N/A	N/A
BLEVE - 28 car	All (applicable for any site)	28 cars	N/A	N/A

3.2 Consequence Analysis

3.2.1 Release Quantity

Release quantity is documented separately, along with detailed rationale, for the accident scenarios addressed in this report [Etkin-2016]. The quantities released were defined as:

- 30th Percentile Spill (P30): 5,700 bbl
- 90th Percentile Spill (P90): 20,000 bbl

3.2.2 Pool Size

Realistic representation of pool size depends upon the exact location, topography of the area, and rate of release of the crude oil from the breach. Pool spread models and Gaussian dispersion models rely on treating the shape of each of these effects as circular. This means that irregular shape release areas must be represented as a circular area for both the spreading phenomena and the vaporization source.

Releases onto river surfaces (Swinomish Channel Swing Bridge and Skagit River Crossing) are represented as a circle of diameter equivalent to the river width at the release location, as the river will confine the spread of liquid within the shoreline. If a release elongates along the river length, the dispersion distance perpendicular to the river will not change as a result.

Releases onto land (Edmonds Ferry Terminal) were modeled for environmental impact explicitly accounting for terrain, topography, and drainage systems (Horn 2016). The specific shape of the 5,700-barrel and 20,000-barrel releases from this work are shown in Figure 1 and Figure 2. These results were used to define a pool source for dispersion as a circular area with a diameter equivalent to the largest diameter along the pool profile on land.

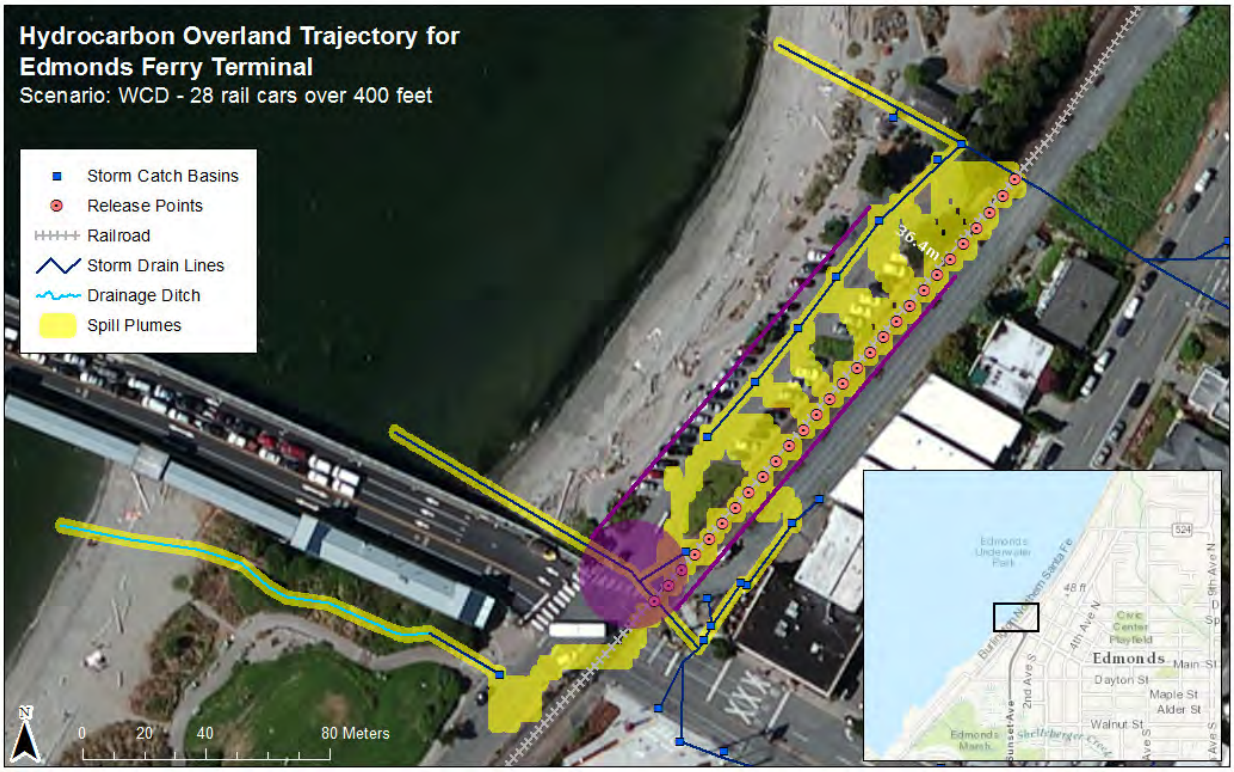


Figure 1: Pool dimensions for releases onto land at Edmonds Ferry Terminal, Volume 28–30 cars

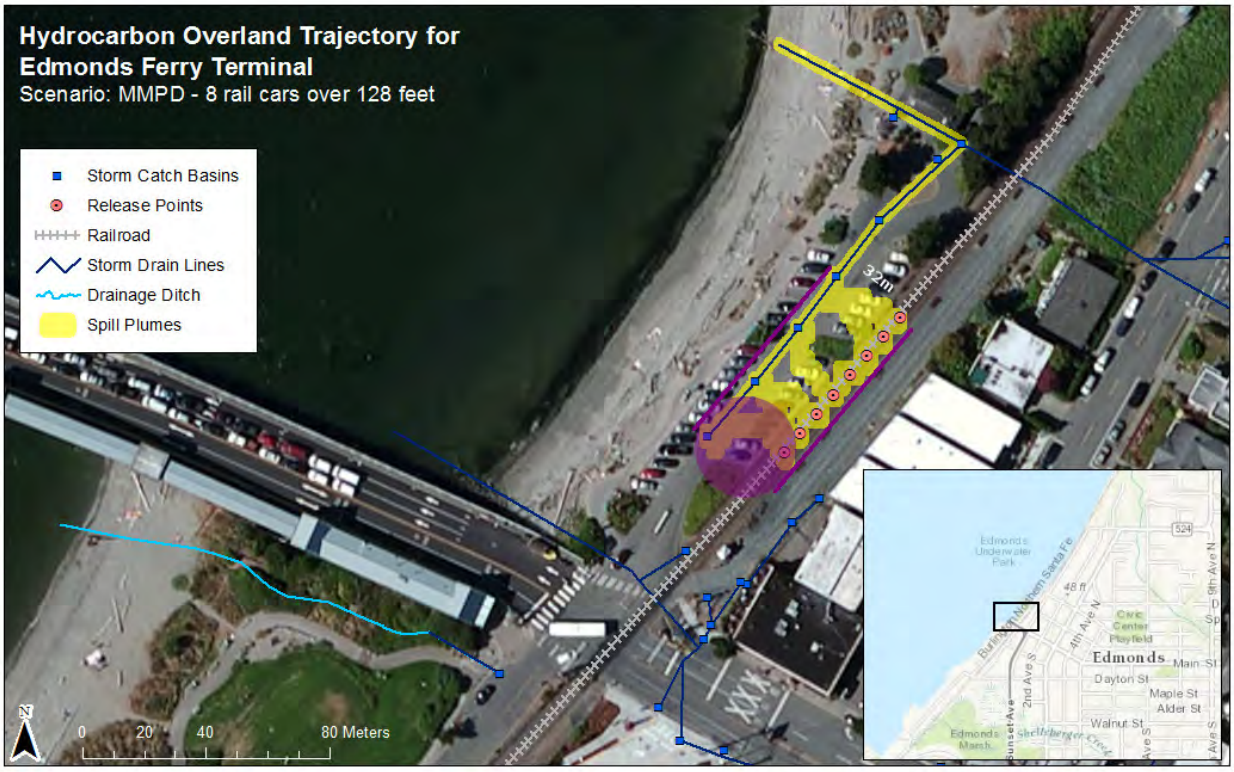


Figure 2: Pool dimensions for releases onto land at Edmonds Ferry Terminal, Volume 7–8 cars

Each of the pools at the three locations are constrained by the geometry of the release, but leading up to this dimension, the spread of the pool was calculated using the pool spread model in PHAST v7.11, which assumed that the driving force for the spread was formed by the hydrostatic difference between the thickness of the current liquid layer and a minimum pool thickness characteristic for the substrate. This results in the rate of spreading decreased as the pool approached the minimum thickness. In this study, the crude oil release can occur on either water or concrete, depending on location. The minimum thickness characteristic of these surfaces on PHAST is shown on Table 3. Where the pool has spread and vaporized to produce a pool of depth equal to the minimum thickness, the spreading is constrained to be consistent with this thickness. Thereafter the radius would no longer be a simple function of time.

Table 3: Spill Substrate Minimum Thickness

Spill Surface	Minimum Thickness (m)
Water	0.001
Concrete	0.005

3.2.3 Discharge Dynamics

As pool formation depends on the rate of release of crude oil from the breach, a breach size must be established to determine the release rate. The discharge behavior in an actual incident would be characterized by a number of tank cars, each leaking from a unique breach size. In this analysis, a simplification was made to treat the release as a single volume flowing through a single breach, and then its equivalent size was calculated. The release duration of the contents from the toppled tank cars was defined to be 60 minutes, based on the default value for maximum release duration suggested by the U.S. Environmental Protection Agency Risk Management Plan (USEPA RMP) (USEPA 1990) for estimation of distance to flammable endpoints. A breach size was calculated knowing the total release volume and duration. Using the discharge modeling in PHAST, and assuming no frictional losses for the fluid as it flowed toward the hole, it was determined that an orifice with a diameter of 18 inches yielded a release duration of 64.6 minutes, which corresponds to the modeling guidelines from EPA RMP.

3.2.4 Conditional Ignition Probability

The probability of a fire or explosion in the event of a release is dependent on an incident and a release first occurring. The expected frequency of a fire or explosion was calculated using the release frequency rates calculated in the probability analysis. Based on a review of historic fires in the petrochemical industry (Cox et al. 1990), there would be an 8-percent probability of an ignition leading to a fire in the event of a release. Of these ignited events, there would be a 30-percent probability that that fire would result in a vapor cloud explosion. Table 4 outlines the expected frequencies and return periods of a fire or explosion based on the release frequencies calculated in the probability analysis (Etkin-2016).

Although physically possible, there have been no BLEVEs involving crude-by-rail trains in the United States. There were roughly a dozen BLEVE events documented in the 40 years of reviewed freight train data from the FRA (FRA 2016b). All of these BLEVEs involved cargos of lighter hydrocarbon products with greater volatility (e.g., liquid petroleum gas, ethanol, mineral spirits), and, as such, are not comparable to crude oil. Because no crude-by-rail train accidents involving BLEVEs have taken place, it is not possible to perform a statistical estimate; therefore, the probability of a BLEVE occurring was not calculated.

Table 4: Frequency and Return Period of a Fire or Explosion in the Event of a Release

	High Estimate Evaluation		Low Estimate Evaluation	
	Frequency (Event/Year)	**Return Period (Years)**	**Frequency (Event/Year)**	**Return Period (Years)**
Oil Release	0.046	22	0.0055	180
Pool Fire	0.0037	270	0.00044	2,300
Vapor Cloud Explosion	0.0011	910	0.00013	7,600

Conditional ignition probability can be understood as the probability of ignition, if a release occurs leading to a vapor cloud dispersion event. In other words, some vapor clouds drift downwind and disperse without ever encountering an ignition source. The conditional probability of ignition characterizes the fraction of events that do ignite.

Ignition probability depends upon the vapor cloud encountering an ignition source. Since this study considers releases that could occur near populated areas as well as on railways located adjacent to roads with no controls on ignition sources (such as in an industrial site, for example), the ignition probability model used in this study assumed a uniform density of ignition sources within the dispersion plume. Research performed by Cox et al. [Cox-1990], which is based on examining a number of fire incidents, provides generic probabilities of ignition and explosion as shown in Table 4.

3.3 Pool Fire Hazards

In the event that an early ignition of a spreading crude oil pool occurred, the thermal radiation resulting from the ignited pool was analyzed. The pool fires were modeled in PHAST 7.11 using a solid flame model with no obstructions. Treating radiation without obstructions from pool fire radiation calculations increases consequence distances. The solid flame model solves for radiative intensities at distances away from the center of a fire and allows for a change in hazard distance due to tilting of the flame by wind. To determine the hazard distance, an average emissive power, a burn rate on land, and an atmospheric transmissivity was calculated during the analysis.

Four directions were determined for the pool fire lethality contour and the rest were interpolated. The farthest direction was in the wind direction, due to wind tilt.

