PEMBINA CORUNNA STORAGE TERMINAL CAVERN
Hazard and Quantitative Risk Assessment

Prepared for:
Pembina Pipeline Corporation

Prepared by:
Stantec Consulting Ltd.

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Pembina Pipeline Corporation (Pembina) operates a 4 km^2 (1,000 acre) hydrocarbon storage terminal about 1 km northeast of the town of Corunna, Ontario. The terminal has an active hydrocarbon cavern storage capacity of 810,835 m^3 with the potential to expand to 1,397,000 m^3 of storage. In addition the terminal has several pipeline connections and a small rail offloading facility.

Pembina is currently considering the conversion of Cavern 45 to hydrocarbon storage and has requested that Stantec Consulting Ltd (Stantec) conduct modelling to assess the consequences and risk associated with the proposed additional hydrocarbon storage at the terminal.

The primary hazards associated with accidental releases from the cavern wellheads result from the flammability of the fluids and includes:

- Flash Fires,
- Jet Fires and Fireballs, and
- Vapour Cloud Explosions.

Source and Consequence modelling was completed to predict extents to selected hazard end points including:

- The Lower Flammable Limit (LFL) and 50% of the LFL (LFL/2),
- Thermal dose units (TDU) anticipated to cause 2nd degree burns to an unprotected receptor, and
- 1 psi (6.89 kPa) overpressure, the distance anticipated to result in injury to individuals as a result of building damage including glass breakage

The estimated distances to selected endpoints are provided in Table E-1. The consequence modelling results are provided graphically in Figure 7-2 and Figure 7-3. The figures provide contours representing regions of potentially high consequence in the event of the release and subsequent ignition. These results can assist in the development of emergency response plans.

Risk modelling considered the likelihood of the release and weather conditions along with the associated consequence, and is provided to assist with land-use planning. The risk results are provided in Figure 7-4 and indicate that the cumulative risk associated with the existing caverns and the proposed Cavern 45 are not predicted to affect the current land use in the vicinity of the Pembina Corunna Storage Terminal.

Table E-1 Maximum Predicted Downwind Extents to Selected Consequence End Points

Cavern	Distance to Selected Consequence End Points			
	LFL	LFL/2	2nd Degree Burns	1 Psi Overpressure
45	595	1,027	348	1,278
3	1,027	1,479	520	1,320
4	909	1,346	457	1,305
5	738	1,088	451	1,184
6	580	855	403	1,067
49	590	1,015	262	<100
49a	1,230	1,901	555	2,158
51	952	1,663	486	1,817
56	609	1,029	331	1,410
59	1,002	1,695	545	2,037

Abbreviations

AER	Alberta Energy Regulator (formerly the Energy Resources Conservation Board (ERCB))
CSChE	Canadian Society of Chemical Engineers
ERP	emergency response plan
GRI	Gas Research Institute
LFL	lower flammable limit
MIACC	Major Industrial Accident Council of Canada
Pembina	Pembina Pipeline Corporation
PG	Pascal Gifford
RMP	Risk Management Program
SLEA	Sarnia-Lambton Environmental Association
Stantec	Stantec Consulting Ltd.
TDU	thermal dose unit
U.S. EPA	United States Environmental Protection Agency

1.0 INTRODUCTION

Pembina Pipeline Corporation (Pembina) operates a 4 km^2 (1,000 acre) hydrocarbon storage terminal about 1 km northeast of the town of Corunna, Ontario. The terminal has an active hydrocarbon cavern storage capacity of 810,835 m^3 with the potential to expand to 1,397,000 m^3 of storage. In addition the terminal has several pipeline connections and a small rail offloading facility.

Pembina is currently considering the conversion of Cavern 45 to hydrocarbon storage. Pembina has requested that Stantec Consulting Ltd (Stantec) conduct modelling to assess the consequences and risk associated with the addition of Cavern 45. The consequence modelling can be used to assist with the development of an emergency response plan (ERP) and the risk model can be used for Land use planning.

A primary public safety hazard associated with the storage caverns is the accidental release of flammable liquids potentially resulting in flash fires, jet fires or vapour cloud explosions. This report documents the assumptions results and conclusions associated with the consequence and risk modelling. The report will include the following major sections:

- System Description
- Hazard Identification
- Source Characterization
- Consequence Modelling
- Risk Modelling
- Results and Conclusions.

2.0 SYSTEM DESCRIPTION

The locations of the existing storage cavern wellheads and the proposed Cavern 45 wellhead are shown in Figure **2-1**. Fluid composition was provided by Pembina for each cavern and is summarized in Table 2-1. Physical operating parameters including storage volume, temperature and pressure, and fluid composition were provided by Pembina and are summarized in Table 2-2 for the assessed caverns.

Based on the information provided by Pembina there will be dual and single entry caverns. For the single entry caverns the release will be in the annulus between the brine and production casing. For the dual entry caverns the release will be through the production casing. A simplified schematic of the proposed systems is provided in Figure 2-2.

Table 2-1 Fluid Compositions for Storage Caverns

Component	Fluid Composition Identification Number			
	1	2	3	4
	Mole Fraction	Mole Fraction	Mole Fraction	Mole Fraction
Ethane	0.0345	0.8	—	—
Propane	0.9521	0.2	1.0	—
isoButane	0.0107	—	—	0.5
n-Butane	0.0027	—	—	0.5

Note:
Fluid Compositions were supplied by Pembina Pipelines Corporation.

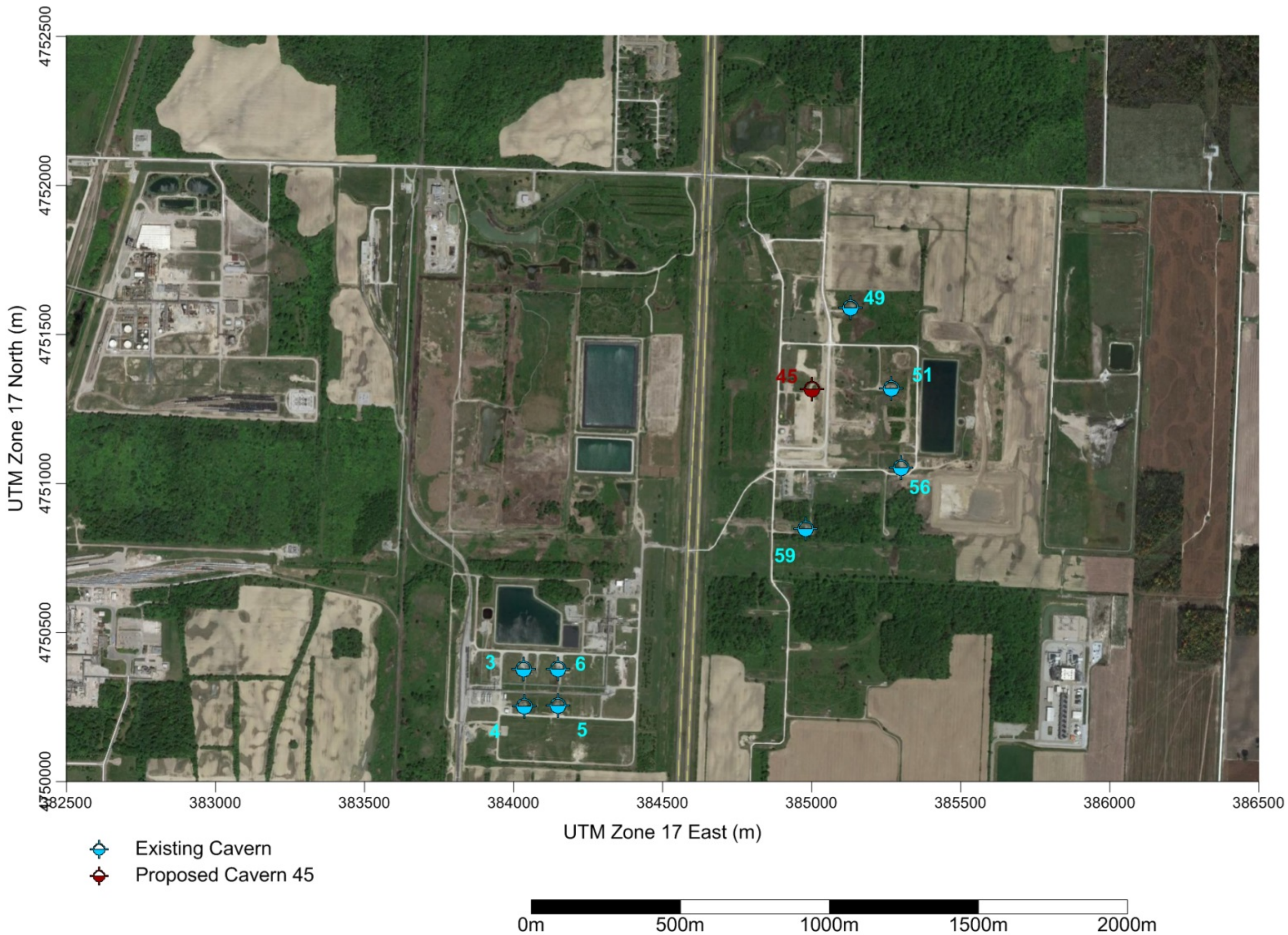

Figure 2-1 **Location of the Pembina Hydrocarbon Storage Terminal and Proposed Caverns**

