SCANDPOWER
Risk Management

Lloyd's Register

Comparative study on gas dispersion

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Client DSB

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Title:

COMPARATIVE STUDY ON GAS DISPERSION

Client: DSB

Client specification:

Perform a comparative study on the performance of different computational tools on gas dispersion predictions. Two integral tools are tested (Phast and Trace) and two CFD tools are tested (FLACS and KFX).
Calculate typical hazardous distances for 13 different land facility plant types

Summary:

See Chapter 1 for summary

0. SUMMARY

The Directorate for Civil Protection and Emergency Planning (DSB) and Scandpower have jointly performed a comparative study on gas dispersion. Both integral tools (Phast and Trace) and CFD tools (FLACS and KFX) has been used in the comparison.

The following have been concluded from the comparative study:

- Simulated gas dispersion distances must be regarded as somewhat uncertain, independent of what tool that is used. However, the spread in results from the different tools are considered to be moderate, and none of the tools are dis-regarded as applicable for gas dispersion calculations.

- It is also seen that different project teams may end up with slightly different results, even if they are using the same tool. This also contributes to a spread in the results. The uncertainty linked to the user is larger for CFD tools than for integral tools since there are more parameters that need to be user specified in the CFD tools (e.g. the grid resolution, the release conditions and the boundary conditions).

- It is seen that low momentum leaks (e.g. pool leaks) are likely to lead to larger hazardous distance than high momentum leaks (jet leaks). This is contributed the fact that high momentum leaks will give larger turbulence and hence better mixing of air and gas.

- It is seen that when obstructions and terrain is not regarded a driver for the results, then both integral tools and CFD tools can be applied with similar accu-racy.

- When obstructions and terrain are considered important for the hazardous distan-ces, only CFD tools can be applied. This will typically be when there are large buildings near the release, when the leaks are in highly congested areas (much process equipment), and when there is potential for release of heavy gas in a sloping and terrain.

- Details of the comparative study are summarized in Chapter 2.6.

Typical safety distances for 13 different land facility plant types (named DSB cases in this report) has also been calculated using Phast. Hazardous distances for the 10^{-4} to 10^{-7} events have been calculated and presented. The following has been concluded from the study of the DSB cases:

- It is generally the activity levels that are dominating the safety distances, and not the amount of storage. Typical activities that are dominating the safety distances are loading and offloading. Typical parameters that are contributing to the seve-rity of a leak are large cross sections and high pressures and large segment volumes.

- Liquid phase releases (LNG/LPG) will normally give significantly longer safety distances than gaseous leaks (typically a factor 2-3 times longer).

- There is often a significant difference in the safety zone referring to ½ LFL and LFL. The safety zone may be more than 2 times larger (longer) if ½ LFL is used as maximum safe gas concentration.

- For jet fires the safety distance is often dominated by the length of the jet fire (and not the distance to flammable gas concentration before ignition). This is a result of the hazardous heat radiation distance being longer than the distance to the non-ignited LFL concentration.

- If ½ LFL is used as the limit for safety distance, then fire simulations can be omitted for the purpose of identifying the safety distances. This is because the hazardous heat radiation distance is seen to be shorter than the distance to the non-ignited ½ LFL distance.

- Details of the DSB case study are summarized in Chapter 3.4.

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1. INTRODUCTION

The tool comparative study and the typical safety distance study has been a joint effort between DSB and Scandpower.

Two main objectives have been identified for this study:

Objective 1:
Assess the potential difference in hazardous distances predicted by different tools (integral tools and CFD), and potential limitations for use of the tools (see Chapter 2, test matrix).

Objective 2:
Establish estimates of typical hazardous distances for different types of onshore industry plants (see Chapter 3, DSB cases).

The current work is a part of a DSB effort for improved safety management at Norwegian land facilities

- stricter requirements on risk models (quantitative rather than qualitative)
- improved knowledge on how to assess the quality of the risk analysis and consequence modelling
- improved basis for land use planning (LUP) in areas around hazardous plants (how to estimate an adequate distance to 3rd party).

From the comparative study it is seen that there are several technical issues that are subject to further studies, but such additional studies has not been covered by the scope of this study, see also Chapter 2.6.

2. COMPARATIVE STUDY (TEST MATRIX)

2.1 Integral tools vs. CFD tools

An integral tool is based on reproducing experimental tests by use of simplified algebraic (non-physical) equations. In addition, semi physical equations are added to predict scenarios that are slightly different from the experimental tests. Integral tools are robust and extremely quick to use (simulation time is in order of seconds). Integral tools can not include effects of physical obstructions or terrain (there are parameters that can be used to emulate an average effect of buildings or trees).

CFD tools (computational fluid dynamics) are based on solving physical equations (Navier Stokes) of the fluid flow on a computer. Semi physical models may also be used to modify the solution field (e.g. turbulence models). CFD tools are also validated against experimental test, but they solve all physical effects in the computational domain and are therefore more reliable than integral models when estimating problems that are very different from the validated experimental tests. CFD tools are more complex to use than integral methods, and the simulation time is much longer than for integral tools (typically hours or days). CFD tools can predict the effects of physical obstructions and terrain, and is therefore applicable for more types of leak events than integral tools.

The main difference of integral and CFD tools is illustrated by comparing Figure 2.1 and Figure 2.2. It can be seen that the behaviour of the gas cloud is distinctly different when an obstruction is inserted (the results are similar for the cases of no obstruction).

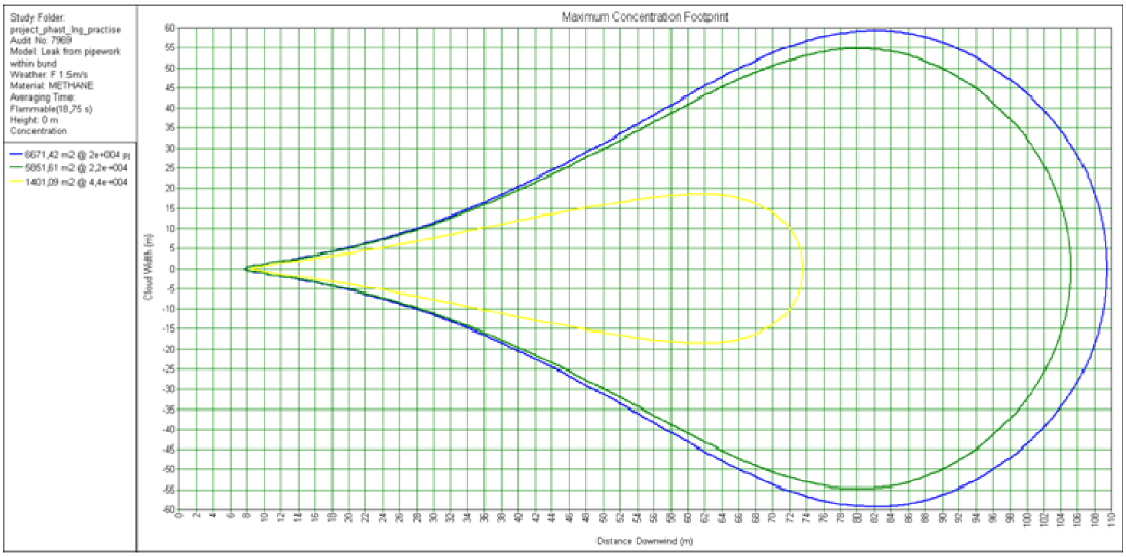

Figure 2.1: Example of integral tool with no effect from obstructions (Phast)

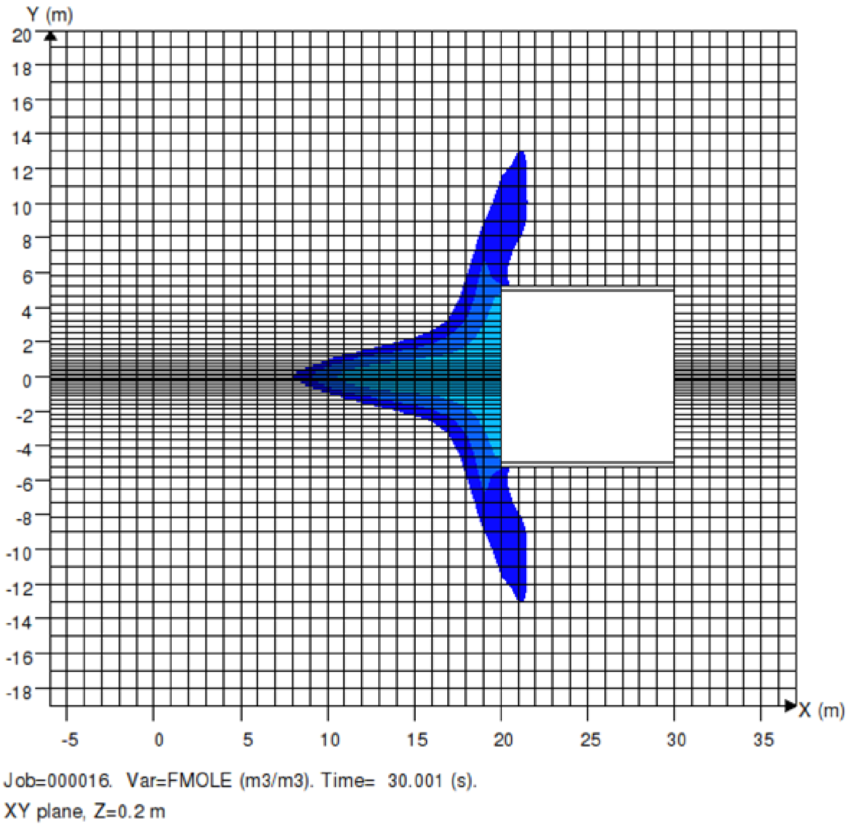

Figure 2.2: Example of CFD tool with includes the effect from obstructions (FLACS)

2.2 Tested tools

2.2.1 Phast

PHAST (Process Hazard Analysis Software Tool) is an integral tool developed by DNV (Ref. /1/). Phast examines the progress of a potential incident from the initial release to far-field dispersion including modelling of pool spreading and evaporation, and flammable and toxic effects.

The results from the analysis can be displayed in tabular & graphical form, so the extent of the impact can be seen, and the effect of the release on the population and environment assessed.

Phast contains models tailored for hazard analysis of offshore and onshore industrial installations. These include

- discharge and dispersion models, including DNV's proprietary Unified Dispersion Model (UDM)
- flammable models, including resulting radiation effects, for jet fires, pool fires and BLEVEs (Boiling Liquid Expanding Vapour Explosion)
- explosion models, to calculate overpressure and impulse effects. Available models include the Baker Strehlow, TNO Multi-Energy and TNT explosion models
- models for the toxic hazards of a release including indoor toxic dose calculations

2.2.2 Trace

TRACE (Toxic Release Analysis of Chemical Emissions) is an integral tool developed by Safer Systems (Ref. /2/). It can be used for evaluating the dispersion, explosive, or flammable properties of a chemical. The results are easily viewed in tabular or graphical formats. Output information can be exported to other applications like word processors, spreadsheets and presentation managers.