3.4 Vapor Dispersion/ Flash Fire Hazards

Vapor dispersion was conducted for all crude oil releases along with any vaporization of hydrocarbon gas. Dispersions were performed using a validated Gaussian plume model, namely, the Uniform Dispersion Model as coded in PHAST 7.11.

To maximize dispersion distances, all simulations were conducted on a flat surface without objects (i.e., buildings, tanks, and other structures). This served as a conservative approach, as nearby objects have the potential to increase mixing, thereby reducing the distance to which the vapor clouds would travel.

The size of the hydrocarbon vapor clouds were defined based on the volume of hydrocarbon mixed with air within its flammable limits. The boundaries of flammable mass were defined using the LFL contour,

and the density of the cloud were determined assuming the cloud were homogenous with a concentration of the midpoint between the upper flammability limit (ULF) and the LFL.

3.5 Explosion Hazards

The acute damage potential of vapor cloud explosions has been proven by many real-world accidents including the significant potential for loss of life, property and business interruption. Much of the motivation behind the development of predictive models is a result of such catastrophic accidents. Physical and chemical properties of hydrocarbon vapor clouds and the layout of the surrounding area influences the dynamics of blast propagation during the explosion.

As a vapor cloud burns and expands, the gasses start to move and become consumed by the flame front. If the process takes place with the unburned gas flowing smoothly into the consuming flame front, the flame front propagates at the laminar burning velocity, which produces a flash fire. If there is turbulence in the gas, the flame velocity can greatly increase above this laminar burning velocity, which can produce high overpressures. Significant turbulence can be generated by obstacles encountered by a flame as it propagates through the vapor cloud in obstructed regions. This process can be reinforced by positive feedback, so that as more obstacles are encountered, more turbulence is generated and this further accelerates the flame. The obstacle density is also referred to as *congestion* in the literature.

A further key factor in determining the magnitude of overpressure generation is the degree to which the cloud is constrained from expanding. As the cloud burns, it heats and expands; if the cloud is constrained to expand in only 1 or 2 dimensions then the positive feedback mechanism leads to higher overpressures than if the cloud were to expand freely. This expansion constraint is referred to as *degree of confinement* in the literature.

For areas around the unit train, confinement and congestion would vary; hence representative release locations of interest were selected that present realistic confinement and congestion scenarios. No damaging blast waves can occur for releases in the open.

To properly estimate the potential explosion associated with each release, the scenario in which the cloud or some portion thereof sits in a congested volume needed to be assessed. For the proposed project, the explosion overpressure results were calculated with the TNO Multi-Energy model described in the Yellow Book (TNO 1997) and contained in PHAST version 7.11, using the reactivity of the fuel in the cloud, the mass of fuel within the source volume, and the congestion/confinement level representative of the explosion source. The area surrounding the release point was assigned a representative congestion and confinement level.

3.6 BLEVEs

A BLEVE may occur if the rail cars containing crude oil are exposed to the flames of a pool fire or high radiation flux, leading to a sudden explosive rupture and consequent overpressure. The blast effect of a BLEVE results from the rapid flashing of liquid and the expansion of vapor in the vessel's head-space when the pressure drops suddenly to atmospheric pressure. The chosen conditions prior to the BLEVE were:

- Railcar Tank Failure Temperature: 800 F (DOT 1990a)
- Failure Pressure: 500 psig (maximum bursting pressure specified for DOT 111 tank cars on §179.201-1 Individual specification requirements)

It should be noted that the conditions specified above are conservative, as the loss of strength on the walls of the vessel engulfed by the fire would cause it to fail before reaching the pressure indicated above.

The explosion impact area of postulated incidents with 1, 7 and 28 tank cars involved in a BLEVE were calculated in this analysis.

3.7 Public Safety Criteria and Injury / Fatality Thresholds

Compilations of data on the impacts of thermal radiation are available in literature (Hymes 1983; TNO 1989; OGP 2010). The impacts of thermal radiation on the human body depend primarily on the level of thermal radiation generated, the duration of exposure, and the ease of escape or finding shelter.

Exposure to thermal radiation requires line of sight to the source; therefore, exposure can be avoided by hiding behind an object or escaping. Table 4 presents the impacts on the human body that could be expected at different thermal radiation exposure levels.

Table 5: Impacts of Exposure to Thermal Radiation on the Human Body

Thermal Radiation (kW/m^2)	Impact on the Human Body
4 kW/m^2	Pain within 15 to 20 seconds and injury after 30 seconds
6 kW/m^2	Pain within approximately 10 seconds; rapid escape only is possible
12.5 kW/m^2	Extreme pain within 20 seconds of exposure; movement to shelter is instinctive; fatality if escape is not possible
20 kW/m^2	Incapacitation, leading to fatality unless rescued
35 kW/m^2	Immediate fatality

For reference, approximately 1.2 kW/ m2 is the incident radiation heat flux from the sun at zenith (Haddad 1981).

A simple flux threshold value was used as the “endpoint” of the consequence analysis. Typically, when specifying thermal radiation thresholds in risk analyses, the following heat flux/ consequence criteria are used (Spouge 1995):

- 4.0 kW/m2: Pain threshold reached in approximately 15 seconds; minimum heat flux level considered appropriate for protection of human health and safety.
- 12.5 kW/m2: Pain threshold in approximately 4 seconds; second-degree burns after 40 seconds; 50-percent lethality in approximately 80 seconds.
- 37.5 kW/m2: Immediate human fatality for unprotected exposure; equipment damage.

The human body can survive relatively high blast overpressure without experiencing barotrauma—injury caused by a change in air pressure—typically affecting the ear or the lung. Data compiled by the Department of Defense (Glasstone and Dolan 1977), (Sartori 1983) summarizes the effects of increasing blast pressure on various structures and the human body. This data originates from weapons tests and blast studies to assess the impact of blast overpressure on structures and people. Table 5 presents the

impacts on structures and the human body that could be expected at different resulting overpressure levels.

Table 6: Impacts of overpressure on structures and the human body

Overpressure (psi)	Impact on Structures	Impact on the Human Body
1 psi	Window glass shatters	Light injuries from fragments
2 psi	Moderate damage to houses	Injuries from flying debris
3 psi	Residential structures collapse	Serious injuries are common; fatalities may occur
5 psi	Most buildings collapse	Injuries are universal, fatalities are widespread
10 psi	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
20 psi	Heavily built concrete buildings are severely damaged or demolished	Fatalities approach 100%

For this analysis, the distance to overpressure endpoints of 1, 3.5 and 8 psi were calculated, based on reference to the National Oceanic and Atmospheric Administration (NOAA) Overpressure Levels of Concern (NOAA 2016) and the Guidance provided by the USEPA Risk Management Program Guidance for Offsite Consequence Analysis (USEPA 1990).

4 Results

Results reported for each site include:

- Dispersion distances to lower and upper flammability limit
- Thermal radiation impact distances to the specified endpoints for early and late pool fires
- Explosion overpressures impact distances to specified endpoints

The flammability range is delineated by the upper and lower flammability limits. Outside this range of air/vapor mixtures, the mixture cannot be ignited (unless the temperature and pressure are increased). The LFL, usually expressed in volume percentage, is the lower end of the concentration range over which a flammable mixture of gas or vapor in the air can be ignited at a given temperature and pressure. The LFL decreases with rising temperatures; therefore, a mixture that is below its LFL at a given temperature may be ignitable if heated sufficiently. The UFL is the maximum percentage of flammable gas or vapor in the air above which ignition cannot take place because the ratio of the gas to oxygen is too high. The upper and lower flammability limits are also known as the upper and lower explosive limits.

A pool fire that occurs early in the release process, as may happen when ignition sources such as sparking or engine heat are available at the beginning of the release, result in a fire of relatively small dimension compared with a fire that occurs late in the release process and has allowed the pool to spread and cover a large area.

In this study, two pool fires were evaluated: early and late. In the early pool fire, immediate ignition was assumed. The pool diameter was defined as when the mass flow into the pool (release rate) equaled the burn rate. In the case of the late pool fire, liquid pool spreading was assumed to take place prior to ignition. The pool diameter was then equal to the maximum dimension attained in the spreading process.

Overpressure (or blast overpressure) is the pressure caused by a shock wave over and above normal atmospheric pressure. The shock wave may be caused by an explosion and the resulting overpressure receives particular attention when measuring impacts on buildings and structures.

4.1 Interpretation of Results

The footprint of a vapor cloud dispersion represents the curve that sweeps out beyond the maximum perimeter of all locations exposed to a concentration of interest during the entire dispersion process. It is not a footprint of an actual cloud at a given time. The figure below was taken from a Computational Fluid Dynamics simulation of natural gas dispersion showing the time-dependent nature of the cloud. It is clear in the figure that when the cloud reaches its maximum extent to the flammability limit, it becomes greatly reduced in mass, and therefore the quantity of fuel available for combustion is also reduced.

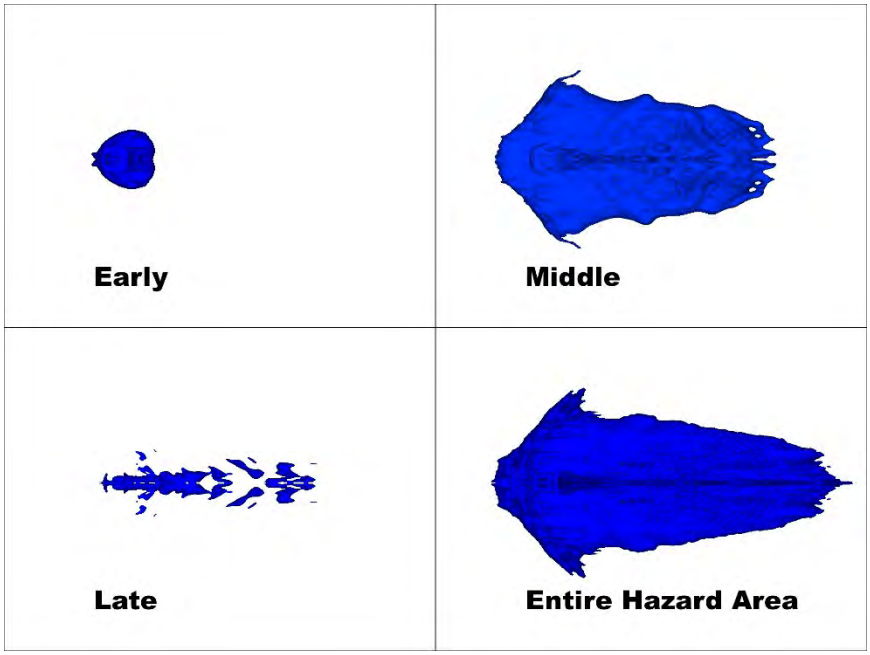


Figure 4: Time-Dependent Vapor Dispersion (Blue area represents flammable region of vapor cloud)

The hazard zones associated with dispersion, thermal radiation, and explosion overpressure are a rotation of the footprint and of the impact of dispersion or combustion. Therefore, the circular plots overlaid on the area maps are not a portrayal of the impact at a given time.

These accidental releases are considered to be high consequence, low probability (HCLP) events. The estimated frequency of the consequences is of the order of one in a million years. Events of this magnitude of frequency and consequence are associated with high hazard industrial facilities. Facilities with HCLP risks manage those risks using engineered safeguards and administrative controls to achieve a tolerable level of safety.

4.2 Swinomish Channel Swing Bridge

Calculated distances to the upper and lower flammability limits for the 5,700-barrel and 20,000-barrel release scenarios for the Swinomish Channel Swing Bridge are presented below in Table 6and shown in Figures 3 to 8. Distances were measured from the center of the pool. The pool size was the same for both release quantities as the both pools were able to spread to the width of the river. The UFLs for the medium wind speed remained very close to the pool radius, meaning that the cloud reached flammable concentrations at the edge of the pool. At the higher wind speed, the UFL was reached at 115 meters, which was approximately another 40 meters outside the pool radius. The farthest extent of flammable concentration reached 639 meters from the pool center as shown in Figure 5. It was also noticeable that the distance to any of the limits—LFL or UFL—were similar for the 5,700-barrel and 20,000-barrel release scenarios. This is because the controlling factor was the pool radius, which was physically constrained by the river banks. The releases differed in the quantities released, which, in turn, controlled the duration of the dispersion process.

Table 7: Swinomish Channel Swing Bridge - Dispersion Distances (m)

	UFL	LFL
Volume: 28-30 cars (20,000 barrels)		
Pool Size: 138 m		
Med Wind	73	632
High Wind	115	320
Volume: 7-8 cars (5,700 barrels)		
Pool Size: 138 m		
Med Wind	72	639
High Wind	115	318

In the two figures that follow, a representative dispersion footprint (teardrop shape figure) is shown within the circular impact area formed by a complete rotation of the dispersion footprint.