Table 2-2 Physical and Operational Parameters of Proposed Cavern 45 and Existing Caverns

Cavern ID	Fluid Composition [1]	Volume (m^3)	Pressure (kPa)	Cavern Temperature (°C)	Surface Pipe Length (m)	Casing Diameter (mm)		Production Casing Depth (m)	Estimated Injection/Surface Pressure (kPa)	Injection Temperature (˚C)
						Production	Brine			
3	2	64,000	8,940	26	300	324	114	598	6,320	5
4	2	85,000	8,930	26	300	299	114	597	6,320	5
5	2	52,000	8,660	26	300	299	114	581	6,120	5
6	2	30,400	5,920	26	300	299	114	447	4,020	5
45	1	267,300	10,030	26	122	178	Dual Entry	610	6,600	5
49	3	112,200	9,680	26	300	168	60.3	579	6,510	5
49a	3	112,200	9,860	26	300	273	60.3	612	6,510	5
51	4	71,800	10,060	26	300	273	114	608	6,320	5
56	4	84,200	9,300	26	300	245	140	598	5,630	5
59	3	265,300	9,480	26	300	245	Dual Entry	579	5,910	5

Note:

1 Refer to Table 2.1 for fluid composition corresponding to number presented.

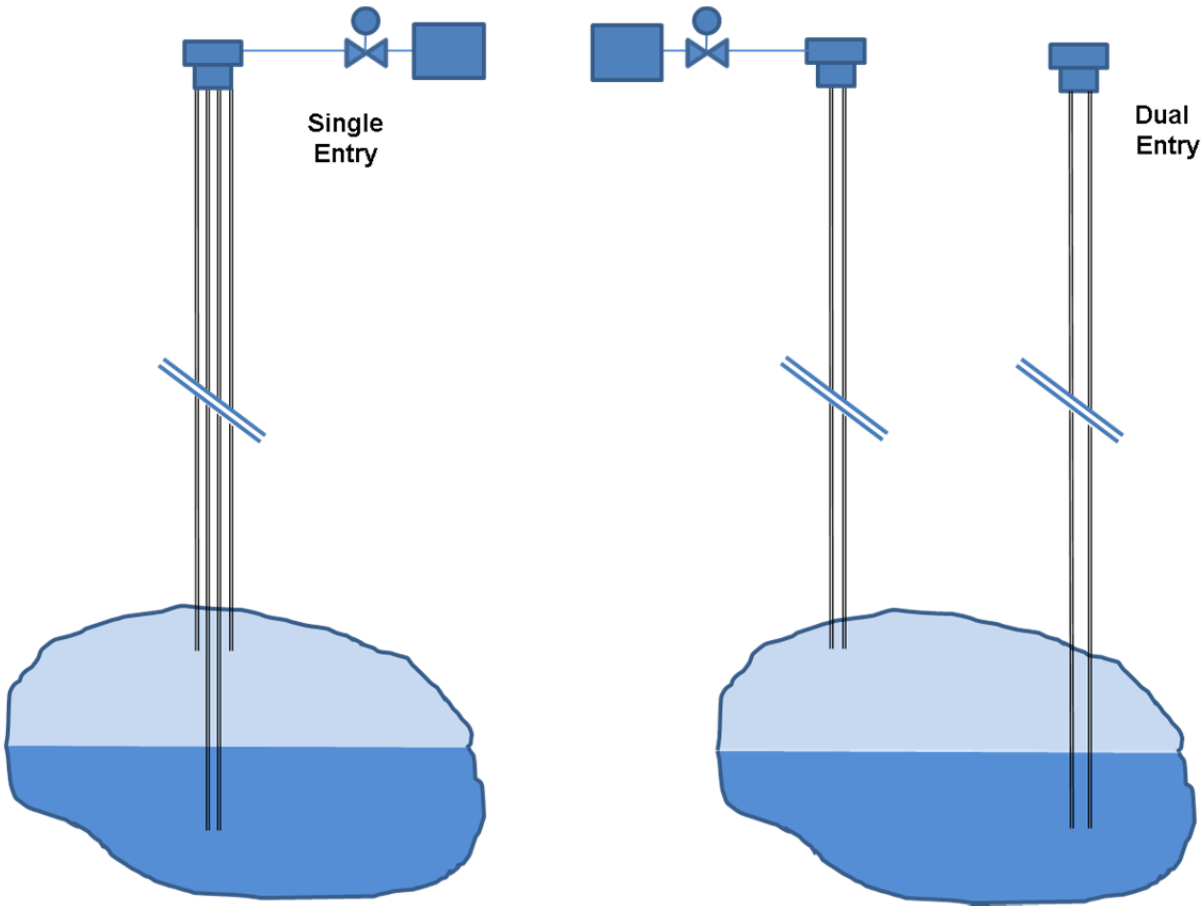

Figure 2-2 Schematic of Simplified Systems Used for Modelling Purposes

3.0 HAZARD IDENTIFICATION

The primary hazard associated with an accidental release from the Facility is associated with a dispersing gaseous cloud and the potential for a flash fire, jet fire, or vapour cloud explosion.

The primary hazards can be summarized as follows:

- **Fireball/Jet Fire:** Results from immediate ignition of the fluid, and the hazard is exposure to thermal radiation;
- **Flash Fire:** Results from delayed ignition of the dispersing vapour cloud, and the hazards are exposure to thermal radiation and direct impingement of the travelling flame front; and
- **Vapour Cloud Explosion:** If there is significant congestion in the flammable region of the vapour cloud, the flame speeds may be high enough to result in a pressure wave being

formed as the flame propagates through the region. In addition to the hazards of the flash fire, there is the potential for exposure to damaging overpressure both directly and through its impact on structures.

The thermal radiation hazards are further summarized in Table 3-1.

Table 3-1 Thermal Radiation Hazard Summary

Hazard Type	Cause	Consequence
Fireball/Jet Fire	Immediate ignition of the fluid.	Exposure to thermal radiation.
Flash Fire	Delayed ignition of the dispersing vapour cloud.	Exposure to thermal radiation and direct impingement of the travelling flame front.
Vapour Cloud Explosion	Significant congestion in the flammable region of the vapour cloud, which causes flame speeds high enough to result in the formation of a pressure wave as the flame propagates through the region.	Exposure to thermal radiation, direct impingement of the travelling flame front, and exposure to damaging overpressure (both directly and through its impact on structures).

3.1 FIREBALL/JET FIRE

The consequences of the thermal radiation hazard associated with fireballs and jet fires are often defined using a dose response relationship. The dose is a combination of the intensity level and duration of exposure and can be used to define the anticipated effects on a receiver. As an example, researchers have defined the dose required to produce first, second, and third degree burns to an unprotected receiver. Table 3-2 provides TDU ranges associated with selected consequences to an unprotected human receptor. For the current assessment, a thermal dose endpoint of 240 $(kW/m^2)^{4/3}s$ was chosen to consider the possibility of second degree burns to personnel as a result of exposure to thermal radiation.

Table 3-2 Harm vs. Thermal Dose Relationship

Harm Caused	Infrared Radiation Thermal Dose (TDU), $(kW/m^2)^{4/3}s$	
	Mean (Observations)	Range (Observations)
Pain	92	86-103
Threshold first degree burn	105	80-130
Threshold second degree burn	290	240-350
Threshold third degree burn	1,000	870-2,600

3.2 FLASH FIRE

The flammable extents of a release can be assessed by estimating the concentration of the fuel in the air as it is transported and dispersed away from the release. The lower flammable limit (LFL) is the lowest concentration at which the released fuel will support combustion in the presence of an ignition source. The LFL is used as one of the modelling endpoints to assess flammable releases. This endpoint is identified in the United States Environmental Protection Agency (U.S. EPA) Risk Management Program (RMP) Guidance (2004) documentation, and is one of the end points used for an alternate assessment of flammable hazards (U.S. EPA 2009). The class of dispersion models typically used for this type of assessment produce time and ensemble average concentration calculations downwind of the release location. These models do not directly account for atmospheric concentration fluctuations that can occur during a release event. These models predict the expected time averaged concentration based on a large number of similar events (referred to as an ensemble average). As a result, many jurisdictions consider some fraction of the LFL concentration to account for the variability about the ensemble mean. As an example, the United Kingdom Health and Safety Executive (UK HSE) considers the extents of the half of the LFL (LFL/2) to be the footprint of a potential flash fire, but will consider arguments and data put forward by a company to support use of the LFL as the extents of a potential flash fire (UK HSE 2007). This assessment will estimate the downwind extents to the LFL and LFL/2 concentrations to provide an indication of the potential region affected by a flash fire in the event of an accidental release and subsequent delayed ignition.