TRACE is used for facility siting studies, emergency preparedness planning, meeting regulatory requirements and quantitative risk analysis studies. TRACE scenarios can be exported to our other products, allowing an engineer to evaluate the impact and then decide if it should be part of the emergency response system.

2.2.3 FLACS

FLACS (FLame ACcelerator Simulator, Ref. /3/) is a leading commercial CFD code for ventilation, dispersion and explosion simulations in complex process areas, developed and traded by GexCon AS. The FLACS code solves the three dimensional, transient gas dynamic partial differential equations (Reynolds Averaged Navier-Stokes equations), in order to calculate the flow parameters as a function of time and space for a defined geometry. A finite volume technique is used, where the equations are solved for a defined number of control volumes.

A distributed porosity concept is implemented in FLACS to handle complex geometries, taking the influence of obstacles such as equipment, piping, explosion panels and walls into account.

Turbulence is modelled by a k-ε turbulence model, with the standard set of constants taken from Launder and Spalding (Ref. /4/). Turbulence production terms are parameterized for sub-grid objects. In order to model combustion, chemical reactions and a flame velocity model are included in the code.

At the upwind boundary of the domain, vertical profiles of wind speed and direction, temperature, turbulent kinetic energy and eddy dissipation rate are imposed according to the atmospheric stability class or to the Monin-Obukhov and surface roughness lengths. At the downwind boundary, a nozzle formulation is used allowing free flow out of the downwind boundary.

FLACS has been extensively validated against experimental results since the 1980s (Ref. /5/). While the main R&D focus in the 1980s and 1990s was on explosion modelling, a significant effort has later been devoted to dispersion modelling. Initial dispersion efforts focused on dispersion of flammable gas clouds, while more recent activities include looking into atmospheric dispersion from gaseous jets, flashing liquids and dispersion from LNG pools (Ref. /6/).

In order to achieve good quality results, the user must take care to follow the guidelines presented in the FLACS user manual (Ref. /3/).

2.2.4 KFX

The commercial CFD software Kameleon FireEx (KFX) is used for the 3D CFD simulations. KFX is a computational fluid dynamics (CFD) code which is based on fundamental physical principles such as conservation of mass, momentum and energy.

In CFD the governing equations for mass, momentum and energy is solved for each control volume in space and time. These equations cannot be solved analytically, so the problem must be solved numerically by discretizing (dividing) the computational domain in space and time. KFX is an incompressible flow solver and uses SIMPLEC (Semi Implicit Pressure linked Equation Consistent) method for pressure and velocity coupling. It supports staggered grid arrangement where the pressure and other scalars are stored in the cell centers and velocities are stored in the face centers of the cell. Turbulence is modelled by standard k-epsilon model and near wall turbulences are modelled by wall functions.

For discretization, second order upwind scheme (with a blending factor 0.9 for the gradients) is used for the momentum and first order Euler implicit scheme is used for time integration. Implicit methods are unconditionally stable and allow stepping solution in large time steps. Nevertheless, to preserve the accuracy of the solution courant number is restricted to max 10 for the jet simulations and 2 for the pool simulations. For turbulent variables k and epsilon, first order upwind scheme is used to achieve stability and to avoid negative k values in the domain. This is recommended by best practice Ref. /7/. Standard under relaxation parameters are used while deriving the solution for all the variables. Default convergence criterion 1e-04 is used to solve the linear system of equations.

A reasonable grid cell size is used for all the simulations to resolve the flow physics. There is no grid independent study performed in any of these simulations. However grid sensitivity test is performed and found accuracy is in the order of cell size O(Δx). In the near field, grid is generally fine and kept 1 m spatial accuracy in both x and y direction. Due to fine near wall mesh requirements in pool simulation (ΔZ: 0.050 m), the grid is stretched to about 5 to 7 m in the far field.

Based on the wind stability class in each simulation, appropriate Mean Obukov length scales are prescribed as per Ref. /8/. Wind velocities at the inlet are calculated as a function of Mean Obukov length scale (L) scaled surface roughness height (Z0) and perpendicular distance from the ground (Z).

Inlet boundaries are treated with prescribed logarithmic velocity profile and outlet boundaries are treated as pressure outlet (gauge pressure = 0). The boundaries are carefully chosen to avoid reflections and back flow from the domain.

KFX is developed by ComputIT, NTNU through a number of joint Industry projects (JIP). It has been verified against large scale experiments and documented in Ref. /9/.

2.3 Definition of test matrix

A test matrix was defined in order to compare the results produced by the tools described in section 3. Two base case scenarios were defined: a free jet releasing 5 kg/s methane, and a LNG pool of 6.8 m diameter. The base case scenarios were defined as follows:

<u>Base case, jet release:</u>

Release rate:	5 kg/s
Jet velocity:	350 m/s
Release height above ground:	2 m
Wind speed:	2 m/s
Wind direction:	Along the jet
Methane temperature:	-112 °C

Temperature of surrounding air:	10 °C
Ground temperature:	10 °C
Ground roughness:	0.035
Atmospheric stability class:	D

<u>Base case, pool release:</u>

Diameter:	6.8 m
Evaporation rate:	0.14 kg/s per m^2
Wind speed:	2 m/s
Temperature of evaporating gas:	-160 °C
Temperature of surrounding air:	10 °C
Ground temperature:	10 °C
Ground roughness:	0.035
Atmospheric stability class:	D

In addition to the base case scenarios, a number of parameter variations were defined (base case shown in bold):

<u>Variations, jet release:</u>

- Leak rate: 0,5 kg/s, **5 kg/s**, 50 kg/s
- Leak direction: up, down, **along the wind**, opposite to the wind
- Ground roughness: **0.035**, 0.02, 0.08
- Stability class: A, **D**, F
- Wind speed: **2 m/s**, 6 m/s, 12 m/s
-
- <u>Variations, pool release:</u>
- Pool diameter: 2.2 m, **6.8 m**, 22 m
- Ground roughness: **0.035**, 0.02, 0.08
- Stability class: A, **D**, F
- Wind speed: **2 m/s**, 6 m/s, 12 m/s

For each variation of one parameter, all other parameters were kept as the base case values.

In addition to the above scenarios, sloping terrain and geometry were simulated with the CFD tools.

2.4 Results - Diffusive leaks (LNG)

2.4.1 Base case

Pool diameter is set as 6.8 m and it is released as a diffusive source by setting a constant evaporation rate 0.14 kg/m^2s throughout the surface area. This will give a mass flow rate 5.084 kg/s released into the atmosphere. Neutral wind condition, class D model with wind speed 2 m/s is chosen for this analysis. Standard k-epsilon turbulence model with wall functions are used in both the CFD codes. The results are shown as plume length with contour plots. The plume lengths are given as distance from leak to gas concentration of Upper flammability limit (UFL), Lower flammability limit (LFL) and ½ Lower flammability limit (½LFL).

From the results of the base case simulation, it can be concluded that both CFD tools and integral tool PHAST agreed well with each other. TRACE shows a discrepancy compared to the other tools for all the plume lengths. Nevertheless, it shows the same trend as the other tools, see Figure 2.3.

FLACS gave a different gas concentration profile than KFX. LFL and ½ LFL distance is about 32 % and 37 % higher in FLACS. The UFL distance is 17 % higher in KFX. From Figure 2.4 it can be concluded that the cloud shape is more diffusive in KFX than in FLACS. This can be attributed to differences in the pool model and turbulence model implementations between the two CFD codes. This is substantiated by reports from several earlier comparative studies of these codes for pool simulations. One such comparison is given in Ref. /10/.

The computational mesh will also affect the results; the near wall cell height from the ground is different in both the codes. In FLACS it is modelled with 0.5 m and in KFX it is 0.050 m. It will affect the near wall velocity profile due to change in wall Y+ values and eventually affects the dispersion.

Table 2.1: Comparison of plume length between Integral and CFD tools

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	102	74	95.6	193.1
LFL	65	49	55.5	114.7
UFL	25.5	31	19.2	46.3

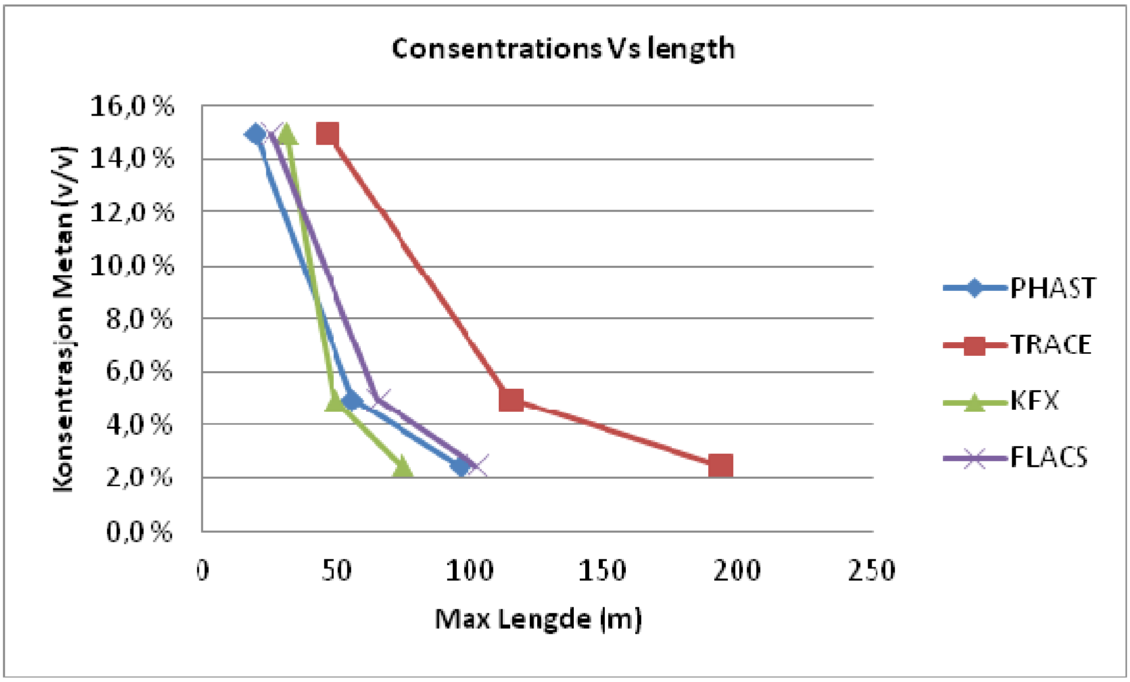

Figure 2.3: LFL, ½ LFL and UFL concentrations of CH4 between CFD tools and Integral tools