UFL LFL

Figure 3: Dispersion impact zone showing vapor cloud footprint in a single direction and its rotation showing all possible locations flammable vapor may reach -
Swinomish Channel Swing Bridge - Volume 28-30 cars, Medium Wind

UFL LFL

Figure 4: Dispersion impact zone showing vapor cloud footprint in a single direction and its rotation showing all possible locations flammable vapor may reach -
Swinomish Channel Swing Bridge - Volume 28-30 cars, High Wind

UFL LFL

Figure 5: Flammable impact zone showing area within which ignition is possible between green and blue circles - Swinomish Channel Swing Bridge - Volume 28-30 cars, Medium Wind

UFL LFL

Figure 6: Flammable impact zone showing area within which ignition is possible between green and blue circles - Swinomish Channel Swing Bridge - Volume 28-30 cars, High Wind

UFL LFL

Figure 7: Flammable impact zone showing area within which ignition is possible between green and blue circles - Swinomish Channel Swing Bridge - Volume 7-8 cars, Medium Wind

UFL LFL

Figure 8: Flammable impact zone showing area within which ignition is possible between green and blue circles - Swinomish Channel Swing Bridge - Volume 7-8 cars, High Wind

Calculated distances to thermal radiation limits for the 5,700-barrel and 20,000-barrel release scenarios are presented in Table 7 and Table 8, and in Figure 9 – Figure 12. Distances to 12.5 kW/m2—if unprotected, a level at which pain would occur in approximately 4 seconds, second-degree burns after 40 seconds, and 50-percent lethality in approximately 80 seconds—remained well within the pool itself, hence within the banks of the river, at less than 50 meters (m) from the center for both wind speeds. There was no difference between the two release quantities because the pool radius controls the radiation levels and the pool radius is limited to the width of the river for both spill quantities. The distances to 4.0 kW/m2— a level at which pain would occur in approximately 15 seconds, and also the level at which protective clothing must be worn for human health and safety—is between 114 and 203 m., which would extend beyond the river boundary, but remain within the mud flats region and lead to very limited exposure of the public. The severe damage level, 37.5 kW/m2 was not reached for any pool fire in this study.

Table 8: Swinomish Channel Swing Bridge - Early Pool Fire Radiation (m)

	4 kW/m^2	12.5 kW/m^2	37.5 kW/m^2
Volume: 28-30 cars (20,000 barrels)			
Pool Size: 138 m			
Med Wind	114	46	Not Reached
High Wind	136	49	Not Reached
Volume: 7-8 cars (5,700 barrels)			
Pool Size: 138 m			
Med Wind	114	46	Not Reached
High Wind	136	49	Not Reached

Table 9: Swinomish Channel Swing Bridge - Late Pool Fire Radiation (m)

	4 kW/m^2	12.5 kW/m^2	37.5 kW/m^2
Volume: 28-30 cars (20,000 barrels)			
Pool Size: 138 m			
Med Wind	168	70	Not Reached
High Wind	203	74	Not Reached
Volume: 7-8 cars (5,700 barrels)			
Pool Size: 138 m			
Med Wind	168	70	Not Reached
High Wind	203	74	Not Reached

4 kW/m² 12.5 kW/m²

Figure 9: Thermal radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Swinomish Channel Swing Bridge - Volume 28-30 cars, Medium Wind

4 kW/m² 12.5 kW/m²

Figure 10: Thermal radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Swinomish Channel Swing Bridge - Volume 28-30 cars, High Wind

4 kW/m² 12.5 kW/m²

Figure 11: Thermal radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Swinomish Channel Swing Bridge - Volume 7-8 cars, Medium Wind

4 kW/m² 12.5 kW/m²

Figure 12: Thermal radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Swinomish Channel Swing Bridge - Volume 7-8 cars, High Wind.

In Table 10 and Figures 14 through 16, blast overpressures from postulated vapor cloud explosions are presented for the Swinomish Channel Swing Bridge. The calculated distance to the destruction of buildings was approximately 750 m, while the distances to serious injury and glass breakage were approximately 835 and 1160 m, respectively. In this release location, there were few buildings within the impact zones for blast overpressure.

Table 10: Swinomish Channel Swing Bridge - Vapor Cloud Explosion

	Distance (m) to 1 psi	Distance (m) to 3.5 psi	Distance (m) to 8 psi
Volume: 28-30 cars (20,000 barrels)			
Pool Size: 138 m			
Med Wind	1156	834	756
High Wind	614	428	383
Volume: 7-8 cars (5,700 barrels)			
Pool Size: 138 m			
Med Wind	1164	837	758
High Wind	615	428	383

Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 13: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Swinomish Channel Swing Bridge – Volume 28-30 cars, Medium Wind

Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 14: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Swinomish Channel Swing Bridge – Volume 28-30 cars, High Wind

Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 15: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Swinomish Channel Swing Bridge – Volume 7-8 cars, Medium Wind

Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

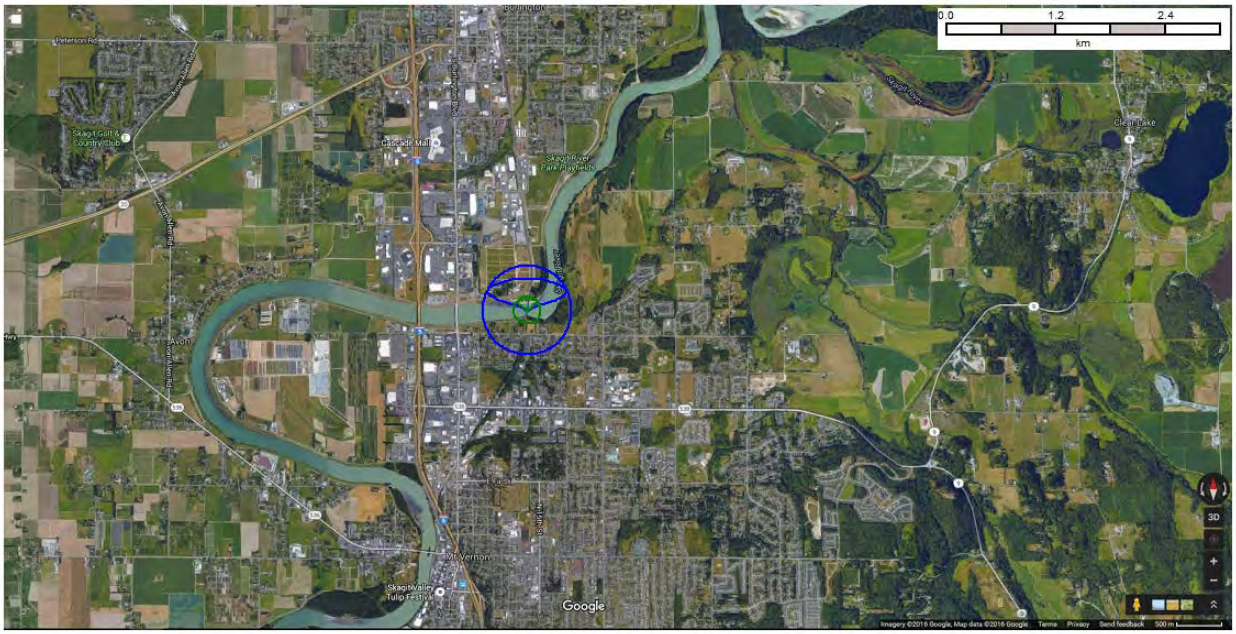
Figure 16: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Swinomish Channel Swing Bridge – Volume 7-8 cars, High Wind

4.3 Skagit River Crossing

Similar results to those presented above are presented in this section for the Skagit River Crossing release location. Calculated distances to the upper and lower flammability limits for the 5,700-barrel and 20,000-barrel release scenarios for the Skagit River Crossing are presented below in Table 10 and shown in Figure 17 to Figure 21. Distances were measured from the center of the pool. The pool size was the same for both release quantities as the both pools were able to spread to the width of the river. At the higher wind speed, the UFL was reached at 129 - 131 meters, which was outside the pool radius but not reaching housing or business structures. The farthest extent of flammable concentration reached around 348 meters from the pool center as shown in Figure 20. It was also noticeable that the distance to any of the limits—LFL or UFL—were similar for the 5,700-barrel and 20,000-barrel release scenarios. This is because the controlling factor was the pool radius, which was physically constrained by the river banks. The releases differed in the quantities released, which, in turn, controlled the duration of the dispersion process.

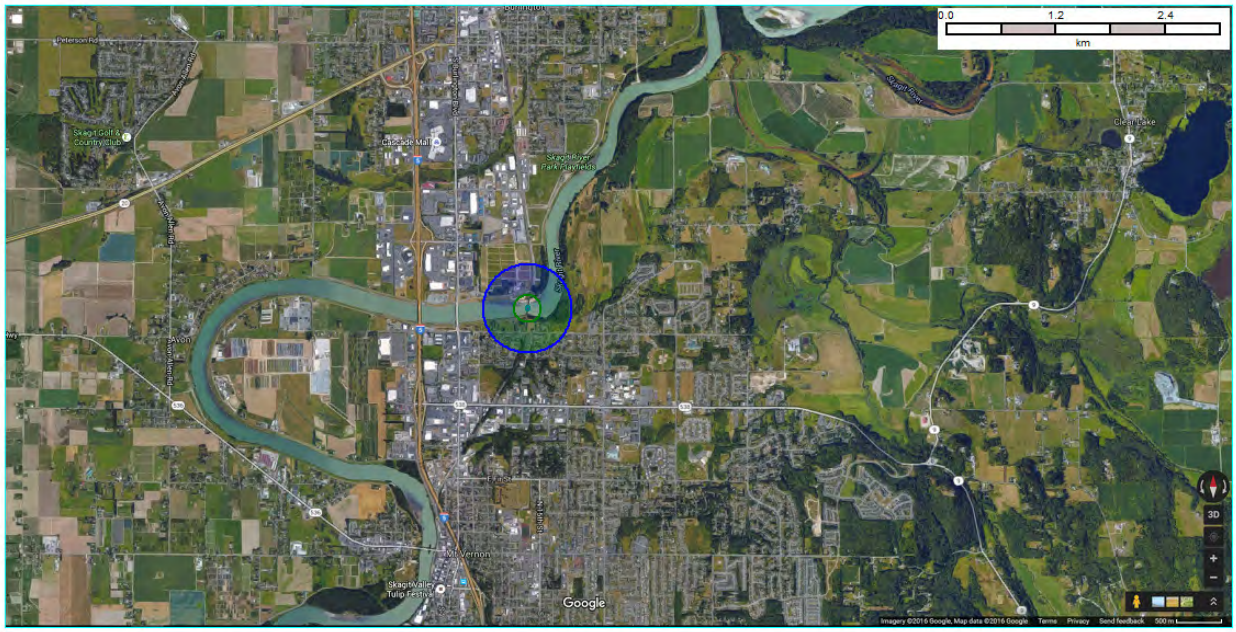
Table 11: Skagit River Crossing - Dispersion Distances (m)

	UFL	LFL
Volume: 28-30 cars (20,000 barrels)		
Pool Size: 135m		
Med Wind	129	344
High Wind	62	192
Volume: 7-8 cars (5,700 barrels)		
Pool Size: 135m		
Med Wind	131	348
High Wind	62	192



UFL LFL

Figure 17: Dispersion impact zone showing vapor cloud footprint in a single direction and its rotation showing all possible locations flammable vapor may reach -
Skagit River Crossing - Volume 28-30 cars, Medium Wind