3.3 VAPOUR CLOUD EXPLOSION

A vapour cloud explosion occurs when the flame speeds within a flash fire are high enough to generate a damaging overpressure wave. The primary consequence of a vapour cloud explosion is the overpressure (the pressure above atmospheric pressure) that a receiver or structure is subjected to as a result of the rapidly advancing flame front. At high levels, the overpressure can cause direct damage to an individual such as rupturing of eardrums or hemorrhaging of the lungs. In addition, at lower levels, the overpressure may cause significant damage to buildings and structures, such as shattering of glass and structural failure. A vapour cloud explosion requires significant congestion to generate the flame speeds necessary to generate damaging overpressures. For example, a complex three dimensional network of piping and vessels found at a congested facility or a dense forested area may result in flame speeds high enough to develop a vapour cloud explosion. In addition, it is generally accepted that only the vapour within the flammable limits and in the congested region contributes substantially to the overpressure. The consequences of this hazardous event will be reviewed in terms of the distance to selected overpressure levels. Overpressure effects are summarized in Table 3-3.

Table 3-3 Overpressure Effects

Pressure		Damage
(psi)	(kPa)	
0.02	0.14	Annoying noise (137 dB), if of low frequency (10-15 Hz)
0.03	0.21	Occasional breaking of large glass windows already under strain
0.04	0.28	Loud noise (143 dB), sonic boom glass failure
0.1	0.69	Breakage of small windows under strain
0.15	1.03	Typical pressure for glass breakage
0.3	2.07	"Safe distance" (probability 0.95 no serious damage beyond this value); projectile limit; some damage to house ceilings; 10% window glass broken
0.4	2.76	Limited minor structural damage
0.5-1.0	3.45-6.89	Large and small windows usually shattered; occasional damage to window frames
0.7	4.83	Minor damage to house structures
1.0	6.89	Partial demolition of houses, made uninhabitable
1-2	6.89-13.8	Corrugated asbestos shattered; corrugated steel or aluminum panels, fastenings fail, followed by buckling; wood panels (standard housing) fastenings fail, panels blowing
1.3	8.96	Steel frame of clad building slightly distorted
2	13.8	Partial collapse of walls and roofs of houses
2-3	13.8-20.7	Concrete or cinder block walls, not reinforced, shattered
2.3	15.9	Lower limit of serious structural damage
2.5	17.2	50% destruction of brickwork of houses
3	20.7	Heavy machines (3,000 lb) in industrial buildings suffered little damage; steel frame building distorted and pulled away from foundations
3-4	20.7-27.6	Frameless, self-framing steel panel building demolished; rupture of oil storage tanks
4	27.6	Cladding of light industrial buildings ruptured
5	34.5	Wooden utility poles snapped; tall hydraulic press (40,000 lb) in building slightly damaged
5-7	34.5-48.3	Nearly complete destruction of houses
7	48.3	Loaded train wagons overturned
10	68.9	Probable total destruction of buildings; heavy machine tools (7000 lb) moved and badly damaged, very heavy machine tools (12,000 lb) survived
300	2068	Limit of crater lip.

NOTE:
Based on Canadian Society for Chemical Engineering (2004).

4.0 SOURCE CHARACTERIZATION

Source characterization is conducted to estimate the source conditions required for consequence modelling. The source properties that can influence the subsequent consequence modelling include:

- Release rate;
- Source temperature;
- Source liquid mass fraction; and
- Source area.

In addition, physical properties of the fluid, such as the flammability limits, heat of combustion, and heat of vapourization, can have a direct impact on the consequence modelling.

A release from a storage cavern will result in a transient release that decays to a near steady state. The initial release rate, how fast this rate decays, and the total duration of the release will depend, in part, on the vapour pressure of the fluid at the storage temperature. For this assessment, the exit conditions are estimated as a function of time by solving the time varying mass, momentum, and energy equations for the fluid flowing within the pipeline. These calculations assume the fluid is “real” and compressible (compressible flow terms are included in the analysis). The “real” fluid properties are estimated using the Peng-Robinson equation of state.

The source conditions used in the consequence modelling were estimated through mass, momentum, and energy balances from the exit plane (plane at which the release exits the pipeline) to the source plane (plane at which the fluid has expanded to ambient pressure; used as the source for the subsequent dispersion modelling). As the fluid moves between the exit plane and the source plane, it is assumed that there is no heat transfer between the fluid and its surroundings (i.e., the fluid expands adiabatically) and the fluid does no work on its surroundings. In the event that the flow is “choked” at the exit plane (i.e., the exit plane pressure is higher than the ambient pressure), an estimate of the expanded conditions is made.

The interaction between the high-speed fluid jet and its surroundings near the release is uncertain.

An obstruction drag coefficient was used to account for the loss of momentum that may occur as the jet interacts with piping or other equipment in the vicinity of the wellhead. The specified obstruction drag coefficient defines the reduction in velocity that results if an obstruction exists between the exit plane and the source plane. The obstruction drag is represented by a coefficient that varies between 0 and 4. A value of 0 represents no obstruction and results in a high speed jet that contains the maximum kinetic energy. A value of 4 results in the stream transferring essentially all of its kinetic energy into thermal energy due to the obstruction, resulting in a low speed cloud.

For this assessment, obstruction drag coefficients of 0, 1, and 2 (0%, 40%, and 66% reduction in stream velocity) were considered. The fluid properties at ambient pressure, after the consideration of the obstruction drag, were estimated using the Peng-Robinson equation of state. For the fluids considered in this assessment rain-out of liquid droplets during at least a portion of the release is anticipated but conservatively (consequences will be overstated) ignored.

In addition the release scenarios were conducted for a range of hole sizes, defined as area ratios of 10%, 50%, and 100% of the wellhead cross sectional area. For the current assessment the simplified system depicted in Figure 2-2 was assumed for the purpose of source modelling. This modelling considered backflow from the surface piping, but due to the small length it is anticipated that the contribution to the release rate profile will not be substantial.

5.0 CONSEQUENCE MODELLING

In the event that ignition is delayed, the consequences will depend on the manner in which the cloud disperses as it is transported away from the source and the flammable extents (flash fire footprint) at the time of ignition. For an immediately ignited release, the consequences will depend on the release rate profile and the associated time varying thermal radiation that impacts a receptor.

5.1 DISPERSION MODELLING

The SLAB dispersion model was used to estimate the flammable extents in the event of delayed ignition (Ermak, 1990). The SLAB model is capable of modelling releases of buoyant and dense gases and contains algorithms to estimate the effects of phase change within the plume and reduced air entrainment resulting from stable density gradients between the plume and the ambient air. The SLAB model is one of the U.S. EPA recommended models for hazard assessments.

SLAB modelling was carried out for a range of meteorological conditions to assess the impact of weather conditions on the dispersion of releases and provide a reasonable estimate of an extreme case. The atmospheric stability is an indication of the level of turbulence and hence the dispersive capability of the atmosphere. Typically, a classification scheme that has six categories ranging from Class A (very unstable) to Class F (moderately stable) is considered to characterize atmospheric stability. The occurrence of these stability conditions can be summarized as follows:

- Unstable Conditions (Classes A through C) are characterized by strong to moderate incoming solar radiation and low to moderate wind speeds. These conditions typically occur on calm, warm, and sunny days where ground heating results in vertical motion of air within the layer of the atmosphere close to the surface. This vertical motion results in increased turbulence. Unstable conditions are restricted to daylight hours;
- Neutral Conditions (Class D) often occurs during overcast conditions or conditions with moderate to high wind speeds. Neutral stability can occur at any time during the day or night; and
- Stable Conditions (Classes E and F) typically occur on calm cool clear nights where radiative cooling of the ground relative to the layer of air above it results in a stable temperature gradient (increasing temperature with altitude). This stable gradient dampens vertical motion and results in a reduction in the level of turbulence. Stable conditions generally occur during nighttime hours.