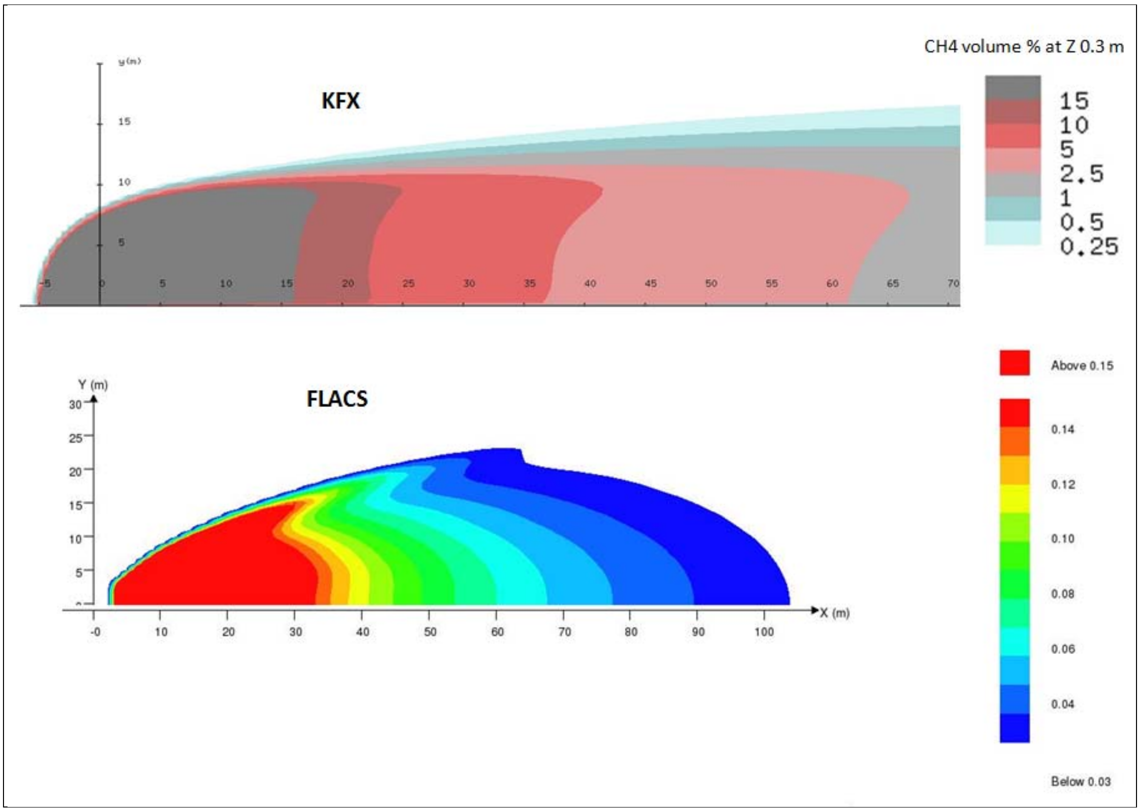

Figure 2.4: Comparison plot of CH_4 concentrations between KFX and FLACS at Z = 0.3 m viewed from above. (Symmetry plane along the x-axis)

2.4.2 Effect of leak size

Both CFD tools and integrated tools are used to simulate the effects of leak size in the pool simulation. 3 leak sizes are modelled by varying the pool diameter 2.2, 6.8 and 22 m (evaporation rate per area is kept unaltered) to give release rates of 0.532 kg/s, 5.084 kg/s and 53.22 kg/s respectively. The source is released as a constant evaporation rate 0.14 kg/m^2s and wind speed is chosen as 2 m/s with neutral stability class D model. Standard k-epsilon turbulence model with wall functions are used in both the CFD codes. The results are shown as plume lengths in tables and graphs. The plume lengths for these scenarios are given in Table 2.2, and Table 2.3.

The comparison plot of LFL, ½ LFL and UFL values are shown in Figure 2.5, Figure 2.6 and Figure 2.7 respectively. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limit (½LFL) for all 3 cases separately.

From the results of this comparison, it can be concluded that both CFD tools and integral tool PHAST agreed well with each other for low release rates. FLACS and TRACE shows a somewhat larger discrepancy in LFL distance for the case 53.22 kg/s when compared to PHAST and KFX.

In general, the differences in the model highlighted in the base case simulations are pronounced for the larger release rates. UFL plume length did not agree for any of the tools for larger release rates.

Table 2.2: Comparison of plume length between integral and CFD tools for 0.53 kg/s

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	27	35.75	37.9	62.7
LFL	17.5	25.25	22.2	37.3
UFL	8	18	8.5	18.4

Table 2.3: Comparison of plume length between integral and CFD tools for 53.22 kg/s

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	303	240	250	613.3
LFL	285	151	119	369.4
UFL	216	98	42	157.1

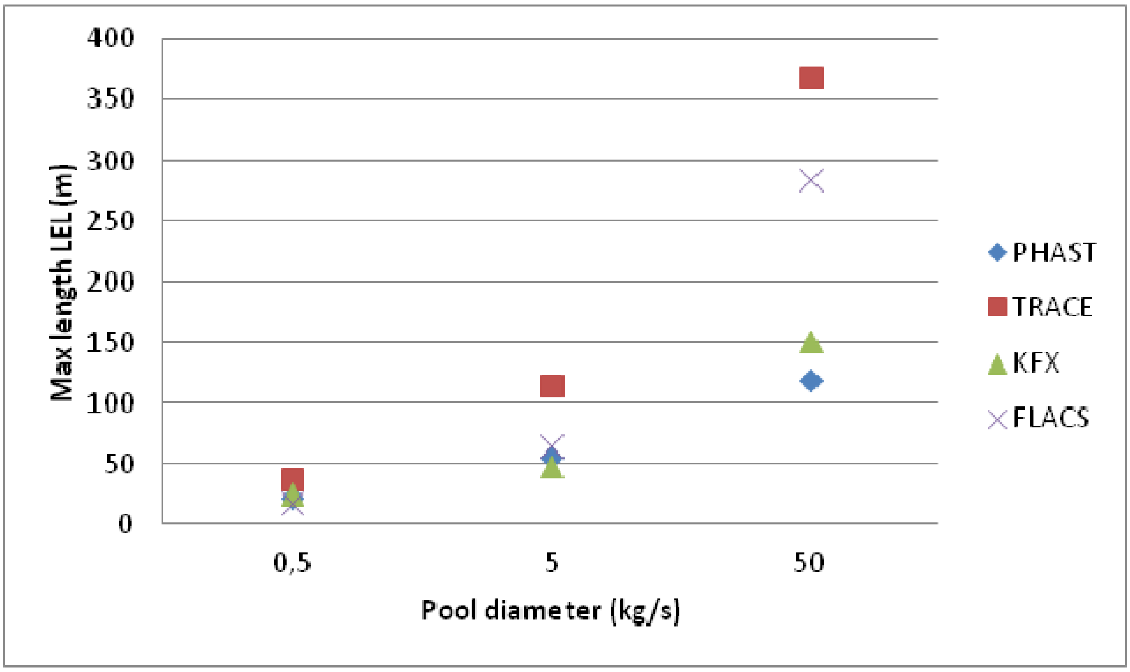

Figure 2.5: LFL plume length of CH4 between CFD tools and integral tools for various leak rates

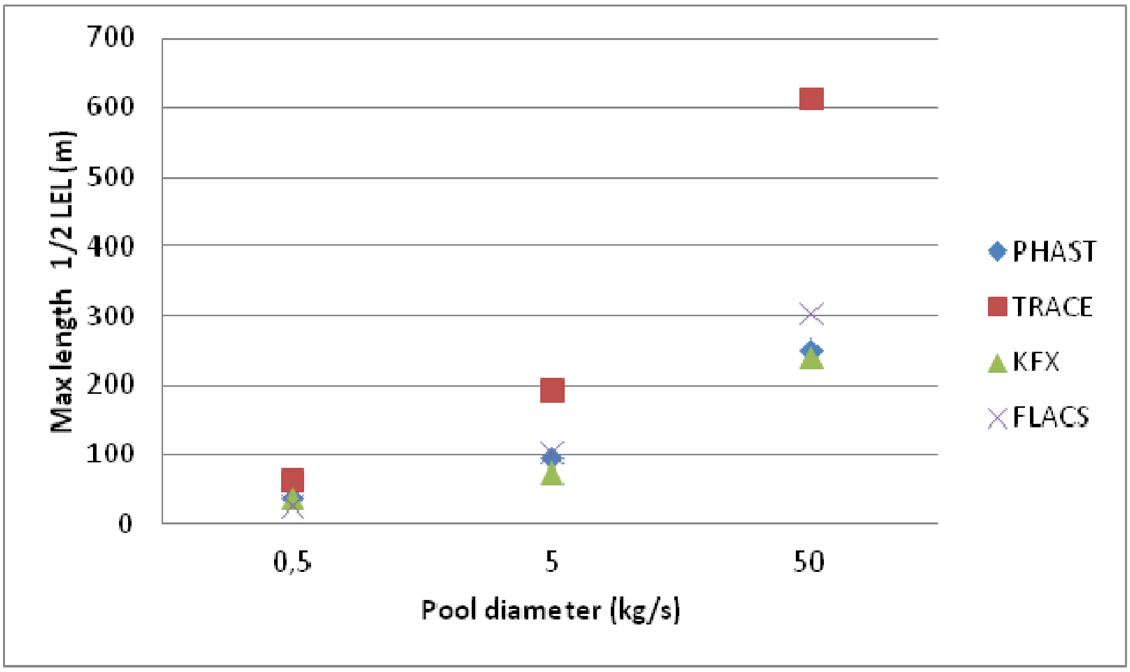

Figure 2.6: ½ LFL plume length of CH4 between CFD tools and integral tools for various leak rates

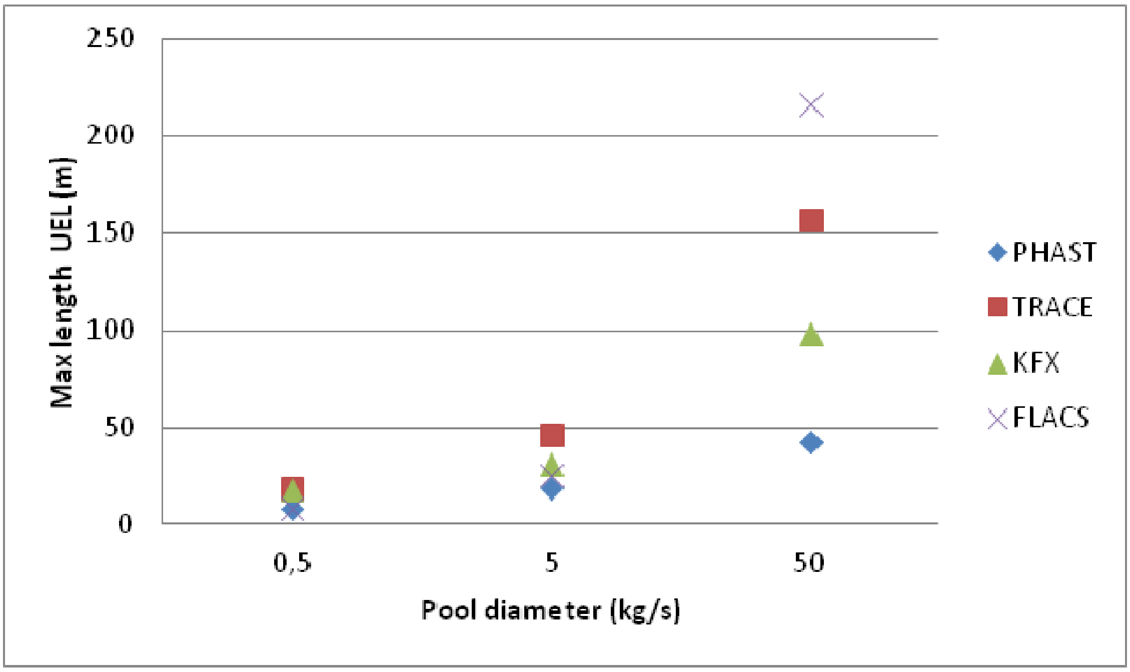

Figure 2.7: UFL plume length of CH4 between CFD tools and integral tools for various leak rates