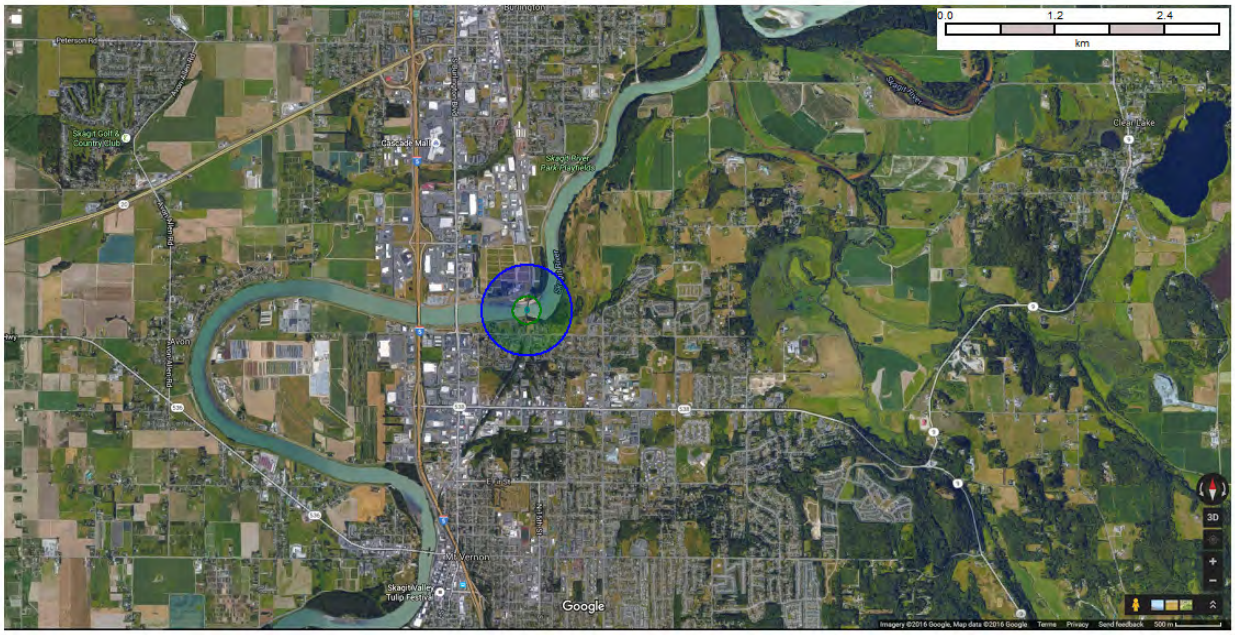


UFL LFL

Figure 18: Flammable impact zone showing area within which ignition is possible between green and blue circles - Skagit River Crossing - Volume 28-30 cars, Medium Wind

UFL LFL

Figure 19: Flammable impact zone showing area within which ignition is possible between green and blue circles - Skagit River Crossing - Volume 28-30 cars, High Wind



UFL LFL

Figure 20: Flammable impact zone showing area within which ignition is possible between green and blue circles - Skagit River Crossing - Volume 7-8 cars, Medium Wind

UFL LFL

Figure 21: Flammable impact zone showing area within which ignition is possible between green and blue circles - Skagit River Crossing - Volume 7-8 cars, High Wind

Calculated distances to thermal radiation limits for the 5,700-barrel and 20,000-barrel release scenarios are presented in Figure 22– Figure 25. Distances to 12.5 kW/m2—if unprotected, a level at which pain would occur in approximately 4 seconds, second-degree burns after 40 seconds, and 50-percent lethality in approximately 80 seconds—remained well within the pool itself, hence within the banks of the river, at less than 70 meters (m) from the center for both wind speeds. There was no difference between the two release quantities because the pool radius controls the radiation levels and the pool radius is limited to the width of the river for both spill quantities. The distances to 4.0 kW/m2— a level at which pain would occur in approximately 15 seconds, and also the level at which protective clothing must be worn for human health and safety—is between 114 and 199 m., which would extend beyond the river boundary, but not reach housing or business structures and lead to very limited exposure of the public. The severe damage level, 37.5 kW/m2 was not reached for any pool fire in this study.

Table 12: Skagit River Crossing - Early Pool Fire Radiation (m)

	4 kW/m²	12.5 kW/m²	37.5 kW/m²
Volume: 28-30 cars (20,000 barrels)			
Pool Size: 135m			
Med Wind	114	46	Not Reached
High Wind	136	48	Not Reached
Volume: 7-8 cars (5,700 barrels)			
Pool Size: 135m			
Med Wind	114	46	Not Reached
High Wind	136	48	Not Reached

Table 13: Skagit River Crossing - Late Pool Fire Radiation (m)

	4 kW/m²	12.5 kW/m²	37.5 kW/m²
Volume: 28-30 cars (20,000 barrels)			
Pool Size: 135m			
Med Wind	165	69	Not Reached
High Wind	199	72	Not Reached
Volume: 7-8 cars (5,700 barrels)			
Pool Size: 135m			
Med Wind	165	69	Not Reached
High Wind	199	72	Not Reached

4 kW/m² 12.5 kW/m²

Figure 22: Thermal radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Skagit River Crossing - Volume 28-30 cars, Medium Wind

4 kW/m² 12.5 kW/m²

Figure 23: Thermal Radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Skagit River Crossing - Volume 28-30 cars, High Wind

4 kW/m² 12.5 kW/m²

Figure 24: Thermal Radiation effect areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Skagit River Crossing - Volume 7-8 cars, Medium Wind

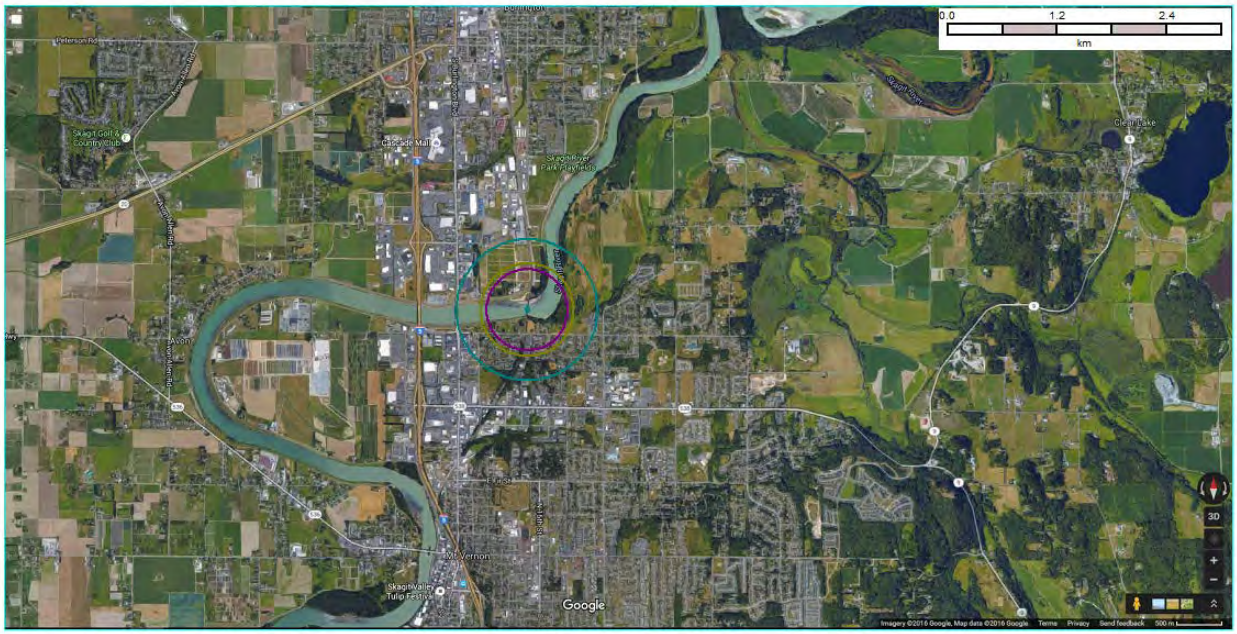
4 kW/m² 12.5 kW/m²

Figure 25: Thermal Radiation effect areas (Late Pool Fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Skagit River Crossing - Volume 7-8 cars, High Wind

In Table 13 and Figure 26 through Figure 29, blast overpressures from postulated vapor cloud explosions are presented for the Skagit River Crossing. The calculated distance to the destruction of buildings was approximately 445 m, while the distances to serious injury and glass breakage were 509 and 777 m, respectively. In this release location, there was some residential and light commercial buildings within the impact zones for blast overpressure.

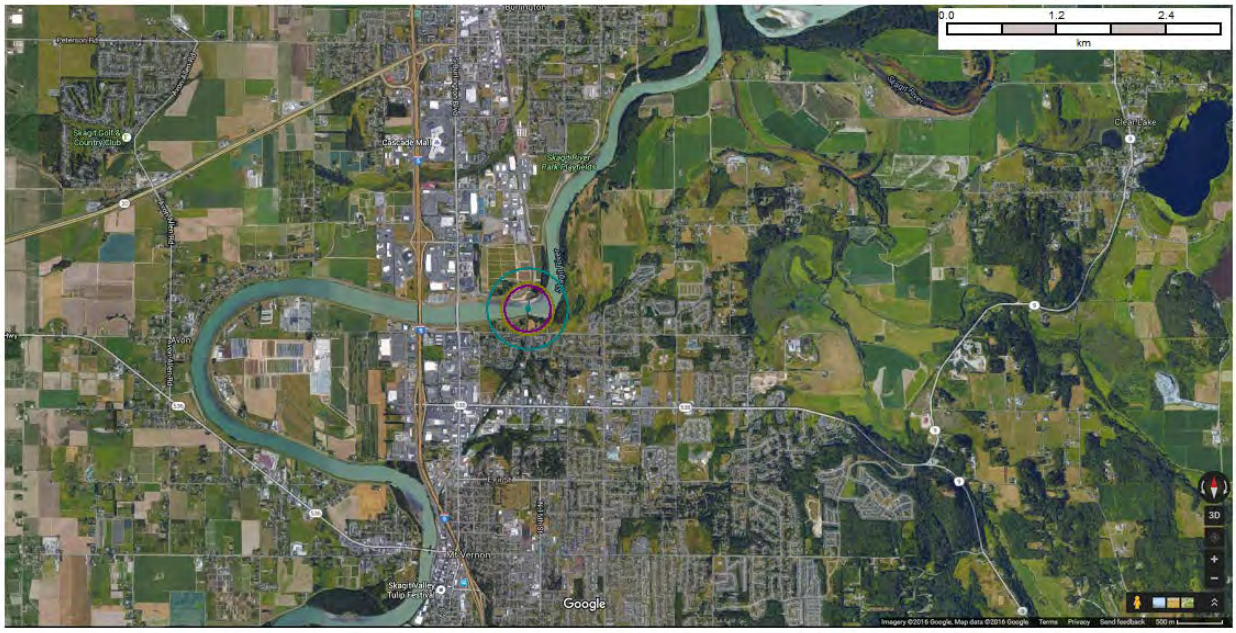
Table 14: Skagit River Crossing - Vapor Cloud Explosion

	Distance (m) to 1 psi	Distance (m) to 3.5 psi	Distance (m) to 8 psi
Volume: 28-30 cars (20,000 barrels)			
Pool Size: 135m			
Med Wind	773	508	444
High Wind	442	288	250
Volume: 7-8 cars (5,700 barrels)			
Pool Size: 135m			
Med Wind	777	509	445
High Wind	443	288	251



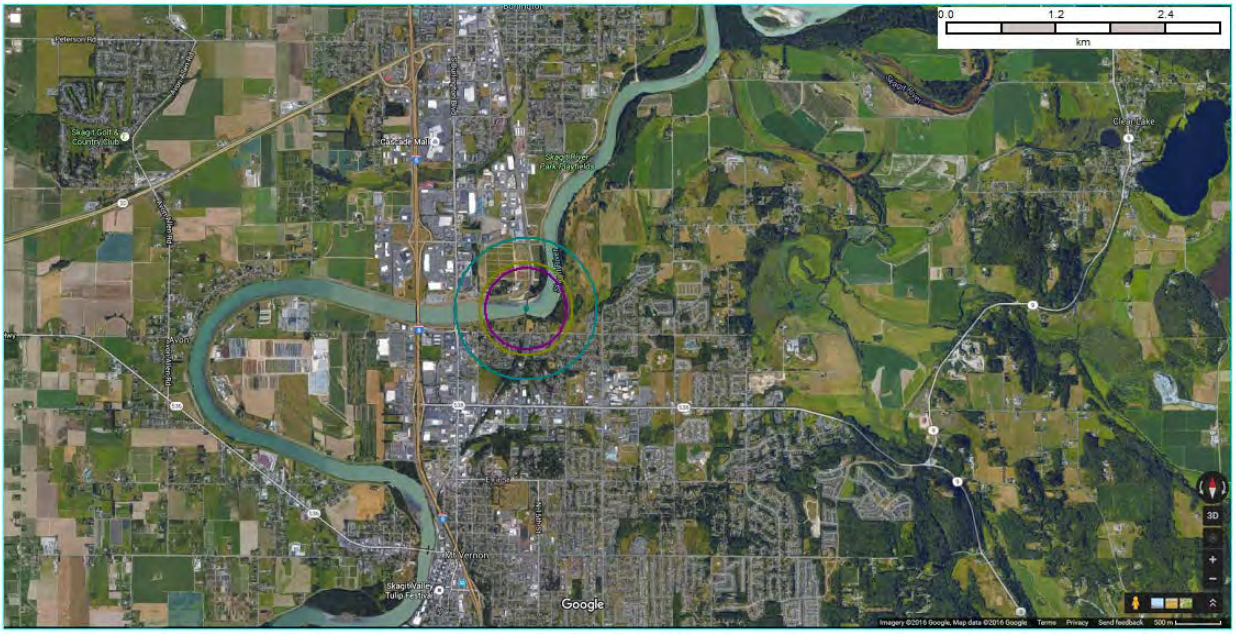
Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 26: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Skagit River Crossing - Volume 28-30 cars, Medium Wind



Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 27: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Skagit River Crossing - Volume 28-30 cars, High Wind



Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 28: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Skagit River Crossing - Volume 7-8 cars, Medium Wind

Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 29: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Skagit River Crossing - Volume 7-8 cars, High Wind

4.4 Edmonds Ferry Terminal

Releases occurring at the Edmonds Ferry Terminal location are presented in this section.