A summary of the weather conditions that were used for modelling in the assessment of calculated hazard distances is presented in Table 5-1. In addition, a surface roughness parameter of 37 cm, and a relative humidity of 70% were assumed.

For the current assessment the downwind extents of the LFL/2 contour were used to estimate the flash fire footprint. The maximum predicted distance from the source to the LFL/2 contour is provided as information for emergency responders. For the purposes of the risk assessment it was assumed that in the event of delayed ignition, a receptor/individual located in a region where the cloud concentration is greater than the LFL will receive a fatal dose of thermal radiation.

Table 5-1 Weather Conditions used in SLAB Dispersion Modelling

Weather Code	Pasquill-Gifford (PG) Stability Class	Wind Speed (m/s)		General Description
		m/s	km/h	
A1.5	A	1.5	5.4	Typically Occurs on sunny days, late morning to mid-afternoon when the sus is at its peak
B2	B	2	7.2	Clear to partly cloudy conditions during the day any time of the year
C2	C	2	7.2	Partially Cloudy Daytime Conditions, also occurs during periods of lower solar elevation
C4	C	4	14.4	
D2	D	2	7.2	Overcast conditions day or night anytime of the year
D5	D	5	18	Moderate to high wind speed conditions any time of day
D10	D	10	36	
E3	E	3	10.8	Night-time conditions slightly overcast
E5	E	5	18	
F1.5	F	1.5	5.4	Clear nights
F2	F	2	7.2	
F3	F	3	10.8	
F4	F	4	14.4	

5.2 THERMAL RADIATION

The thermal radiation consequence was estimated using thermal dose units (TDU). The release rate and thermal radiation intensity are time-varying so the thermal radiation dose can be estimated using the following equation:

Equation 5-1

$$D = \int_0^T I^{4/3} dt$$

Adapted from (O'Sullivan & Jagger, 2004)

where:

D = dose (1 TDU = 1 $(kW/m^2)^{4/3}s$)
I = thermal radiation intensity (kW/m^2)
T = the exposure duration (seconds)

For the purpose of the risk modelling an estimate of the probability of lethality is required. The thermal dose unit accounts for the duration and exposure level. The probability of lethality (P) can be estimated using equation below and assuming Eisenberg probit parameters of *a* = -14.9 and *b* = 2.56 (UK HSE, 2010, pp. 20-21).

Equation 5-2

$$P(L) = \frac{1}{2}\left[1 + erf\left(\frac{b\ln(D) + a - 5}{\sqrt{2}}\right)\right]$$

(Uijt de Haag & Ale, 2005)

For the current assessment, the thermal radiation consequence was estimated using algorithms presented by Cook et al. (1987) which characterize the jet fire as a line source with a user-specified degree of anisotropy. The line source was simulated as a series of point sources. A fully isotropic line source will emit radiant energy in all directions at every point along the line. A fully anisotropic source simulates a surface emitter. Investigators have found that the isotropic assumption over estimates the thermal radiation in the near field and the fully anisotropic assumption under estimates thermal radiation in the near field. Both extremes perform similarly in the far field because they can be approximated as a point source. Based upon the recommendations of Cook et al. (1987), a 50% degree of isotropy was assumed.

Wind speed will affect the predicted curvilinear shape of the flame (Cook, Hammonds, & Hughes, 1987). High wind speed (i.e., lower jet momentum to ambient momentum ratio) will bring the flame closer to the ground but will also stretch it out when compared to the flame during lower wind speed.

The following additional assumptions were made relating to the thermal dose estimation for an individual near an ignited release:

- At the onset of the release the individual is assumed to remain stationary, or “stunned”, for 5 seconds;
- The individual will then move directly away from the release site at a speed of 2.5 m/s (9.0 km/h);
- The individual is assumed to be oriented to receive the maximum thermal radiation from the source; and
- Wind speeds of 2, 5, and 10 m/s (7.2, 18, and 36 km/h) were applied.

The individual will accumulate thermal dose over the duration of the release, based on the time-varying intensity level of thermal radiation emitted from the source and the time-varying distance between the individual and the release point.

For this assessment, the distance to thermal dose distances of 80 and 240 TDU (approximate threshold for 1st and 2nd degree burns) were estimated.

5.3 VAPOUR CLOUD EXPLOSION MODELLING

For the current assessment the Multi-Energy Method has been used to complete the vapour cloud explosion modelling. Based on the current understanding of vapour cloud explosions, this method assumes that only the regions of a cloud in congested or confined areas will contribute, substantially, to the generation of damaging overpressures. Primary input considerations for this model are the definition of the congested region and the estimate of blast strength or explosion class.

The current assessment of potential congested regions in the vicinity of the facility is provided by the shaded regions in Figure 5-1. The green shaded regions represent treed areas that may provide sufficient congestion and the beige areas are structures on the plant site that may provide sufficient congestions. The treed and facility areas were assumed to have heights of 10 and 5 m respectively.

Based on the guidance provided relating to the application of this method, an initial blast strength of class 7 has been chosen for the congested regions. This blast strength is representative of a near detonation and it is anticipated that this should overstate the overpressure and associated damage effects.

The procedure used to complete the explosion modeling can be outlined as follows:

- The dispersion modeling was conducted over the range of weather conditions and release scenarios.
- At 20 second intervals (ignition times) and at 10 degree angle increments estimates of the explosive volume were made based on the flammable extents of the cloud that overlay the denoted congested regions
- Based on the explosive volumes at each time step and angle increment combination, the overpressure was calculated for a fixed grid spacing over the domain depicted in Figure 5-1 (51 east points by 51 north points)
- For each release scenario and weather condition case the maximum overpressures predicted over the domain were tabulated.

The cloud volumes were estimated based on the region of the cloud above the LFL that overlay the congested regions. In the event that the cloud, at a particular time and angle combination, overlays more than one congested region, it was conservatively assumed that the effects of the blasts would be cumulative. An overpressure of 1 psi (6.89 kPa) is the threshold for potentially serious injuries to people as a result of property damage caused by an explosion (TSSA 2010) and is used as the consequence endpoint for the overpressure assessment.

Figure 5-1 Assumed Congested Regions for Explosion Modelling

6.0 RISK MODELLING

Risk assessment provides a means of evaluating the safety of a proposed industrial activity by comparing the risk associated with the activity to accepted guidelines. It is important to note, that while knowledge of a credible worst-case hazard extent is useful for emergency planning purposes, this information does not necessarily provide a complete measure of safety and, as a result, is difficult to use for land use planning purposes. The identification of the extents of a hazard is not traditionally or solely used to determine the acceptability of a development. Safety refers to the acceptability of the risk. It considers the likelihood that an accident will occur and produce an adverse outcome. For example, while the consequences associated with an uncontrolled release may be large, if the frequency of occurrence is low or not measurable, then the facility may in fact be considered safe, since the risk is low.

6.1 QUANTITATIVE RISK ANALYSIS

Quantitative risk analysis provides a means of generating numerical estimates of risk by combining the consequences associated with a range of accidental release events with their expected frequency. Simply defined, risk provides an estimate of the likelihood of harm: either to an individual or to society as a whole. For this assessment, individual risk estimates have been given as “an annual chance of fatality” at specific locations in the vicinity of a release from the hydrocarbon storage vessels. A common and convenient expression of the individual risk is:

Equation 6-1

$$\text{Risk} = \text{Frequency} \times \text{Consequence}$$

Where:

Frequency = an approximation of the annual probability of an event
Consequence = the probability of lethality for a specified event

Results of the risk analysis provide a numerical measure of the incremental individual risk associated with an accidental release from the hydrocarbon storage vessels. This information can be used to compare and assess land use and development activities near the proposed facilities.

6.2 PROBABILITY AND FREQUENCY INFORMATION

A variety of probability and frequency information is needed to evaluate risk.

6.2.1 Frequency Analysis

Frequency analysis is used to quantify the occurrence of accidental release events such as an uncontrolled release. Accident frequency information provides an historical measure of how often similar events have occurred in the past. The cavern failure frequency was estimated based on guidelines introduced by the Major Industrial Accident Council of Canada (MIACC) guidelines (MIACC, 1997). For screening level purposes MIACC suggests that large releases occur at a frequency of one release in 10,000 years (1.0E-4) and small releases occur at a frequency of one in 100 years (1.0E-2). It is anticipated this is a conservative estimate of the release frequency as industry accident databases such as those prepared by SCANDPOWER (SCANDPOWER 2008) RIVM (Dutch National Institute for Public Health and the Environment) (RIVM 2009), and the AER (Alberta Energy Regulator) would indicate lower release frequencies for producing gas wells which should be a reasonable analogue for cavern wellheads.