2.4.3 Effect of surface roughness

Both CFD tools and integral tools are used to simulate the effects of surface roughness for the pool simulation. Surface roughness is given as scaled roughness height (Z0) 0.035m, 0.2 m and 0.8 m with release rate of 5.084 kg/s. The source is released as a constant evaporation rate 0.14 kg/m^{2}s and wind speed is chosen as 2 m/s with neutral stability class D model. Standard k-epsilon turbulence model with wall functions are used in both the CFD codes. The results are shown as plume length with tables and graphs. In tables Table 2.4 and Table 2.5, the plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limit (½LFL) for this cases separately. Comparison plots for LFL, ½ LFL and UFL are shown in Figure 2.8, Figure 2.9and Figure 2.10 respectively.

From the results of these simulations, it can be concluded that CFD tools and integral tool PHAST agreed well with each other for LFL and ½ LFL plume lengths. TRACE predicted a larger hazardous distance for all the cases. However it captures the trend and shows a steady decline in plume length for increasing surface roughness. In general the discrepancies are larger for UFL when compared to LFL and ½ LFL plume lengths. PHAST shows a different trend for UFL plume length on contrary to CFD tools and TRACE.

It should be noted that the surface roughness is defined differently in the integral tools and the CFD tools; in the integral tools the surface roughness is a parameter intended to represent objects in the computational domain (e.g. buildings and trees), whereas the surface roughness in the CFD tools is a parameter used to tune the turbulence model on the surface boundary condition.

Table 2.4: Comparison of plume length between Integral and CFD tools for roughness Z0 = 0.2 m

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	62.5	60	78	155.3
LFL	40	38	41.2	94.7
UFL	18	26	13.4	38.5

Table 2.5: Comparison of plume length between Integral and CFD tools for roughness Z0 0.8 m

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	44	46	66	122.6
LFL	28	31	32.6	74.3
UFL	13	17	20	30.2

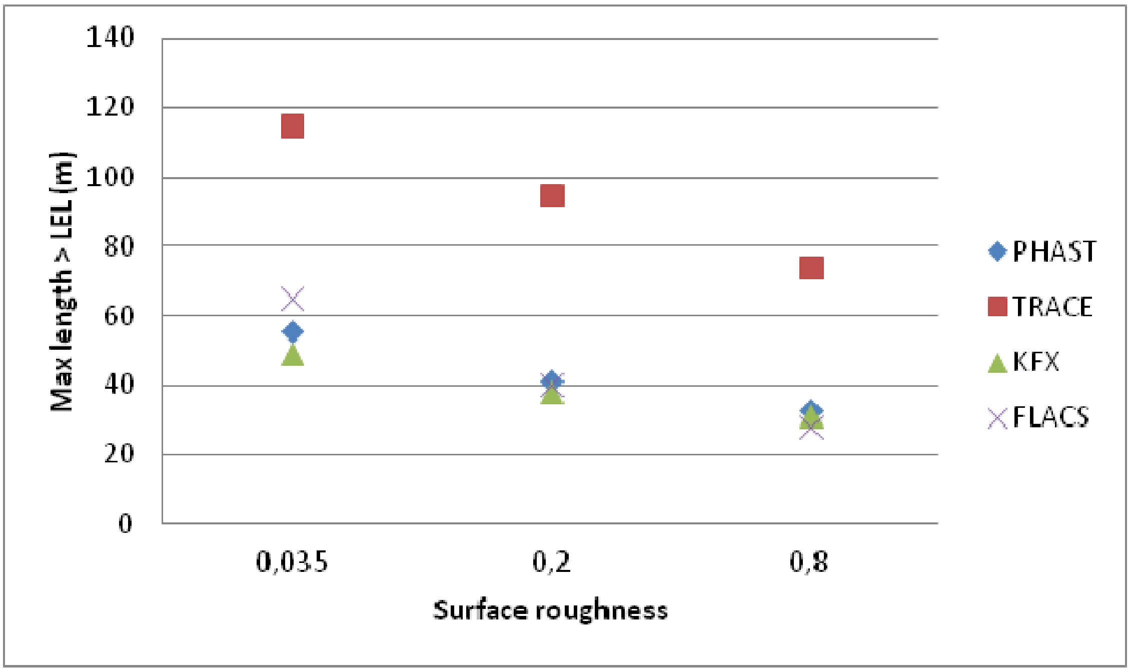

Figure 2.8: LFL plume length of CH4 between CFD tools and integral tools for various surface roughness

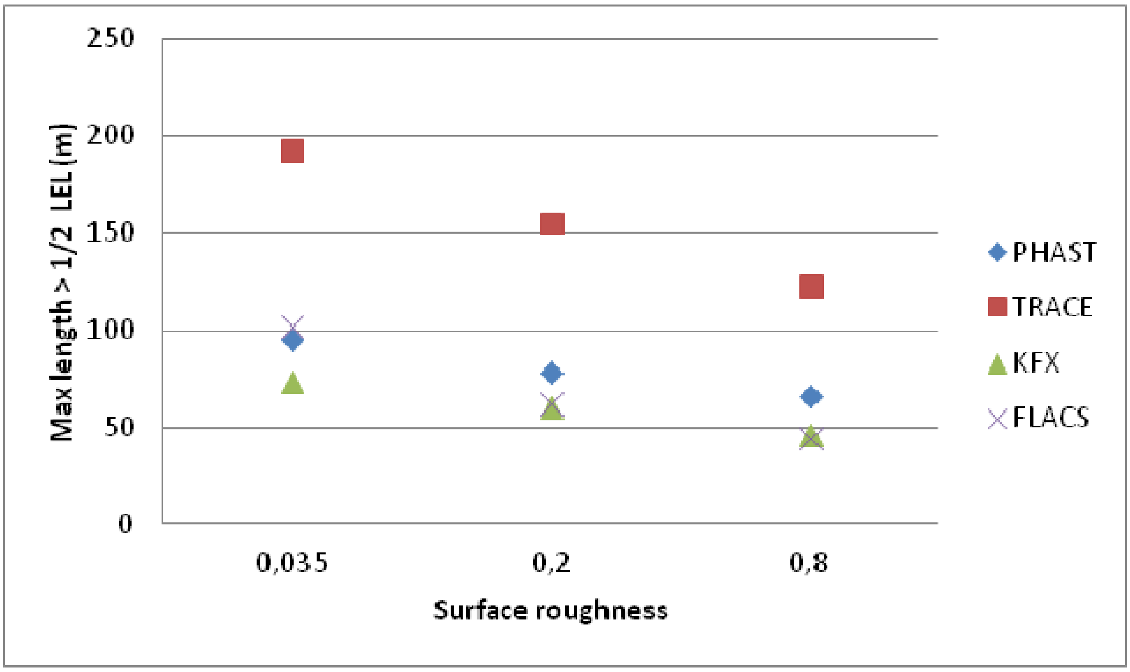

Figure 2.9: ½ LFL plume length of CH4 between CFD tools and integral tools for various surface roughness

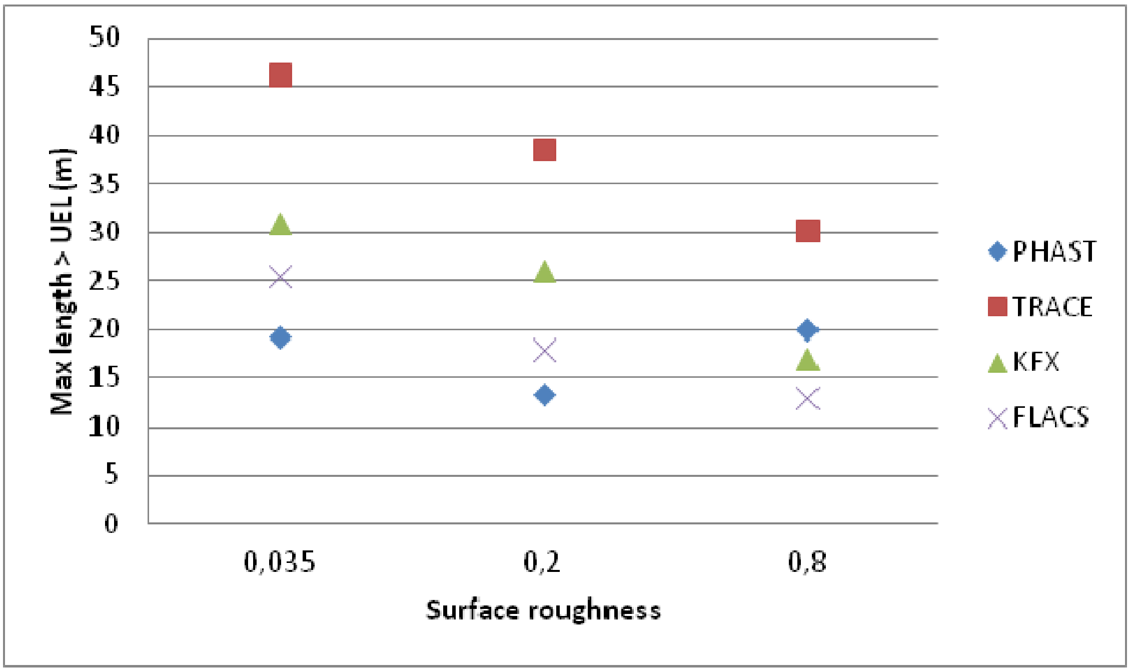

Figure 2.10: UFL plume length of CH4 between CFD tools and integral tools for various surface roughness

2.4.4 Effect of wind speed

Both CFD tools and integral tools are used to simulate the effects of wind speed for the pool simulation. Wind speed is chosen as 2, 8 and 12 m/s with neutral stability class D model. Surface roughness is given as scaled roughness height (Z0) 0.035 m. The source is released as a constant evaporation rate 0.14 kg/m^{2}s to get a release rate of 5.084 kg/s. Standard k-epsilon turbulence model with wall functions are used in both the CFD codes. The results are shown as plume length in tables and graphs. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limit (½ LFL) for all 3 cases separately.