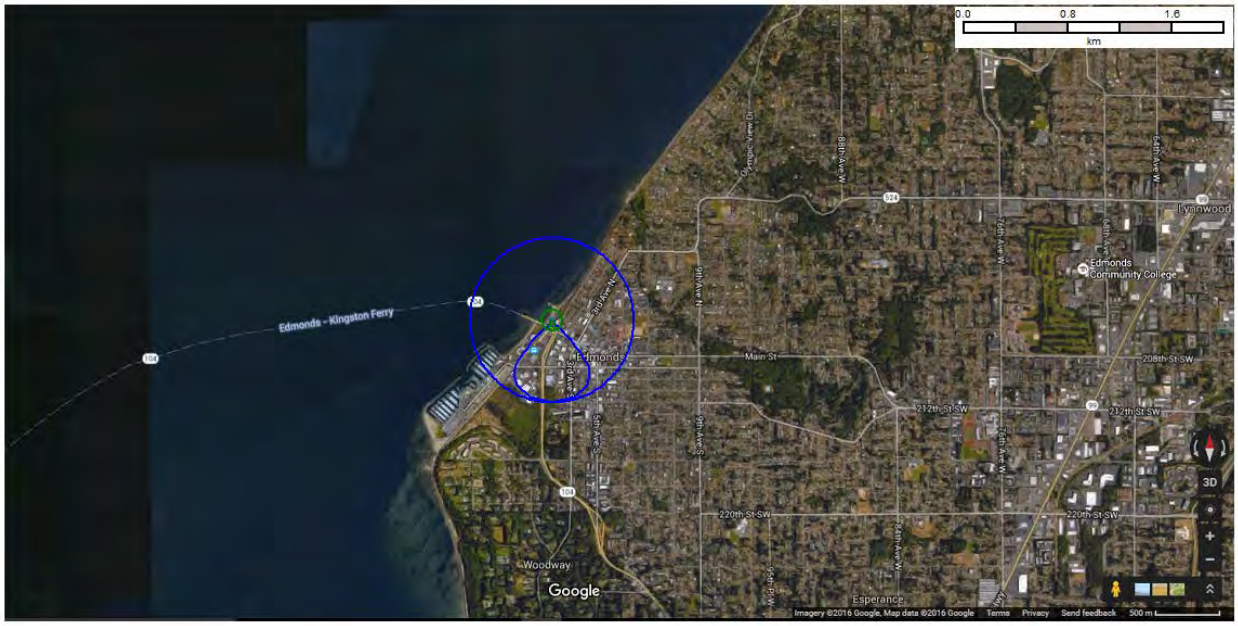
The releases at this location were modeled on land and constrained from spreading due to the topography and drainage at the site, which resulted in the distances being similar for the 5,700-barrel and 20,000-barrel release scenarios. The releases differed in the quantities released, which, in turn, controlled the duration of the dispersion process.

Because the release location was in a coastal region, hydrocarbon vapor could disperse either over land or over open water. The dispersion was highly affected by the surface over which it occurred, therefore, results are shown for the Edmonds Ferry Terminal as two circular impact areas of different radii.

Calculated distances to the upper and lower flammability limits for the 5,700-barrel and 20,000-barrel release scenarios for the Edmonds Ferry Terminal are presented below in Table 14 and shown in Figure 30 to Figure 34. Distances were measured from the center of the pool. The pool size was the same for both release quantities as both pools were constrained by the land topography. At the higher wind speed, the UFL was reached at 125 meters over water, but dispersion over land was reduced by the turbulence to 24 meters. The farthest extent of flammable concentration reached 776 meters from the pool center over water, and 89 meters in the land direction, as shown in Figure 33Figure 5.

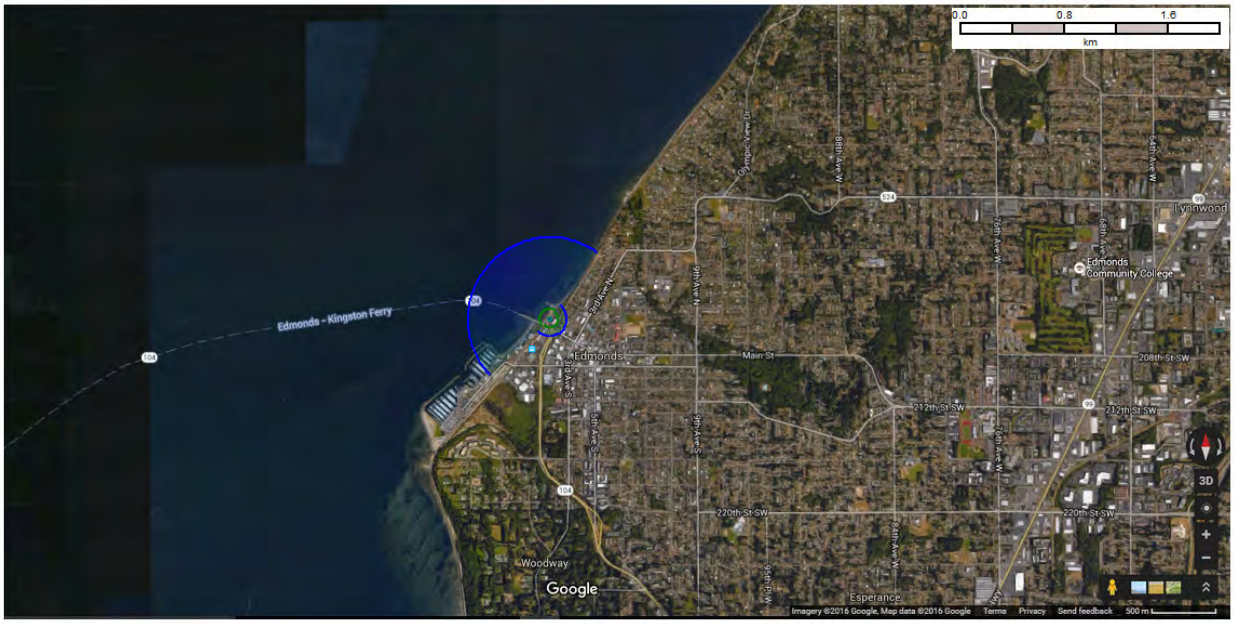
Table 15: Edmonds Ferry Terminal - Dispersion Distances (m) (at "Open Water"/ "City")

	UFL	LFL
Volume: 28-30 cars (20,000 barrels)		
Pool Size: 36.4m		
Med Wind	83 / 34	631 / 78
High Wind	125 / 24	346 / 77
Volume: 7-8 cars (5,700 barrels)		
Pool Size: 32m		
Med Wind	91 / 43	776 / 89
High Wind	112 / 25	384 / 76



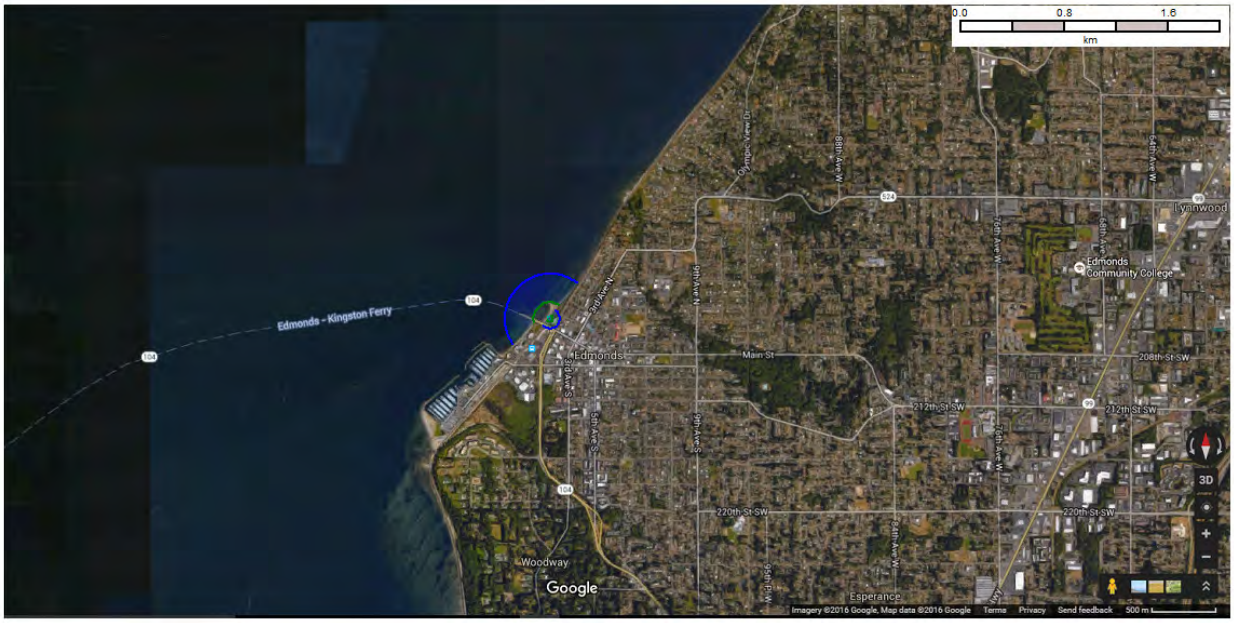
UFL LFL

Figure 30: Dispersion impact zone showing vapor cloud footprint in a single direction and its rotation showing all possible locations flammable vapor may reach -
Edmonds Ferry Terminal - Volume 28-30 cars, Medium Wind



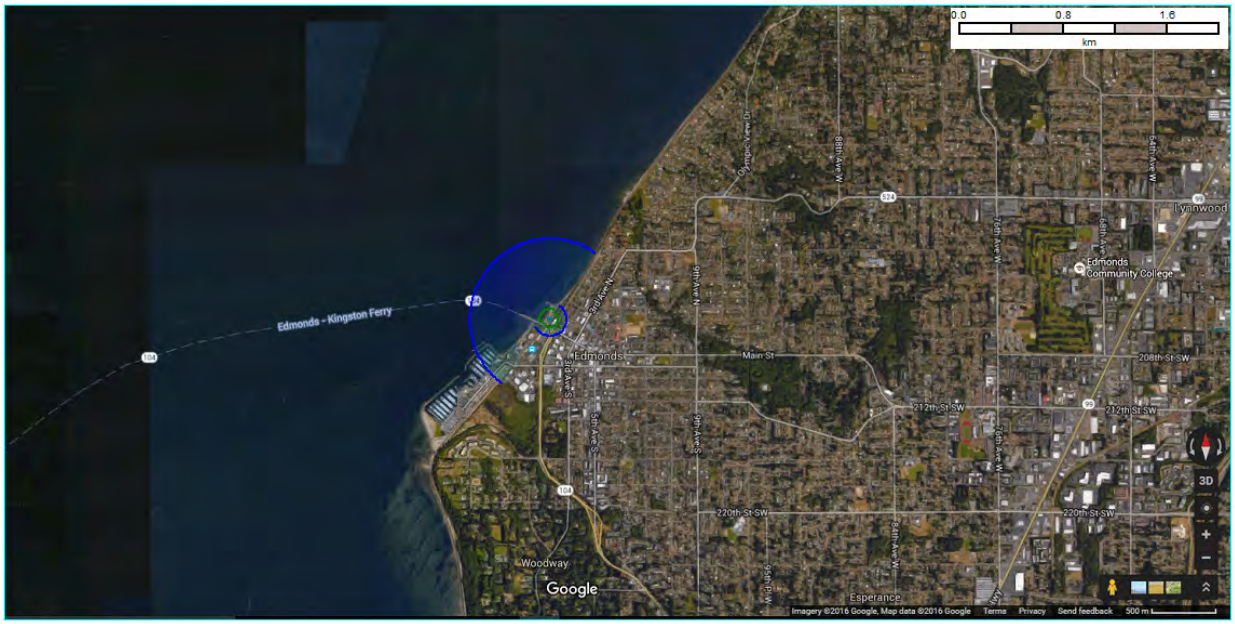
UFL LFL

Figure 31: Flammable impact zone showing area within which ignition is possible between green and blue circles - Edmonds Ferry Terminal - Volume 28-30 cars, Medium Wind