For the current assessment the rupture is categorized as a large release and a release from a 5 mm hole is categorized as a small release. Table 6-1 summarizes the probability and frequency information related to the selected release events.

Table 6-1 Summary of Probability and Frequency Information

Parameter	Units	Value
Failure Frequencies		
Leak (5 mm hole)	Failures/wellhead/Year	1.0E-02
Full Rupture	Failures/wellhead/Year	1.0E-04
Probability of Composition		
Propane	%	50
Butane	%	50
Probability of Receptor Location		
Outdoors	%	100
Indoors	%	0

6.2.2 Ignition Frequency

Event trees are often used to assist in the development, and quantification of probabilities of possible hazard outcomes following an accidental release. Figure 6-1 shows a simplified event tree used in the current assessment for a pipeline rupture. As indicated in the event tree, immediate ignition was assumed to occur 15% of the time and delayed ignition was assumed to occur 12% (Muhlbauer, 2004) of the time, resulting in an overall estimated ignition probability of 25.2%. Investigators have found that immediate ignition depends on factors that include the release rate, hole size, and fluid composition and delayed ignition depends on factors including the population density and land-use. The Gas Research Institute (GRI) has conducted an assessment based on a review of incident databases and has found that typically, the ignition probability ranges from about 4 to 15%.

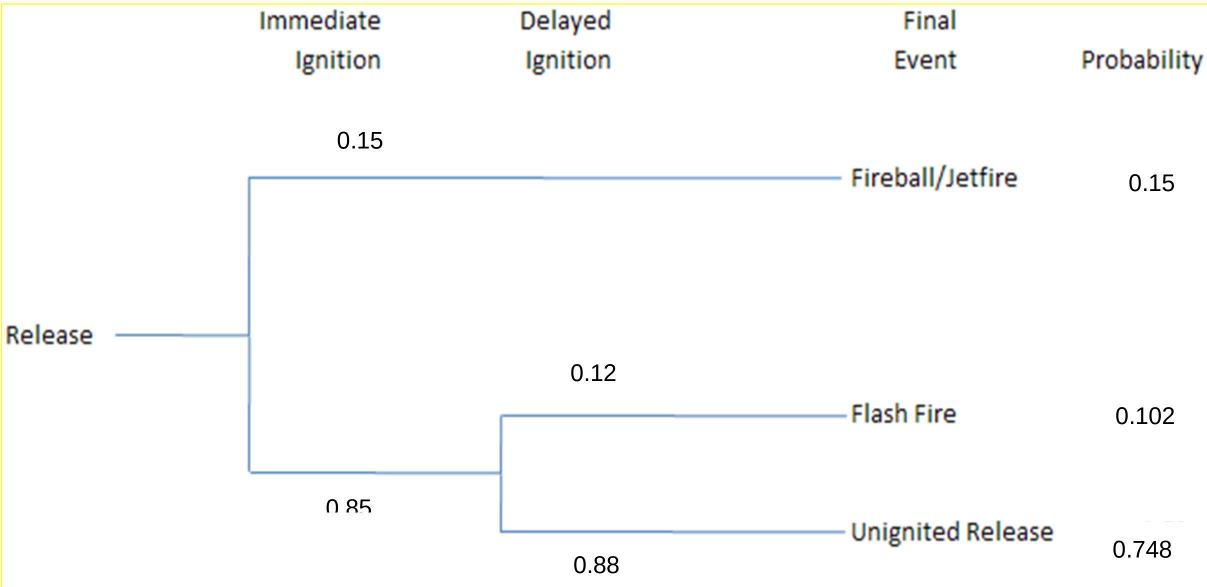

Figure 6-1 Event Tree to Estimate the Probability of Ignition for a Pipeline Rupture

6.2.3 Site-Specific Meteorology

The meteorology used for the dispersion and consequence modelling is described in the following section.

Data from the Environment Canada surface meteorological data at Windsor Airport were used for the base meteorology in conjunction with wind speed, wind direction and solar radiation data from the Sarnia-Lambton Environmental Association (SLEA) Moore Line Station (to provide local wind speed and direction information representative of the study area). The joint frequency distribution of wind direction and wind speed are presented in Figure 6-2 in a "wind rose" format, which is essentially a stacked bar chart in a polar format. The orientation of the bar typically represents the 16 cardinal direction points of a compass, and depicts the direction the wind is blowing from for each 22.5 degree sector. The length of each bar represents the frequency (%) that the wind is blowing from the given direction. Each bar is divided into segments to represent different wind speed classes.

The figure indicates that winds are predominantly from the south-southwest. The frequencies estimated for the representative meteorological conditions are provided in Table 6-2. The estimated probability of occurrence of the wind direction and weather conditions will be combined with the indicated frequencies to estimate the individual/location risk.

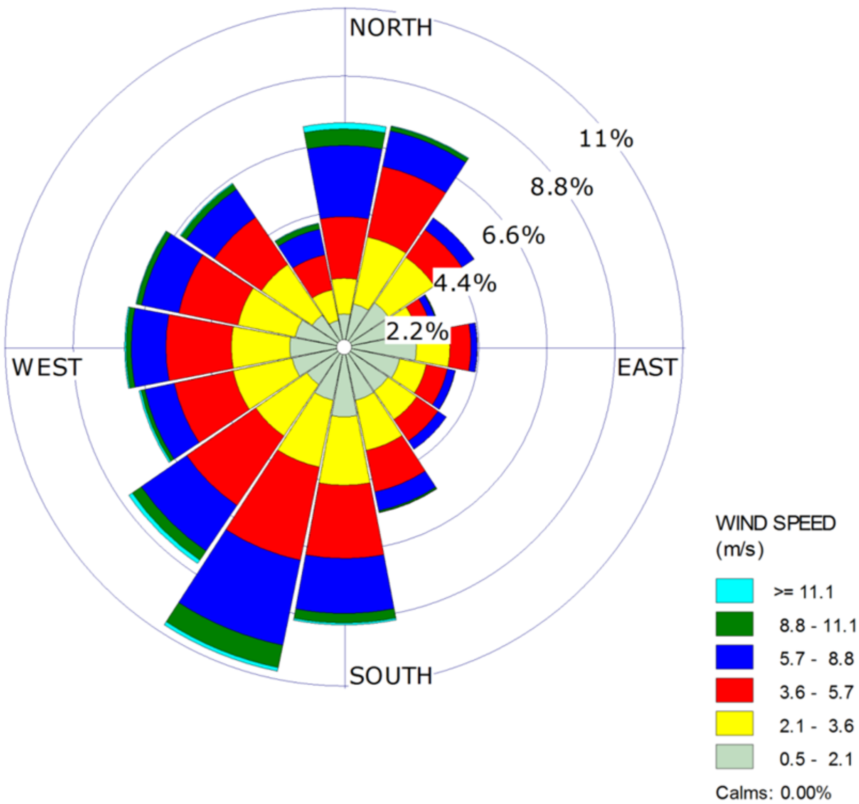

Figure 6-2 Wind Speed and Direction Frequency Distribution for the Corunna Area

Table 6-2 Estimated Frequencies of the Identified Meteorological Conditions Occurring in the Sarnia Area

Meteorology Code	Stability Class	Wind Speed (m/s)	Wind Speed (km/h)	Frequency of Occurrence (%)
A1.5	A	1.5	5.4	2.1
B2	B	2	7.2	3.2
C2	C	2	7.2	3.8
C4		4	14.4	5.4
D2	D	2	7.2	4.7
D5		5	18.0	37.9
D10		10	36.0	10.5
E2	E	2	10.8	8.8
E5		5	18.0	3.6
F1.5	F	1.5	5.4	13.0
F2		2	7.2	6.0
F3		3	10.8	1.2
F4		4	14.4	0.0
Total:				**100%**

6.3 RISK ACCEPTABILITY CRITERIA

Risk acceptability criteria can be defined for off-site and on-site activities. “Offsite” refers to risk levels to the public beyond the boundaries of the risk source. “On-site” refers to the risk to workers at the facility. “On-site” risks are the direct responsibility of the duty holder and are not considered in this assessment.

The Major Industrial Accident Council of Canada (MIACC), “Working Group on Land Use Planning and Control” has published proposed risk criteria for Canadian applications (MIACC, 1997). In 2008, the Canadian Society of Chemical Engineers (CSChE) recommended an update to the MIACC guidelines (PSM CSChE, 2008) to address sensitive developments such as hospitals and child care. The process safety sub-group of the CSChE defines 5 zones, with associated recommended land use, based on the estimated individual risk:

- **Zone A** – No land use other than the risk source, annual individual Risk > 100 in a million;
- **Zone B** – Manufacturing, warehouses, open space (parkland golf, courses),annual individual risk between 10 and 100 in million;
- **Zone C** – Low density residential and commercial, annual individual risk between 1 and 10 in a million;

- **Zone D** – High density residential and commercial, annual individual risk between 0.3 and 1 in a million;
- **Zone E** – Unrestricted development, including sensitive development such as hospitals and child care, annual individual risk < 0.3 in a million.