From the results of these simulations, it can be concluded that the CFD tools and the integral tool PHAST agreed well with each other for LFL and ½ LFL plume lengths. TRACE shows a larger discrepancy for all the cases. The comparison plots for LFL, ½ LFL and UFL are shown in Figure 2.11,Figure 2.12 and Figure 2.13respectively. In general the discrepancies are larger for UFL when compared to LFL and ½ LFL plume lengths. PHAST and KFX show a different trend for UFL plume length on contrary to FLACS and TRACE.

Table 2.6: Comparison of plume length between integral and CFD tools for wind 6 m/s

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	58	70	79.6	38.1
LFL	37	50	51.2	22.8
UFL	14	33	22.8	0.7

Table 2.7: Comparison of plume length between integral and CFD tools for wind 12 m/s

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	38	48.5	66.5	20.4
LFL	21.5	32	43.3	0.5
UFL	5.5	21.5	22	0.4

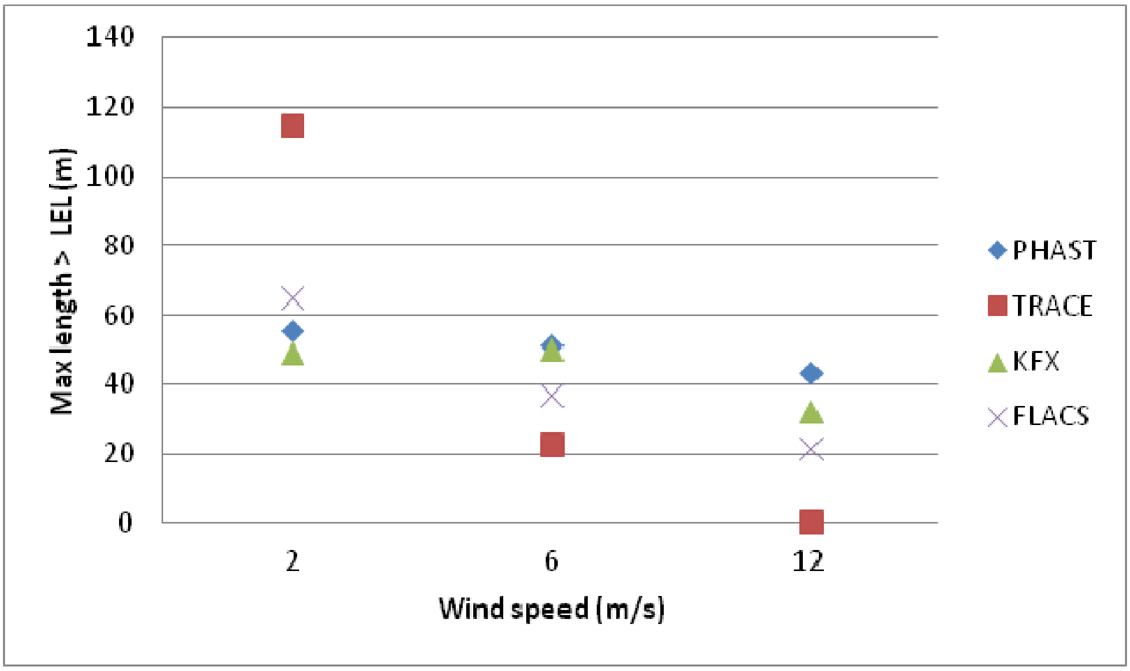

Figure 2.11: LFL plume length of CH4 between CFD tools and integral tools for various wind speeds

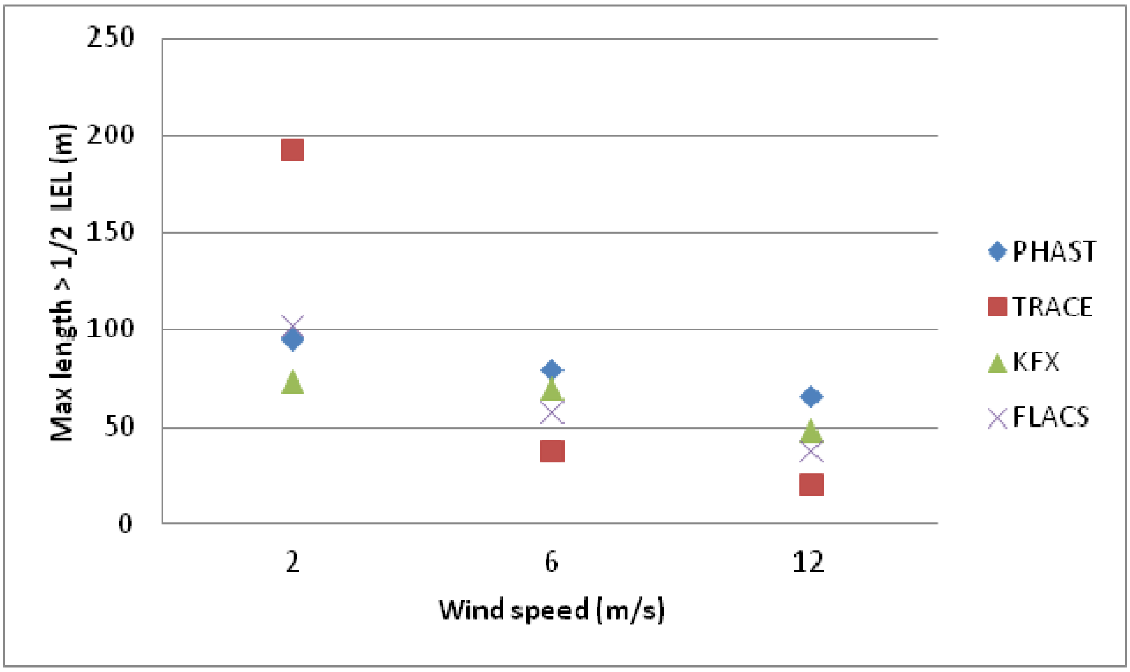

Figure 2.12: ½ LFL plume length of CH4 between CFD tools and integral tools for various wind speeds

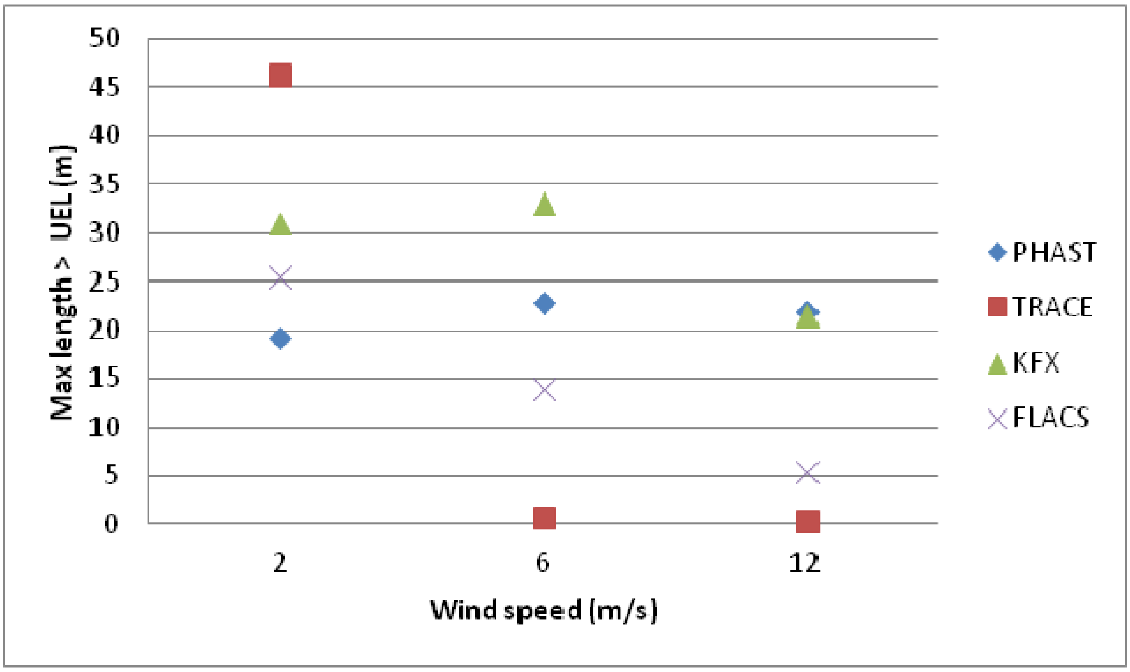

Figure 2.13: UFL plume length of CH4 between CFD tools and integral tools for various wind speeds

2.4.5 Effect of wind stability

Both CFD tools and integral tools are used to simulate the effects of wind stability class for the pool simulation. Wind speed is chosen as 2 m/s with scaled surface roughness height (Z0) 0.035 m for this analysis. The source is released as a constant evaporation rate 0.14 kg/m^{2}s to get a release rate of 5.084 kg/s. Standard k-epsilon turbulence model with wall functions are used in both the CFD codes. The results are shown as plume length in tables and graphs. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limit for all 3 cases separately.

In general all the models agreed to show the same trend i.e. the plume lengths are increasing for the wind stability class A, D and F in ascending manner. It is evident that stability class A has high turbulence levels and results in more turbulent diffusion. Diffusion tends to spread the concentrations in all directions and shortens the plume length by lowering the convection strength. So class A predicts a lower plume length when compared to other classes.

In CFD, stability class A cannot be modelled due to some modelling difficulties with standard k-epsilon models. So both KFX and FLACS are not capable to simulate this stability class. The plume length agrees well for stability class D between CFD tools and PHAST. The discrepancies are larger for F class. The reason can be attributed to some differences in length scales for Mean Obokuv length and other turbulence parameters as discussed in base case simulations.