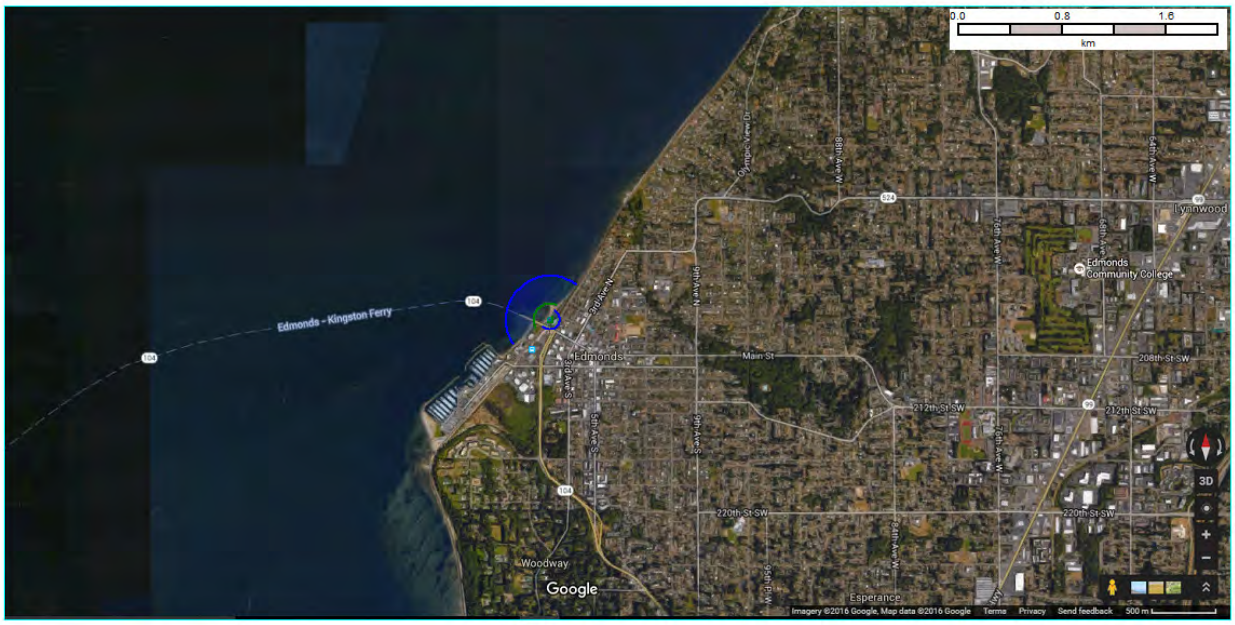
UFL LFL

Figure 32: Flammable impact zone showing area within which ignition is possible between green and blue circles - Edmonds Ferry Terminal - Volume 28-30 cars, High Wind



UFL LFL

Figure 33: Flammable impact zone showing area within which ignition is possible between green and blue circles - Edmonds Ferry Terminal - Volume 7-8 cars, Medium Wind



UFL LFL

Figure 34: Flammable impact zone showing area within which ignition is possible between green and blue circles - Edmonds Ferry Terminal - Volume 7-8 cars, High Wind

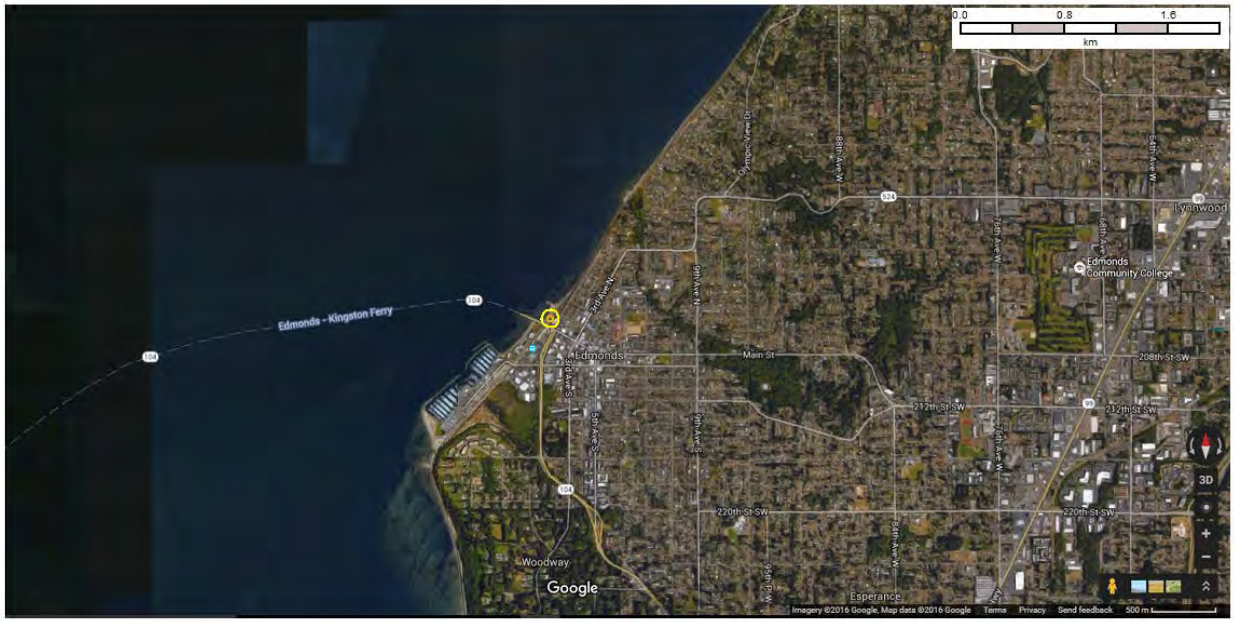
Calculated distances to thermal radiation limits for the 5,700-barrel and 20,000-barrel release scenarios are presented in – Figure 12. Distances to 12.5 kW/m2—if unprotected, a level at which pain would occur in approximately 4 seconds, second-degree burns after 40 seconds, and 50-percent lethality in approximately 80 seconds—remained well within the pool itself, at less than 23 meters (m) from the center for both wind speeds. There was no difference between the two release quantities because the pool radius controls the radiation levels and the pool radius is limited by the topography for both spill quantities. The distances to 4.0 kW/m2— a level at which pain would occur in approximately 15 seconds, and also the level at which protective clothing must be worn for human health and safety—is between 56 and 75 m., which would expose Brackets Landing and frontage businesses, but not extend to Sunset Avenue. Sheltering inside a building would effectively protect public from this exposure. The severe damage level, 37.5 kW/m2 was not reached for any pool fire in this study.

Table 16: Edmonds Ferry Terminal - Early Pool Fire Radiation (m) (at "Open Water"/ "City")

	4 kW/m²	**12.5 kW/m²**	**37.5 kW/m²**
Volume: 28-30 cars (20,000 barrels)			
Pool Size: 36.4m			
Med Wind	66 / 66	22 / 22	Not Reached
High Wind	75 / 75	23 / 23	Not Reached
Volume: 7-8 cars (5,700 barrels)			
Pool Size: 32m			
Med Wind	56 / 56	19 / 19	Not Reached
High Wind	67 / 67	21 / 21	Not Reached

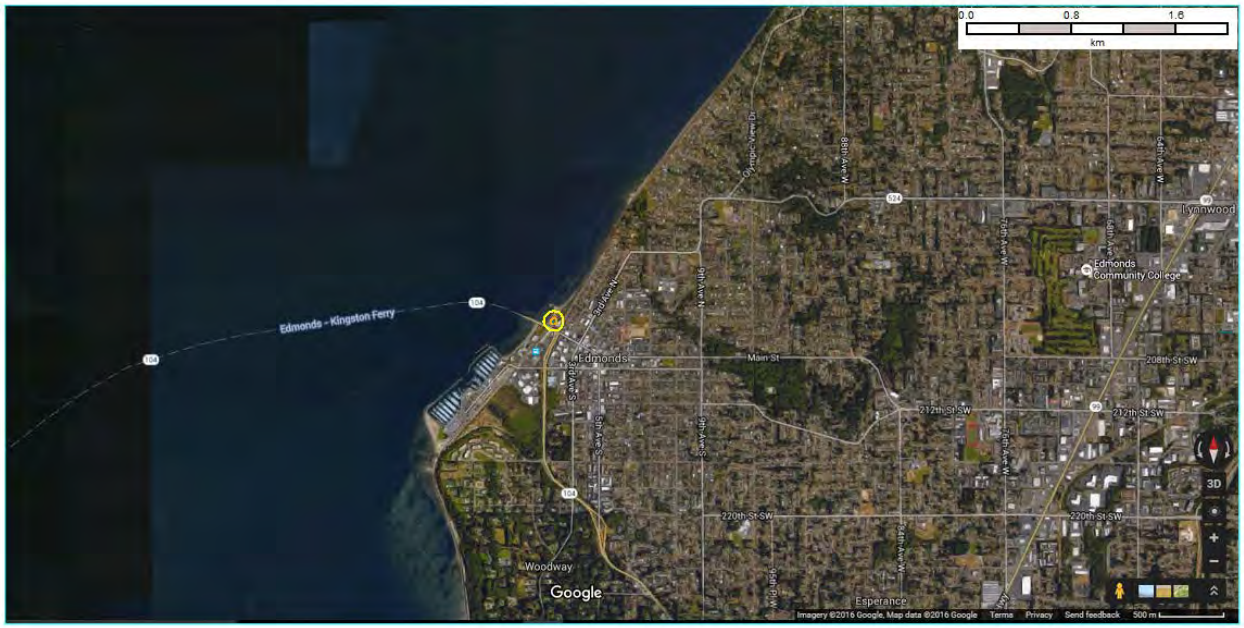
Table 17: Edmonds Ferry Terminal - Early Pool Fire Radiation (m) (at "Open Water"/ "City")

	4 kW/m²	**12.5 kW/m²**	**37.5 kW/m²**
Volume: 28-30 cars (20,000 barrels)			
Pool Size: 36.4m			
Med Wind	66 / 66	22 / 22	Not Reached
High Wind	75 / 75	23 / 23	Not Reached
Volume: 7-8 cars (5,700 barrels)			
Pool Size: 32m			
Med Wind	56 / 56	19 / 19	Not Reached
High Wind	67 / 67	21 / 21	Not Reached



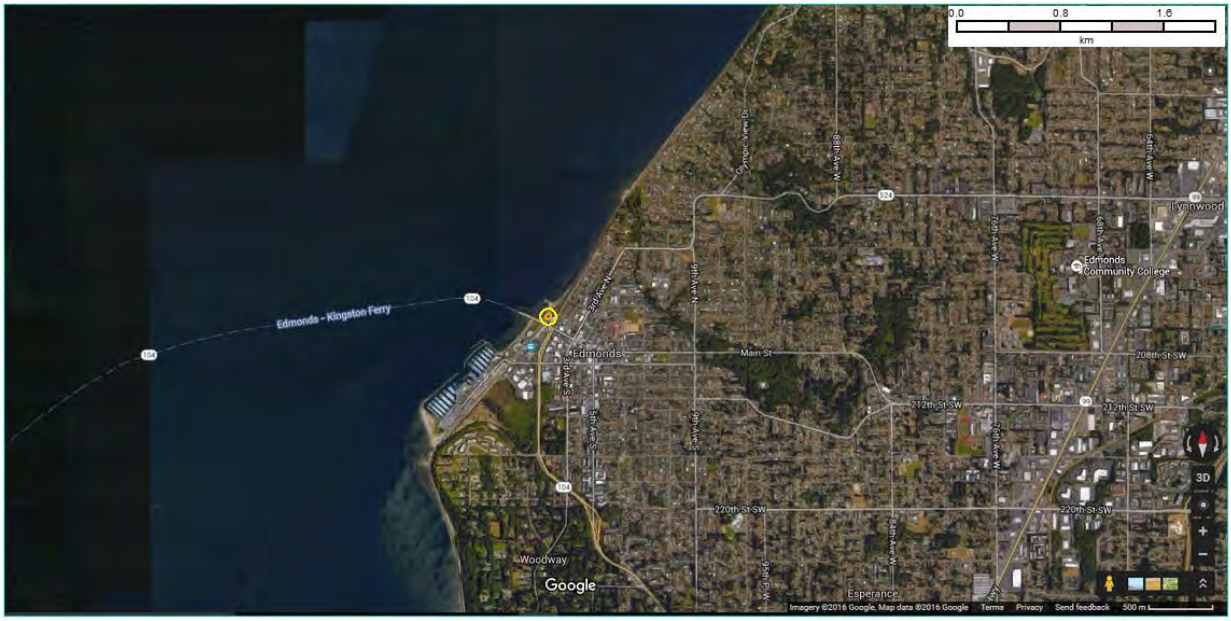
4 kW/m² 12.5 kW/m²

Figure 35: Thermal radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Edmonds Ferry Terminal - Volume 28-30 cars, Medium Wind