A graphical representation of the MIACC risk acceptability criteria is provided in Figure 6-3. This figure provides criteria that land use planners can consider in determining permitted land uses in municipal plans and zoning bylaws. It is recommended that land uses adjacent to facilities should be graded on the basis of decreasing sensitivity to a major accident.

It noted that the MIACC acceptability criteria implicitly accounts for societal risk concerns. MIACC proposed that zoning bylaws include a reference to an accepted methodology for defining the minimum separation distances to be maintained between industrial and adjacent land uses. These individual risk criteria for land use planning are summarized in (MIACC 1997) and were based on, consideration of similar criteria adopted in the U.K. and Netherlands. The MIACC criteria are intended to be applied for off-site, public safety planning.

For additional context, Table 6-3 presents some common individual risks associated with various causes.

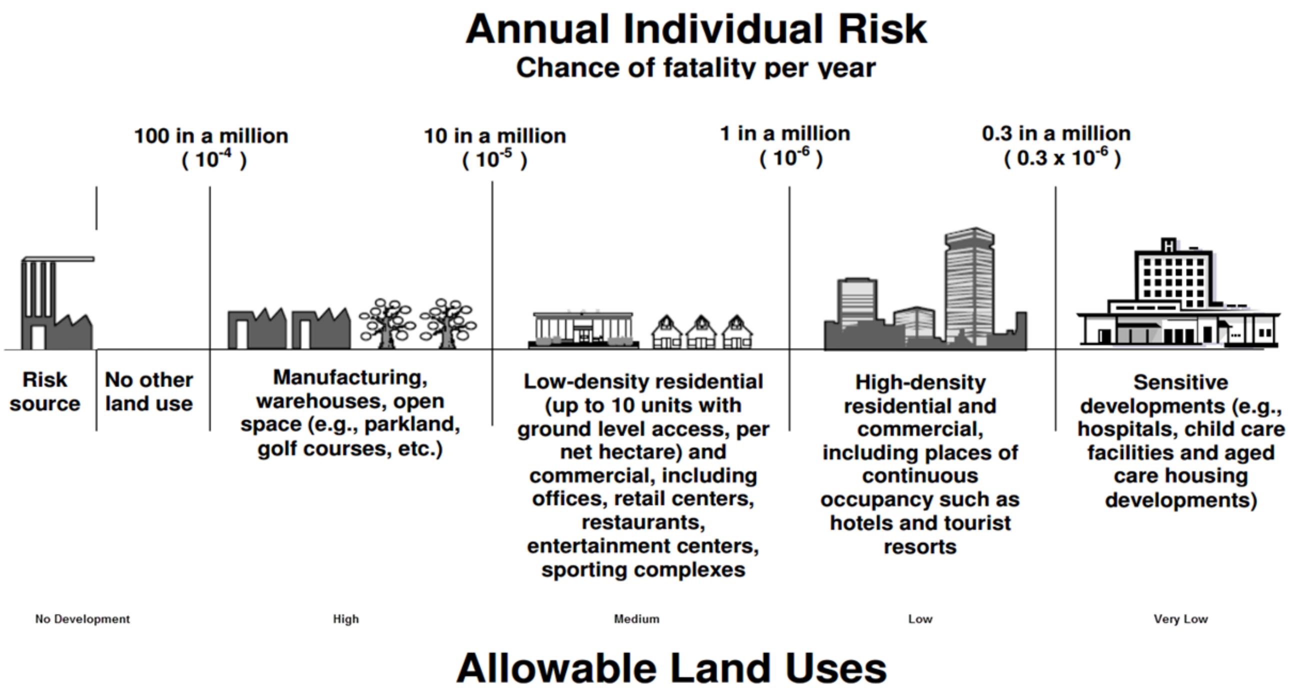

Figure 6-3 Modified MIACC Guidelines for Acceptable Land Use in the Vicinity of Industrial Facilities (PSM CSChE, 2008)

Table 6-3 Common Risks (CSChE 2004)

Cause	Individual Risk (Chances in a million of death per year)
Motor Vehicle Accident	109
Falls	82
Dwelling Fires	7.9
Water Transport Accidents	3.6
Excessive Cold	3
Electrical Current	1.1
Railway Accidents	1.1
Earth Movements	0.4
Lightning	0.2
Cataclysmic Storm	0.03

7.0 RESULTS

This section provides results associated with the source characterization, consequence modelling and risk modelling.

7.1 SOURCE CHARACTERIZATION

Source characterization was conducted for the cavern wellheads for a range of hole sizes. Examples of release rate profile associated with a100% area rupture at Caverns 45, along with release rate profiles for existing Caverns 4, 49a, and 59 are provided in Figure 7-1. Caverns 4, 49, and 59 were chosen as they had the highest volume of storage for a given fluid composition. The release profiles are characterized by an initially high but rapidly decreasing flow rate over the first 20 seconds of the release, followed by a prolonged, gradually decaying flow. Initial release varies between caverns, with Cavern 45 peaking at roughly 500 kg/s and steadying to a flow rate of over 250 kg/s.

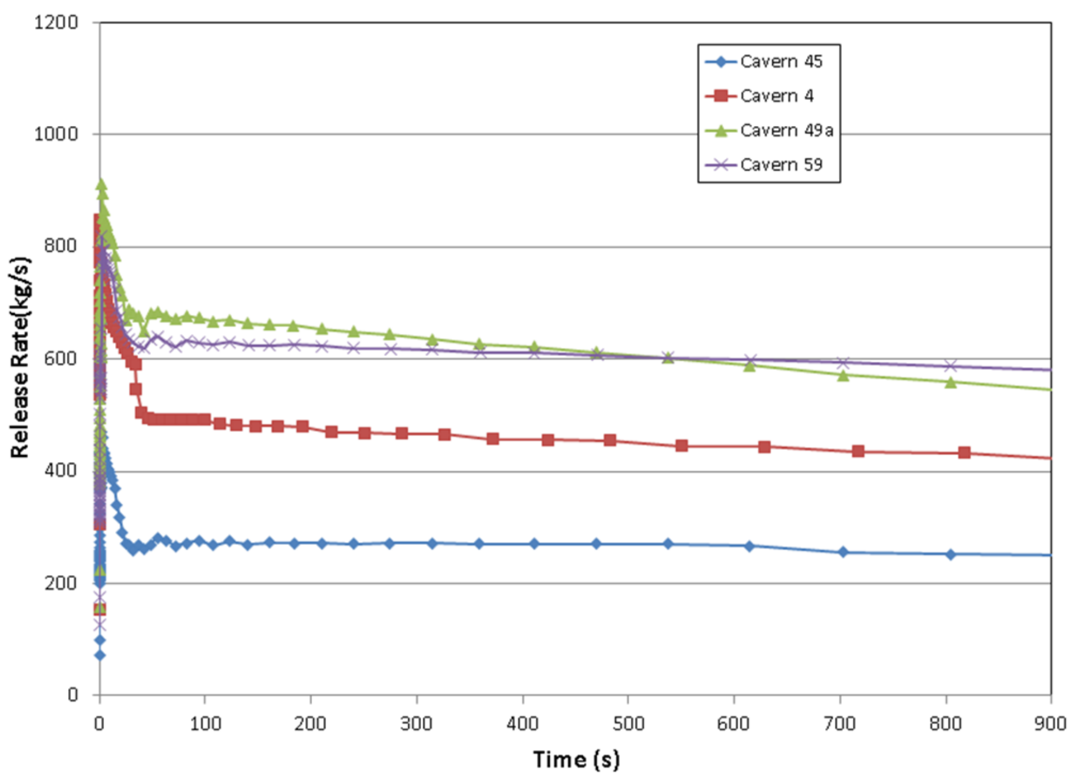

Figure 7-1 Release Rate Profile for an Accidental Wellhead Release at Selected Caverns

7.2 CONSEQUENCE MODELLING RESULTS

The consequence modelling was conducted for the proposed fluids, cavern wellheads, rupture sizes, release profiles and weather conditions. The flash fire (delayed ignitions), Jet-fire (immediate ignition) and vapour cloud explosion modelling consequence results are presented in the following subsections.