Table 2.8: Comparison of plume length between integral and CFD tools for wind stability class A

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	NA	NA	50.2	159.4
LFL	NA	NA	34.7	96.4
UFL	NA	NA	17.3	39.8

Table 2.9: Comparison of plume length between integral and CFD tools for wind stability class F

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	127	86	282	250.1
LFL	93	56	134	143.7
UFL	41.5	35	25	73.5

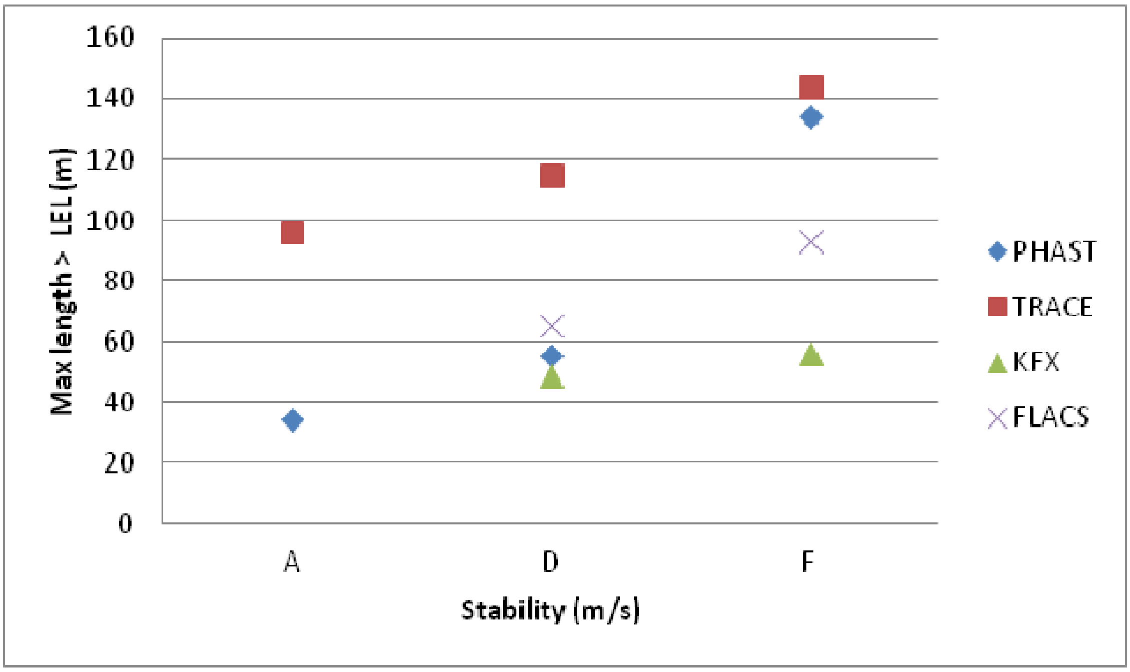

Figure 2.14: LFL plume length of CH4 between CFD tools and integral tools for various wind stability class

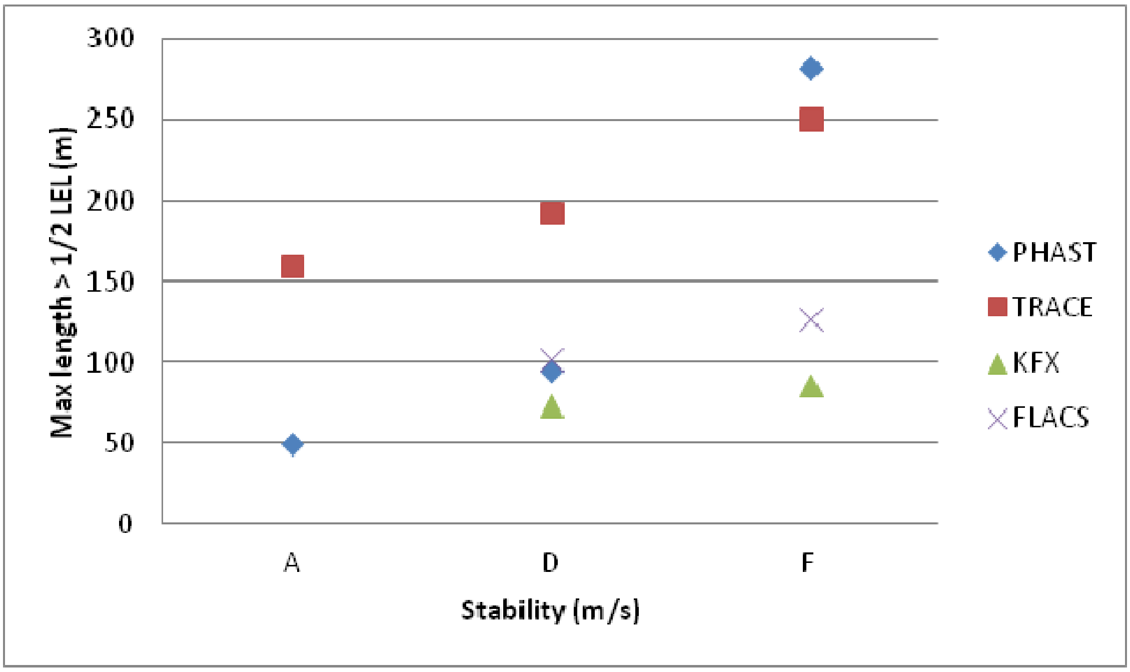

Figure 2.15: ½ LFL plume length of CH4 between CFD tools and integral tools for various wind stability class

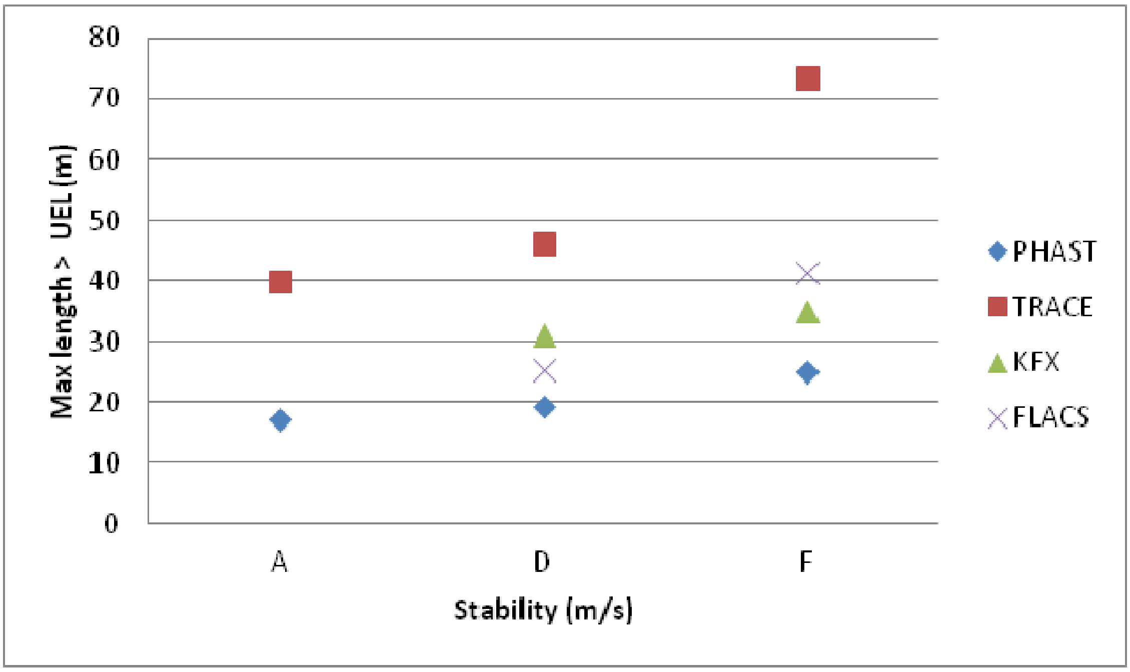

Figure 2.16: UFL plume length of CH4 between CFD tools and integral tools for various wind stability class

2.4.6 Effect of sloping terrain

Only KFX and FLACS are used to simulate the effects of sloping terrain for the base case pool simulation (as this is not an option in the integral tools). 5 % slope is considered for this simulation. It is modelled by tuning the acceleration vectors gx and gz to induce some horizontal body forces in all the cells. Wind speed is chosen as 2 m/s with scaled surface roughness height (Z0) 0.035 m for this analysis. The source is released as a constant evaporation rate 0.14 kg/m^{2}s to get a release rate of 5.084 kg/s. Standard k-epsilon turbulence model with wall functions are used in both the CFD codes. The results are shown as plume length in tables and graphs. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limit for all 3 cases separately.

When compared to base case KFX simulations (0 % slope), the plume length for LFL, ½ LFL and UFL are increased to 7 %, 8.2 % and 9.7 % respectively. It is to be noted that in the current scenario, pool spreads only in gas phase; the liquid pool size is fixed as constant.