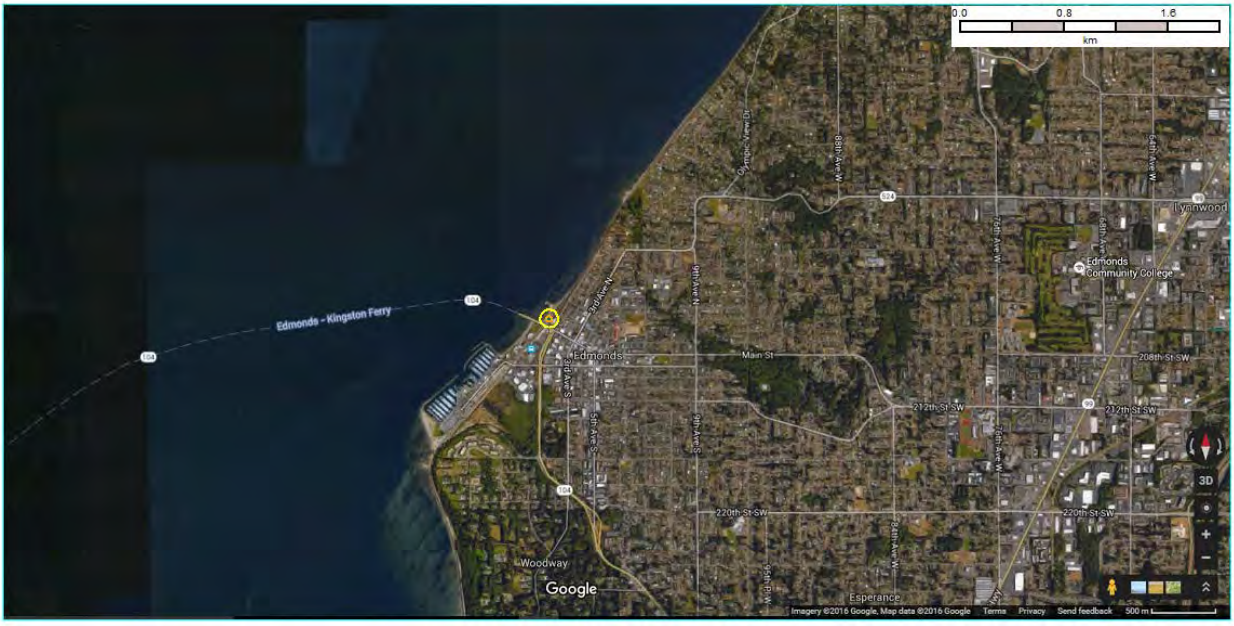
4 kW/m² 12.5 kW/m²

Figure 36: Thermal radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Edmonds Ferry Terminal - Volume 28-30 cars, High Wind



4 kW/m² 12.5 kW/m²

Figure 37: Thermal radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Edmonds Ferry Terminal - Volume 7-8 cars, Medium Wind



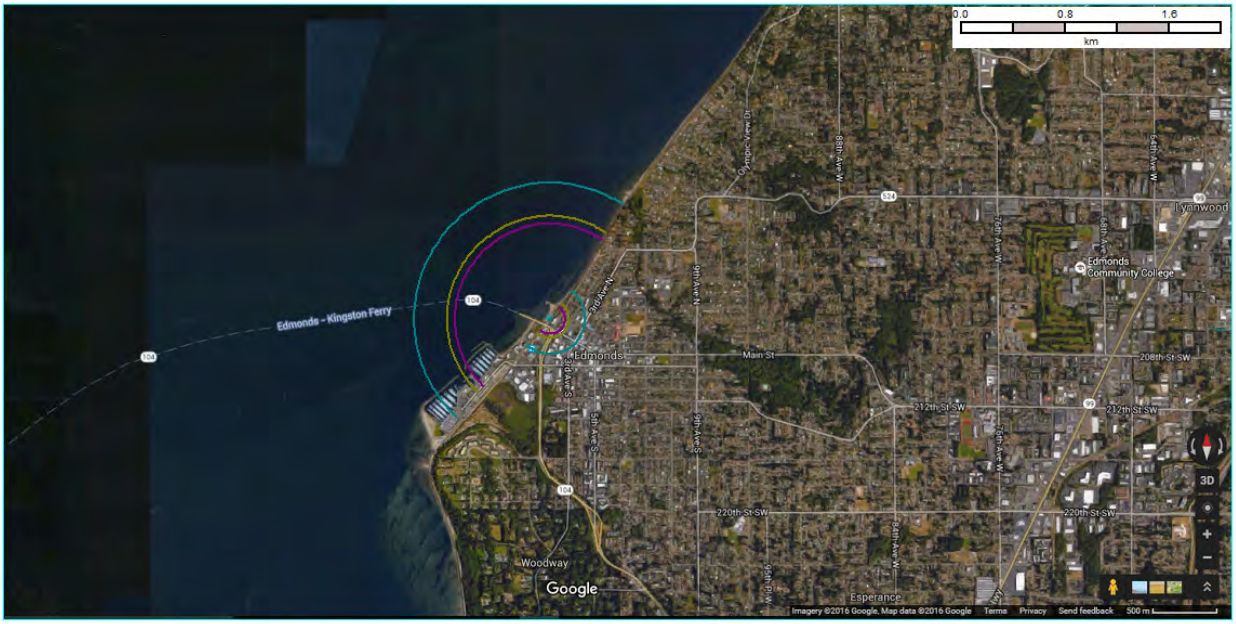
4 kW/m² 12.5 kW/m²

Figure 38: Thermal radiation impact areas (late pool fire) showing levels for injury, where protection is required (yellow) and 50-percent lethality in approximately 80 seconds (gold) - Edmonds Ferry Terminal - Volume 7-8 cars, High Wind

In Table 17 and Figure 39 through Figure 42, blast overpressures from postulated vapor cloud explosions are presented for the Edmonds Ferry Terminal. The calculated maximum distance to the destruction of buildings was 874 m over water and 137 m towards the city. The maximum distances to serious injury and glass breakage were 938 m and 1204 m over water and 172 m and 317 m over land, respectively. In this release location, there was some residential and light commercial buildings within the impact zones for blast overpressure.

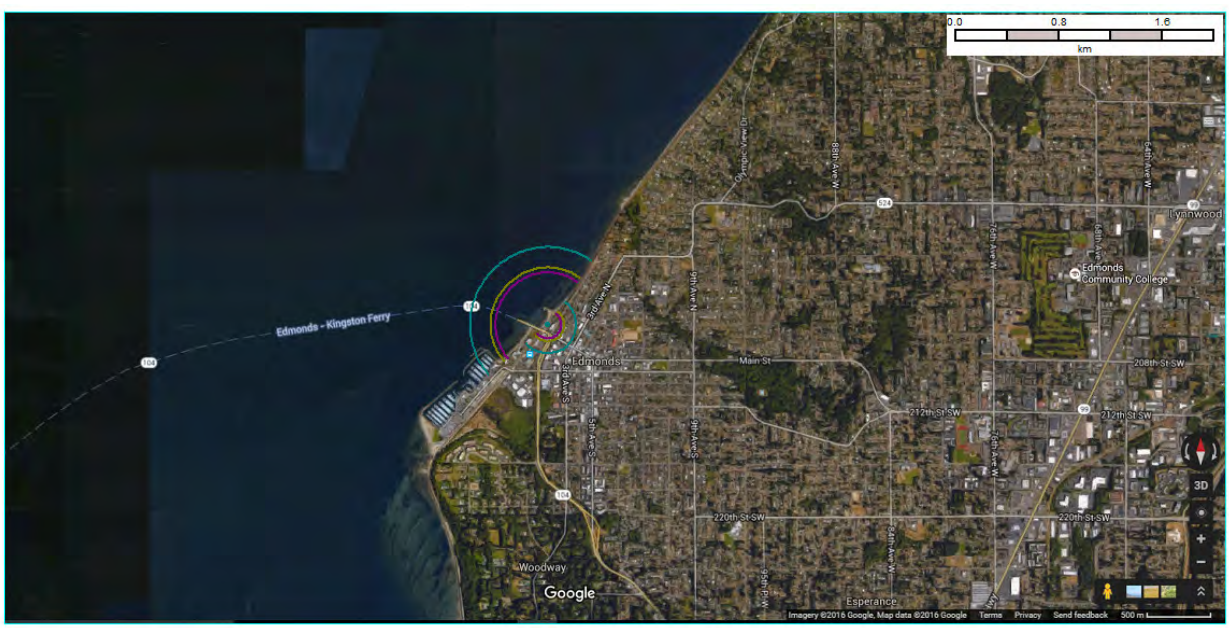
Table 18: Edmonds Ferry Terminal - Vapor Cloud Explosion (at "Open Water"/ "City")

	Distance (m) to 1 psi	Distance (m) to 3.5 psi	Distance (m) to 8 psi
Volume: 28-30 cars (20,000 barrels)			
Pool Size: 36.4m			
Med Wind	1045 / 273	790 / 148	729 / 119
High Wind	599 / 221	440 / 129	402 / 106
Volume: 7-8 cars (5,700 barrels)			
Pool Size: 32m			
Med Wind	1204 / 317	938 / 172	874 / 137
High Wind	667 / 228	491 / 131	449 / 108



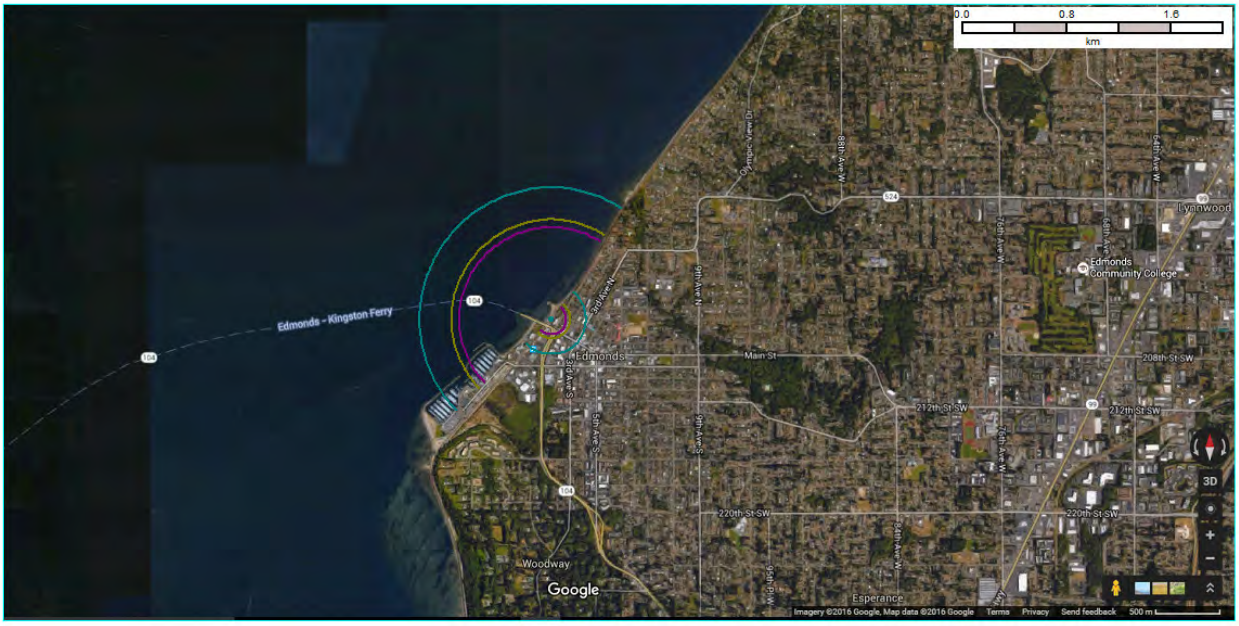
Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 39: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Edmonds Ferry Terminal - Volume 28-30 cars, Medium Wind