7.2.1 Flash Fire Consequence Results

The maximum predicted downwind distances to the LFL and LFL/2 concentrations for the existing and proposed caverns are provided in Table 7-1. The maximum predicted distances occurred at Cavern 49a, and were 1,230 m and 1,901 m for the LFL and LFL/2, respectively. The proposed Cavern 45 was predicted to have maximum LFL and LFL/2 extents of 595 m and 1,027 m, respectively.

The maximum predicted extents to the LFL and LFL/2 for the selected release scenarios and weather conditions considered are presented in Figure 7-2.

Table 7-1 Predicted Maximum Flammability Extents for Storage Caverns

Cavern	LFL	LFL/2
	Downwind Distance (m)	Downwind Distance (m)
3	1,027	1,479
4	909	1,346
5	738	1,088
6	580	855
45	595	1,027
49	590	1,015
49a	1,230	1,901
51	952	1,663
56	609	1,029
59	1,002	1,695

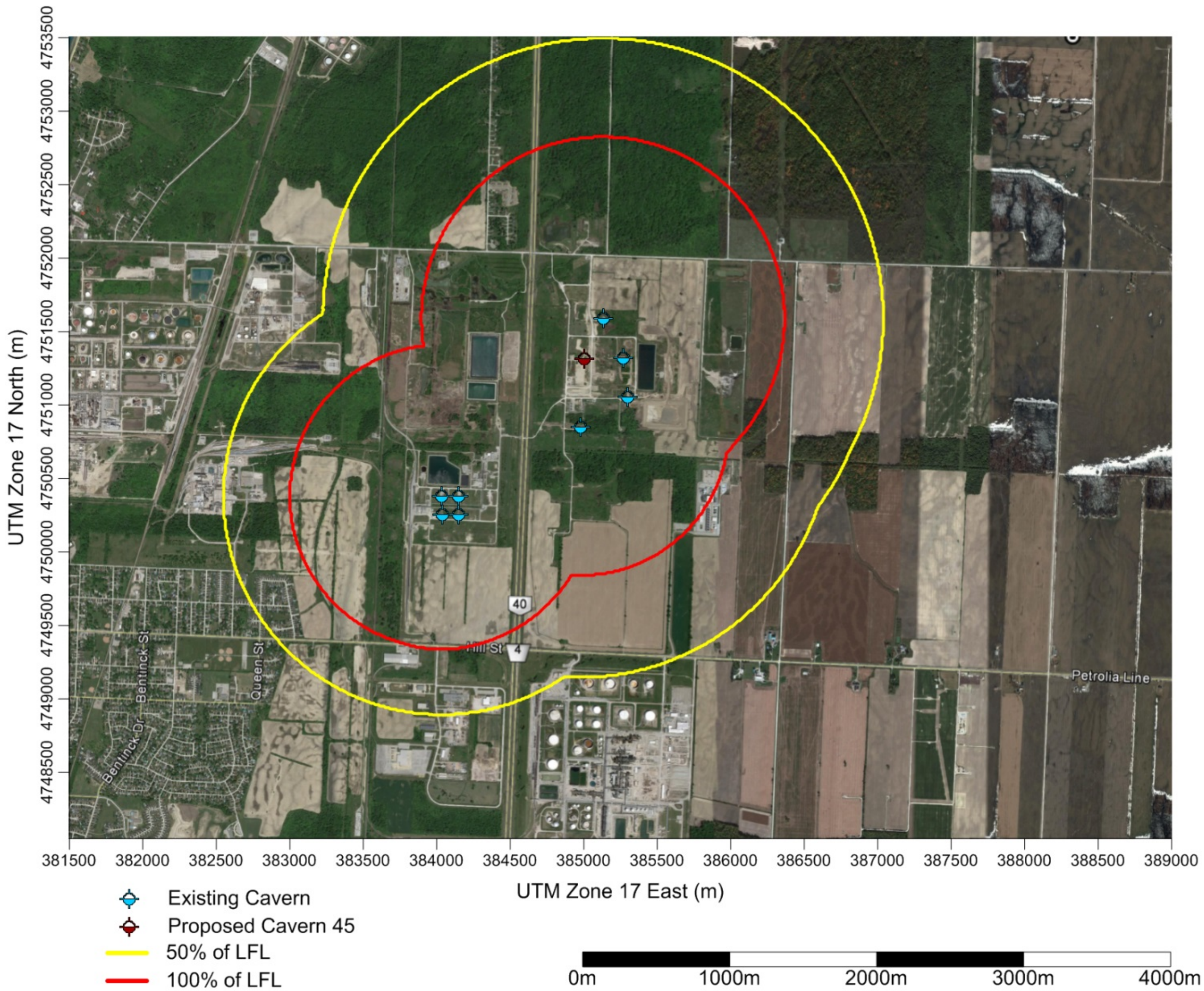

Figure 7-2 Maximum Predicted Extents to the LFL and LFL/2 Concentrations for All Considered Release Scenarios, Cavern Locations and Weather Conditions

7.2.2 Jet Fire Consequence Results

The maximum predicted distances to first and second degree burns for an unprotected receptor are provided in Table 7-2. The maximum predicted distances to first and second degree burns occurred at Cavern 59 and were 841 m and 545 m, respectively. Predicted maximum distances to first and second degree burns for Cavern 45 were 554 m and 348 m, respectively.

Table 7-2 Maximum Predicted Distances to First and Second Degree Burns for an Unprotected Receptor

Cavern	First Degree	Second Degree
	Downwind Distance (m)	Downwind Distance (m)
3	655	520
4	587	457
5	587	451
6	534	403
45	554	348
49	424	262
49a	658	555
51	702	486
56	427	331
59	841	545

7.2.3 Vapour Cloud Explosion Consequence Results

The maximum predicted downwind distances to the selected overpressure endpoint of 1.0 psi (6.89 kPa) are provided in Table 7-3. The maximum predicted distance 2158 and occur for caverns 49a. The predicted distances are dependent on the wind direction and the proximity of the release site to congested areas.

The maximum predicted extents to selected overpressure endpoints overlaid on the region in the vicinity of the facility are provided in Figure 7-3. The dependence of the predictions on the assumed congested regions is indicated in the figure.

Table 7-3 Maximum Predicted Extent to 6.89 kPag Overpressure Threshold

Cavern	6.89 kPag Overpressure
	Downwind Distance (m)
3	1,320
4	1,305
5	1,184
6	1,067
45	1,278
49	<100
49a	2,158
51	1,817
56	1,410
59	2,037