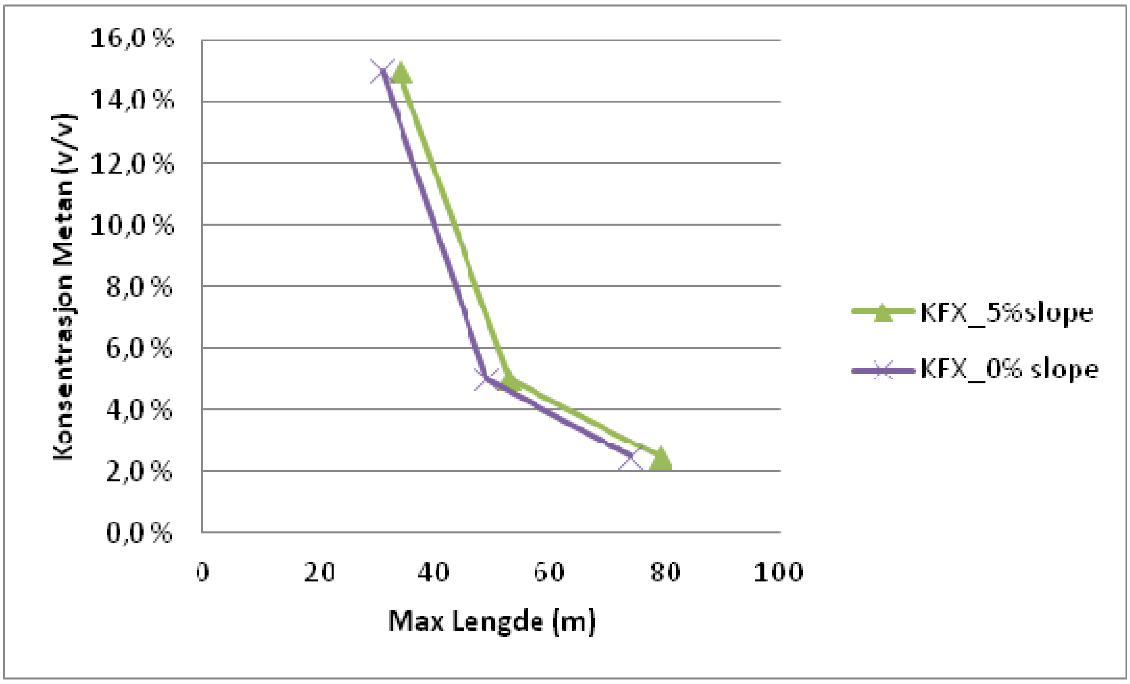

Figure 2.17: LFL, ½ LFL and UFL plume length of CH_4 for slope 5 % and 0 %

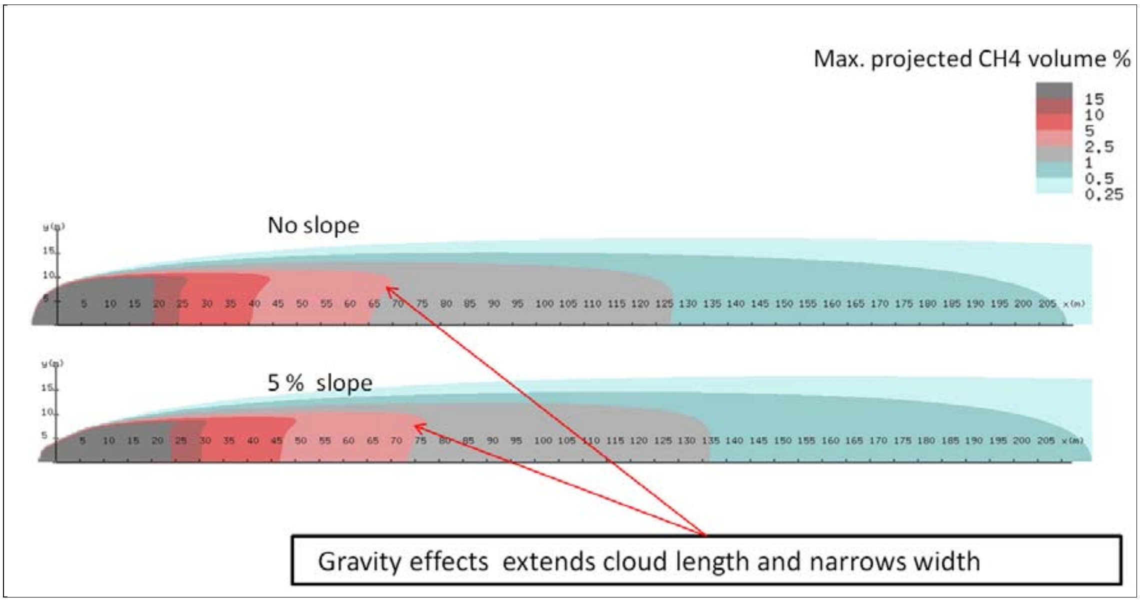

Figure 2.18: Comparison plot of CH_4 concentrations for 0 % and 5 % slope in KFX simulation viewed from above (symmetry plane along the x-axis)

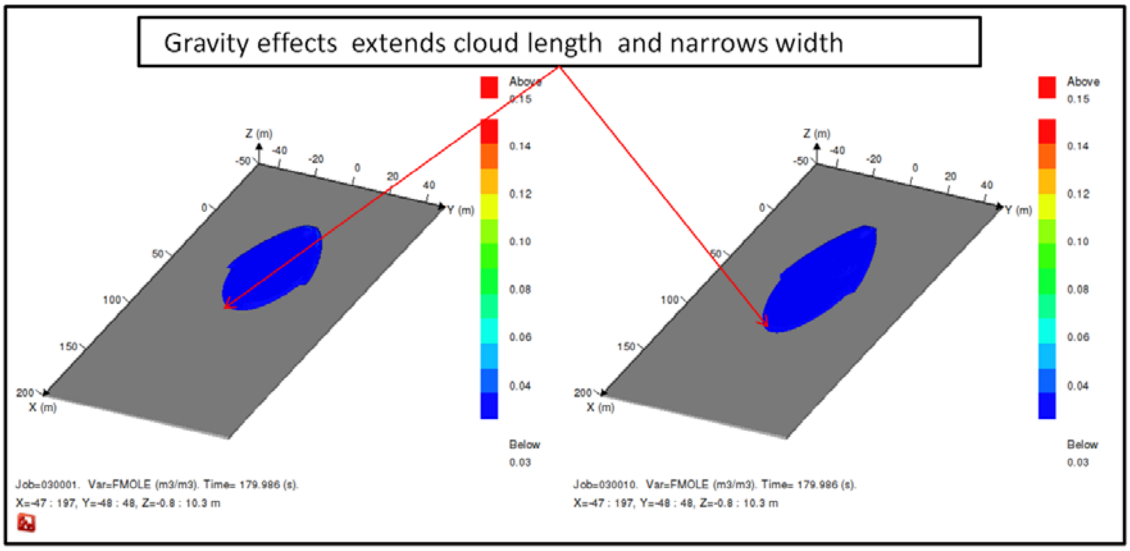

Figure 2.19 Comparison plot of CH4 concentrations for 0 % and 5 % slope in FLACS simulation viewed from above

2.5 Results - Jet leaks (methane)

2.5.1 Base case

Methane is released at 350 m/s with mass flow rate 5 kg/s. Neutral wind class D and wind speed 2 m/s is chosen for this analysis. A logarithmic wind profile is chosen with scaled roughness height (Z0)0.035 m for the ground. Standard k-εpsilon turbulence model with wall functions are used in both the CFD codes. The results are shown as plume length with contour plots. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limits (½ LFL).

In general all tools agreed very well for UFL and LFL plume lengths. But ½ LFL lengths have shown some discrepancies among each other in both CFD and integral tools. In CFD tools, air entrainment and turbulence viscosity plays an important role in the mixing process and therefore leads to somewhat different plume lengths. In KFX, air entrainment from under expanded part of the jet is additionally added to the jet release. This is not possible to implement in FLACS, which is validated for pure hydrocarbon releases. The entrained air in the KFX simulations is drawn from the atmosphere and enters the jet release cell from the release cell sides. In FLACS air entrainment in the compressible (supersonic) part of the jet is not added to jet cell, air entrainment is only simulated in the subsonic velocity region. After jet expansion, the mixing is largely governed by the turbulent viscosity which is a function of kinetic energy (k) and dissipation rate (ε).

$$\mu_t = C_\mu \frac{k^2}{\varepsilon}$$

k - Specific turbulent kinetic energy (m^2/s^2)
ε - Specific dissipation rate (m^2/s^3)
C_μ - 0.09 (empirical constant)

Both k and ε are strongly depends upon the model coefficients which are tuned for certain types of flows in both the codes. These model coefficients will affect the turbulent viscosity and eventually it affects the flow field. These effects are much pronounced in the far field (where the convection strengths are low and turbulence diffusion rates are high) when compared to the near field (higher convection).

Table 2.10: Comparison of plume length between integral and CFD tools

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	53	64.5	95.6	31
LFL	20	17	19.5	17
UFL	6.5	8.5	6.5	7

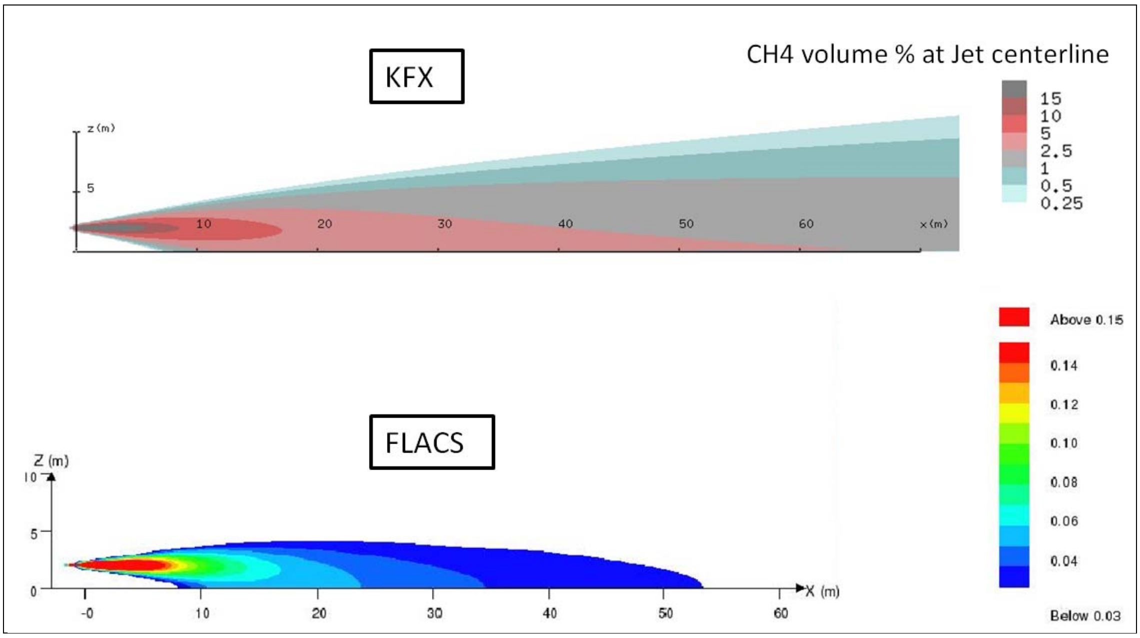

Figure 2.20: Comparison plot of CH4 concentrations for the base case jet simulations between KFX and FLACS at jet centre line (viewed from side in XZ plane)

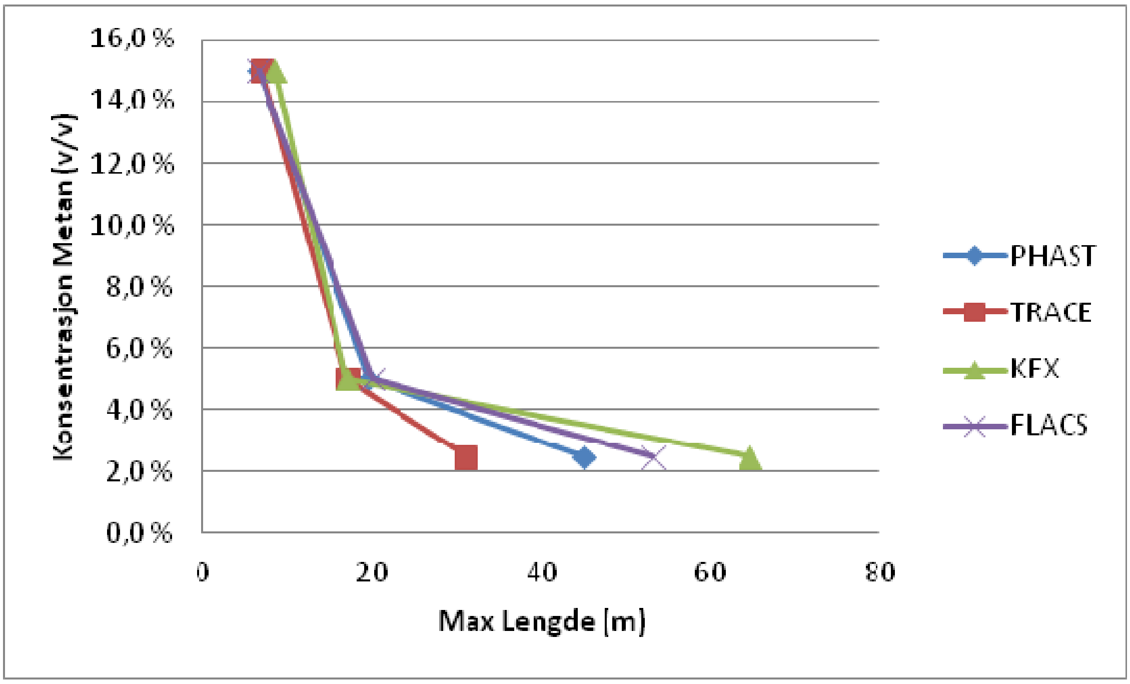

Figure 2.21: Comparison plot of CH_4 concentrations for the base case jet simulations between CFD and integral tools (½ LFL: 2.5 %, LFL: 5 %, UFL: 15 %)

2.5.2 Effect of leak size

Both CFD tools and integral tools are used to simulate the effects of leak sizes in the jet simulation. Three release rates are used: 0.5 kg/s, 5 kg/s and 50 kg/s. The remaining parameters are the same as for the base case simulation. The results are shown as plume length in tables and graphs. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limits (½ LFL).