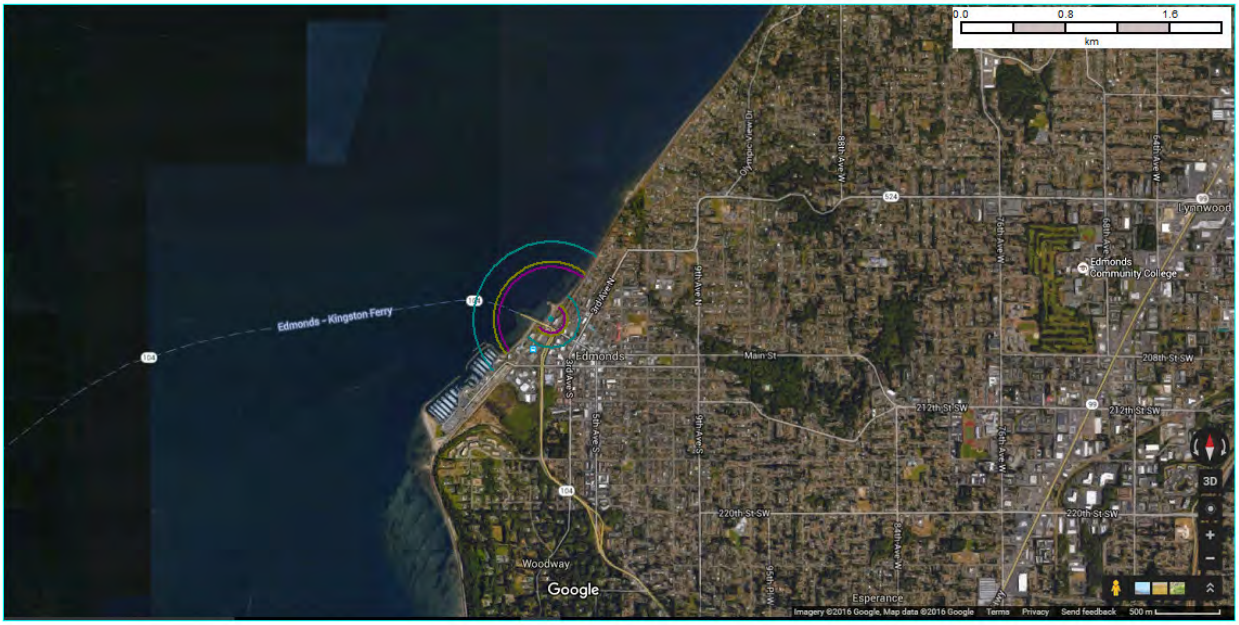
Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 40: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Edmonds Ferry Terminal - Volume 28-30 cars, High Wind



Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 41: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Edmonds Ferry Terminal - Volume 7-8 cars, Medium Wind



Distance to 1 psi Distance to 3.5 psi Distance to 8 psi

Figure 42: Vapor cloud explosion impact areas showing levels for glass breakage (teal), serious injury (olive) and destruction of buildings (magenta) - Edmonds Ferry Terminal - Volume 7-8 cars, High Wind

4.5 BLEVE

Overpressure impacts from BLEVEs do not depend upon the environmental conditions or the spill size. They do depend upon the quantity and properties of the fuel being heated in the tank car, and the strength of the steel vessel. The results below were tabulated to represent the range of BLEVE impacts with three different assumptions about the number of tank cars involved. These results can be applied to any of the study locations.

Table 19: BLEVE distances (m)

	Distance (m) to 1 psi	Distance (m) to 3.5 psi	Distance (m) to 8 psi
Volume			
1 tank car (650 barrels)	157	74	46
7 tank cars (4,550 barrels)	476	225	139
28 tank cars (18,200 barrels)	300	142	88

5 Conclusions

This report identifies and evaluates public exposure from fire and/or explosion from potential crude oil releases, including pool fires, vapor cloud explosions, and BLEVEs. The consequences of these releases are considered HCLP events.

The frequency and return period of these potential events were calculated for this analysis. The calculated average frequency of a pool fire would be 0.000103 pool fires per year or one in every 9,689 years. The calculated average frequency of a vapor cloud explosion would be 0.000031 vapor cloud explosion per year or one in every 32,300 years. It was not possible to calculate the frequency or return period of a BLEVE. The number of historic BLEVEs that have occurred is insufficient; therefore, no analogous data set can be used as a substitute.

The potential consequences of a pool fire are measured by the level of exposure to thermal radiation (heat) that people could experience, specifically the exposure levels beginning at the center of the pool fire and then moving out from the center (i.e., thermal radiation levels decrease as the distance from the center of the pool fire increases). Table 20 presents the maximum distances from the center of a pool fire at which different modeled levels of thermal radiation would be experienced at each hypothetical release location.

Table 20. Thermal Radiation from a Pool Fire

	Level of Thermal Radiation					
	Pain within 15 to 20 seconds and injury after 30 seconds (4 kW/m²)		**Extreme pain within 20 seconds of exposure; movement to shelter is instinctive; fatality if escape is not possible (12.5 kW/m²)**		**Immediate fatality (35 kW/m²)**	
	Maximum Distance from Pool Fire (meters) under all Scenarios					
	Early Pool Fire	**Late Pool Fire**	**Early Pool Fire**	**Late Pool Fire**	**Early Pool Fire**	**Late Pool Fire**
Swinomish Channel Swing Bridge						
5,700-Barrel Release	136 meters	203 meters	49 meters	74 meters	--	--
20,000-Barrel Release	136 meters	203 meters	49 meters	74 meters	--	--
Skagit River Crossing						
5,700-Barrel Release	136 meters	199 meters	48 meters	72 meters	--	--
20,000-Barrel Release	136 meters	199 meters	48 meters	72 meters	--	--
Edmonds Ferry Terminal (water/land)						
5,700-Barrel Release	67/67 meters	67/67 meters	21/21 meters	21/21 meters	--	--
20,000-Barrel Release	75/75 meters	75/75 meters	23/23 meters	23/23 meters	--	--

Note: The 35 kW/m² level of thermal radiation was not reached under any scenario. The modeling at the Edmonds Ferry Terminal includes analysis of land and water.

The potential consequences of a vapor cloud explosion are measured by the overpressure generated by a shockwave and consider the impacts on people and structures at various distances relative to the center of the explosion. Table 21 presents the distance from the explosion at which different levels of overpressure would be experienced.

Table 21. Overpressure from a Vapor Cloud Explosion

	Level of Overpressure		
	Window glass shatters and light injuries from fragments (1 psi)	**Residential structures collapse and serious injuries are common (3.5 psi)**	**Destruction of Buildings and most people are killed (8 psi)**
	Maximum Distance from Vapor Cloud Explosion (meters) under all Scenarios		
Swinomish Channel Swing Bridge			
5,700-Barrel Release	1,164 meters	837 meters	758 meters
20,000-Barrel Release	1,156 meters	834 meters	756 meters
Skagit River Crossing			
5,700-Barrel Release	777 meters	509 meters	444 meters
20,000-Barrel Release	773 meters	508 meters	444 meters
Edmonds Ferry Terminal (water/land)			
5,700-Barrel Release	1,204/317 meters	938/172 meters	729/119 meters
20,000-Barrel Release	1,045/273 meters	790/148 meters	729/119 meters

Note: The modeling at the Edmonds Ferry Terminal includes analysis of land and water.

In the event of a BLEVE, the resulting overpressure from the explosion was analyzed. Table 22 presents the distance from the explosion at which different levels of overpressure would be experienced.

Table 22. Overpressure from a Potential BLEVE

	Level of Overpressure		
	Window glass shatters and light injuries from fragments (1 psi)	**Residential structures collapse and serious injuries are common (3.5 psi)**	**Destruction of Buildings and most people are killed (8 psi)**
	Maximum Distance from BLEVE (meters)		
1 tank car (650 barrels)	157 meters	74 meters	46 meters
7 tank cars (4,550 barrels)	300 meters	142 meters	88 meters
28 tank cars (18,200 barrels)	476 meters	225 meters	139 meters

6 References

Cox, A.W., F.P. Lees, and M.L. Ang. 1990. Classification of Hazardous Locations. IIGCHL. IchemE.

DNV 2010a. Obstructed Region Explosion Model (OREM) Theory, DNV Software, London. March 2010.

DNV 2010b. Software, PVAP Theory Document. Det Norske Veritas, London. 2010.

U.S. Department of Transportation (USDOT). 1990a. 49CFR179. 49 CFR Appendix B to Part 179—Procedures for Simulated Pool and Torch-Fire Testing, which describes a test designed to measure thermal effects on DOT 111 railcars.

U.S. Department of Transportation (USDOT). 1990b. 49CFR171b. 49 CFR Part 179,201-1 - Maximum bursting pressure specified for DOT 111 railcars on §179.201-1 - Individual specification requirements.

U.S. Environmental Protection Agency (USEPA). 1990. 40CFR68.112(r)(7), Clean Air Act, Risk Management Program (RMP) Rule. 1990.

Etkin, Dagmar Schmidt. 2016. Crude-by-Rail Spill Risk Analysis for Proposed Shell Puget Sound Refinery (PSR) Rail Unloading Facility: Rail Spill Probability and Volume Analysis, Environmental Research Consulting. March 18, 2016.

Haddad. 1981. Hazard and Risk Assessment in Urban Planning. UNSW Seminar, copies from New South Wales Department of Planning and Environment, 21 pp. 1981.

Horn. 2016. Evaluation of Hydrocarbon Releases from Crude-by-Rail using Trajectory, Fate, and Effects Modeling for the Shell Puget Sound Refinery Environmental Impact Statement. RPSASA. April 22, 2016.

Hymes, J. 1983. The Physiological and Pathological Effects of Thermal Radiation. SRD Report R275. UKAEA. September 1983.

National Oceanic and Atmospheric Administration (NOAA). 2016. Overpressure Levels of Concern. Available online: http://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/overpressure-levels-concern.html.

OGP. 2010. Risk Assessment Data Directory, Vulnerability of Humans. Report No. 434 – 14.1, International Association of Oil and Gas Producers. March.

Shell. 2015. Crude Oil Evaluation Data Sheet (COED), Reference BAKK20140703. November 30, 2015.

TNO. 1989. Methods for the Determination of Possible Damage to People and Objects Resulting from Release of Hazardous Materials. CPR 16E, Voorburg. December 1989.

TNO. 1997. Methods for the calculation of physical effects, (The Yellow Book), CPR14E. Sdu Uitgevers, The Hague. 1997.Glasstone S, Dolan PJ, eds. [1977]. The effects of nuclear weapons. 3rd ed. U.S. Department of Defense and the Energy Research and Development Administration.

Sartori, L. [1983]. The effects of nuclear weapons, Physics Today, March, pp. 32-41.

Appendix A: Summary Report

Provided as a separate file.

Appendix B: Selection of Surface Roughness Length

The Surface Roughness Length represents the height above the ground at which the wind speed goes to zero. Surface roughness affects the height that a particle moves from the ambient air flow above the ground (for example in the vapor cloud) into a "captured" deposition region near the ground. That is, the vapor dispersion analysis assumes that the "vapor particle" will remain stagnant once it reaches a certain point above the actual land surface, based on surface roughness height. Surface roughness height is defined by individual elements on the landscape, such as trees, buildings, and other obstructions. The surface roughness parameter is defined as 1/30 of the effective average height of protuberances over the terrain.

To be consistent with the recommended method for determining land use for dispersion coefficients, the land use located downwind of the release is generally acceptable for determining surface roughness. The following surface roughness parameters are available in PHAST 7.11:

0.2mm - Open water
5mm - Mud flats or snow; No vegetation, no obstacles
30 mm - Open flat terrain; Grass, few isolated objects
10 cm - Low crops; Occasional large obstacles
25 cm - High crops; Scattered large obstacles
50 cm - Parkland, bushes; Numerous obstacles
1m - Regular large obstacle coverage (suburb, forest)
3m - City centre with high and low rise buildings

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