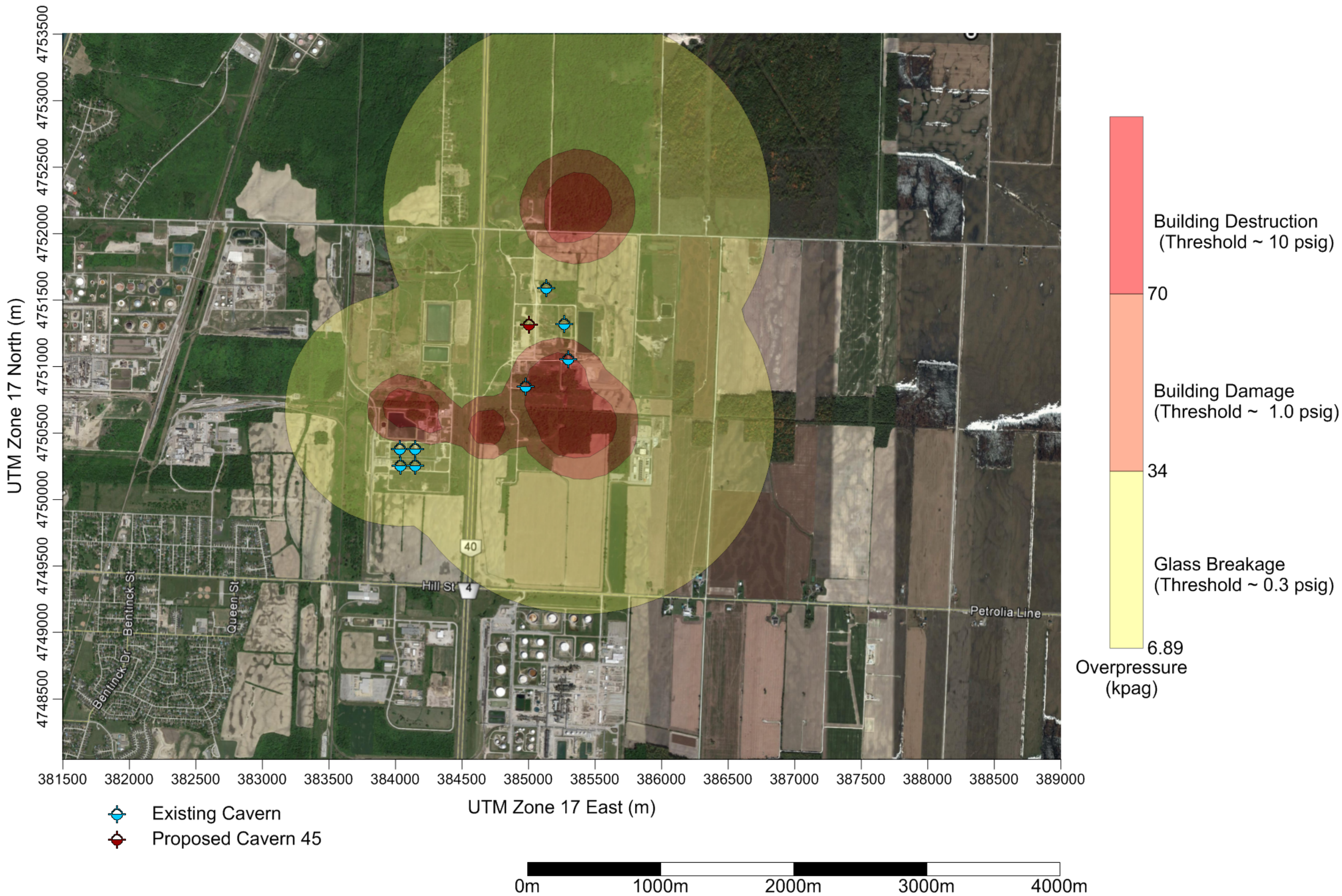

Figure 7-3 Predicted Extents to Selected Overpressure Criteria

7.3 RISK RESULTS

The estimated incremental individual (location) risk associated with the proposed storage caverns is provided in Figure 7-4. The results indicate that, based on the modified MIACC guidelines, the proposed storage caverns are not predicted to place restrictions on the current land usage in the vicinity of the storage terminal.

The risk associated with storage bullets (Stantec 2010) is not predicted to contribute in a substantial way to the offsite risk associated with the facility. As a result, based on the modified MIACC guidelines, the cumulative risk associated with the primary risk sources at the facility is not predicted to place restrictions on the current land usage in the vicinity of the storage terminal.

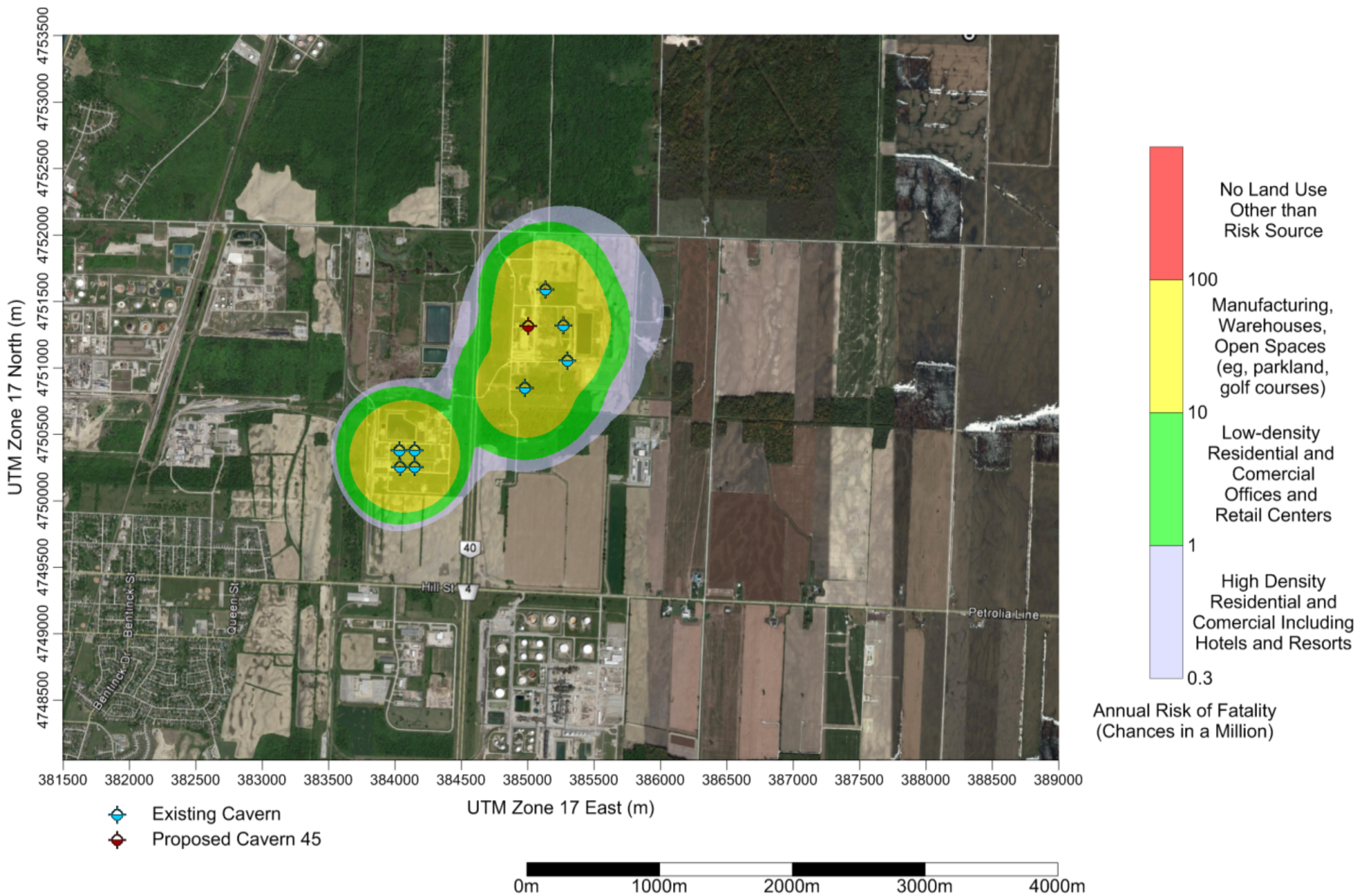

Figure 7-4 **Predicted Cumulative Individual/Location Risk Associated with the Proposed and Existing Storage Caverns at the Corunna Hydrocarbon Storage Terminal**

8.0 CONCLUSIONS

Source, consequence and risk modelling were conducted for proposed cavern wellheads at the Pembina Corunna hydrocarbon storage terminal. The consequence modelling results are summarized below:

- The maximum predicted distances to the LFL and LFL/2 are 1,230 m and 1,901 m respectively, and occur for Cavern 49a. The maximum predicted distances to the LFL and LFL/2 for Cavern 45 was 595 m and 1,027 m, respectively.
- The maximum predicted distance to the extents of the 2nd degree burn criteria is 545 m and occurs for Cavern 59. The maximum predicted distance to the extents of the 2nd degree burn criteria for Cavern 45 is 348 m.
- The maximum predicted distance to the 1 psi (6.89 kpa) overpressure criteria was 2,158 m and occurs at Cavern 59. The maximum predicted distances to the 1 psi (6.89 kpa) overpressure criteria for Cavern 45 was1,278 m.

The predicted cumulative individual/location risk results support the current land use in the vicinity of the Pembina Corunna hydrocarbon storage facility.

9.0 CLOSURE

This report has been prepared for the sole benefit of Pembina Pipeline Corporation and their representatives. Any other person or entity without the express written consent of Pembina Pipeline Corporation and Stantec may not rely upon the report.

Any use which a third party makes of this report, or any reliance on decisions made based on it, is the responsibilities of such third parties. Stantec accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

Should additional information become available, which differs significantly from our understanding of conditions presented in this report, we request that this information be brought to our attention, so that we may reassess the conclusions provided herein.

Brian Bylhouwer, Environmental Scientist, has prepared this report. In accordance with the Stantec Project Management Framework. Wade Gieni, Air Quality Scientist conducted the Quality Review and Arthur Springer, Air Quality Engineer, completed the Independent Review. We trust that the above information meets with your present requirements. Should you have any questions or require further information, please contact Arthur Springer directly at (403) 781-4103.

STANTEC CONSULTING LTD.

Brian Bylhouwer, M.RM., ENV SP
Environmental Scientist
Phone: (902) 468-7777
Fax: (403) 716-8128
Brian.Bylhouwer@stantec.com

Arthur J. W. Springer, M.Sc., P.Eng.
Air Quality Engineer
Phone: (403) 781-4103
Fax: (403) 716-8128
Arthur.Springer@stantec.com

Wade B. Gieni, B.Sc., QEP
Air Quality Scientist
Phone: (403) 781-547
Fax: (403) 716-8128
wade.gieni@stantec.com

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