From the results it can be concluded that at low flow rates, plume lengths agreed very well between all the tools. At large flow rates, discrepancies are found to be high. KFX predicts larger plume lengths than its counter parts. It shows that jet momentum decays faster in FLACS than in KFX. The possible reason can be due to differences in air entrainments and turbulent viscosity predictions.

Table 2.11: Comparison of plume length between integral and CFD tools for 0.5 kg/s

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	13.2	11.75	12.4	10
LFL	7.5	5.75	7.1	5
UFL	3.5	3.0	2.2	2

Table 2.12: Comparison of plume length between integral and CFD tools for 5 kg/s (Base case)

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	53	64.5	95.6	31
LFL	20	17	19.5	17
UFL	6.5	8.5	6.5	7

Table 2.13: Comparison of plume length between integral and CFD tools for 50 kg/s

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	157	246.5	193	177
LFL	78.2	112	79.4	68
UFL	19	45.25	20	68

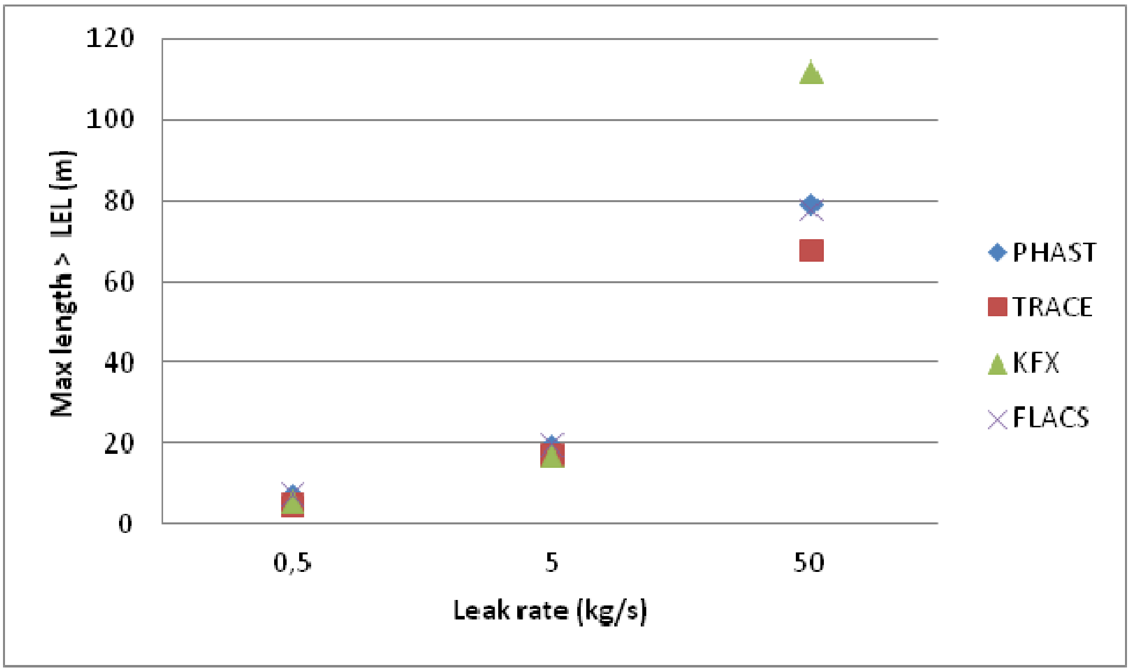

Figure 2.22: LFL plume length of CH_4 between CFD tools and integral tools for various leak rates

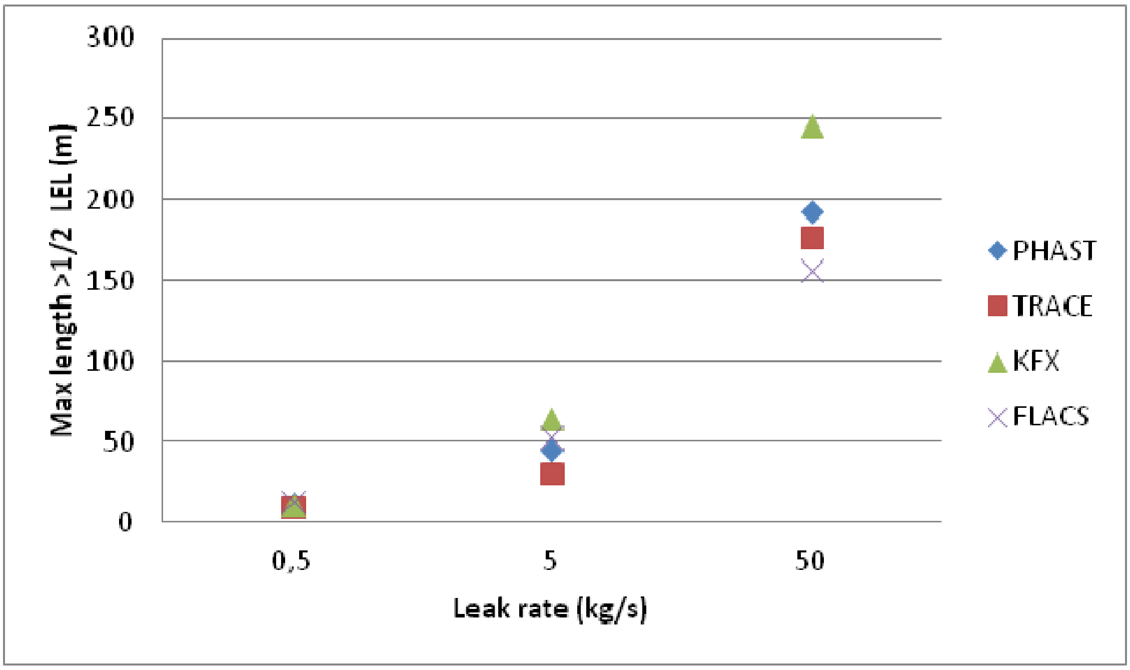

Figure 2.23: ½ LFL plume length of CH4 between CFD tools and integral tools for various leak rates

2.5.3 Effect of leak direction

Both CFD and integral tools are used to simulate the effects of leak direction in the jet simulation. 4 leak directions were performed, as defined in Table 2.14. The remaining parameters are the same as for the base case simulations. The results are shown as plume length in Table 2.15. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limits (½ LFL). A graphical representation of the results is shown in Figure 2.24 and Figure 2.25.

Table 2.14: Jet leak directions relative to wind direction

Leak direction	Description
0º (base case)	Aligned with wind flow direction +X
90º (upward)	Normal to wind flow direction + Z
180º (opposite)	Opposite to wind flow direction -X
270º (downward)	Normal to wind flow direction –Z
90º (sideways)	Normal to wind flow direction +Y

Table 2.15: Comparison of plume length between CFD and integral tools for various jet leak directions

Plume length [m]	Upward		Downward		Opposite		Side	
	FLACS	KFX	FLACS	KFX	FLACS	KFX	FLACS	KFX
½ LFL	6.9	5	22	23	58	74.5	35	32
LFL	2.3	2	13	10	27	19.2	20	18
UFL	0.5	1	1	4	6.5	9	6.5	10

From the graph and plots, it can be seen that the results agree very well for upwards, side wards and aligned wind conditions. The jet leaks in downward and opposite direction to wind shows a large discrepancy between CFD tools. Both TRACE and PHAST are incapable to model these scenarios.

KFX and FLACS introduce numerical diffusion for the downward jet leaks due to Cartesian gridding system. This zone occurs after jet impingement on the ground. The numerical diffusion can be seen in the concentrations plots shown in Figure 2.26 and Figure 2.27. The problem might be reduced by using a more uniform grid, but will still remain somewhat, as the grid is Cartesian. One remedy can be to use a curvilinear grid such as O-grid in the jet location. But this is not supported by KFX and FLACS.

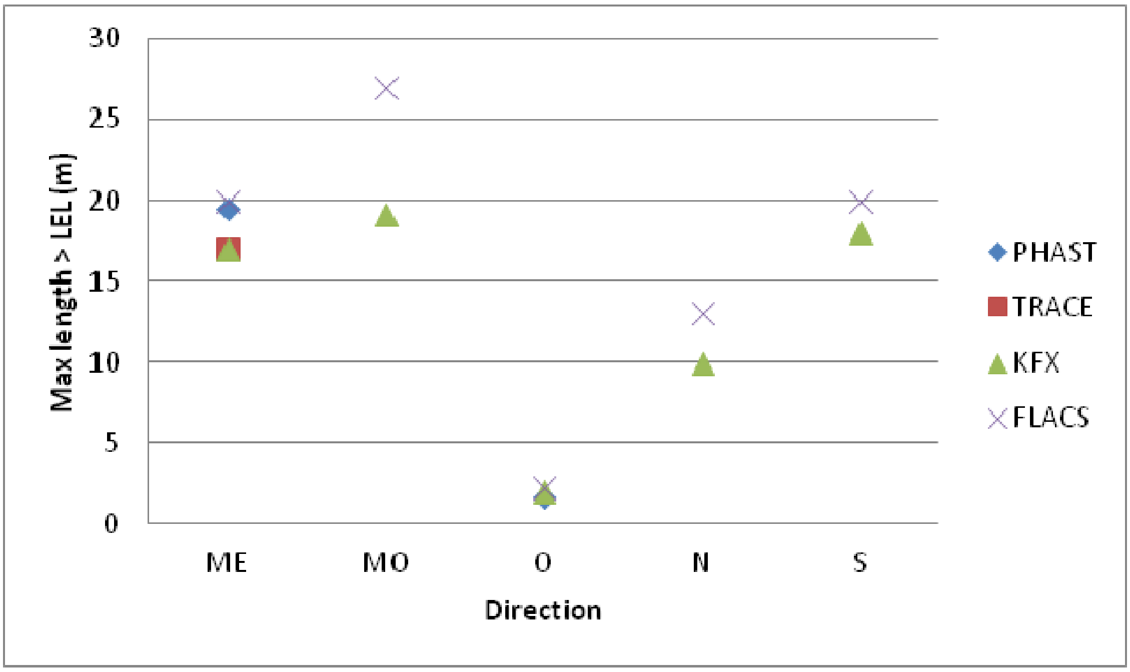

Figure 2.24: LFL plume length of CH4 between CFD tools and integral tools for various leak rates

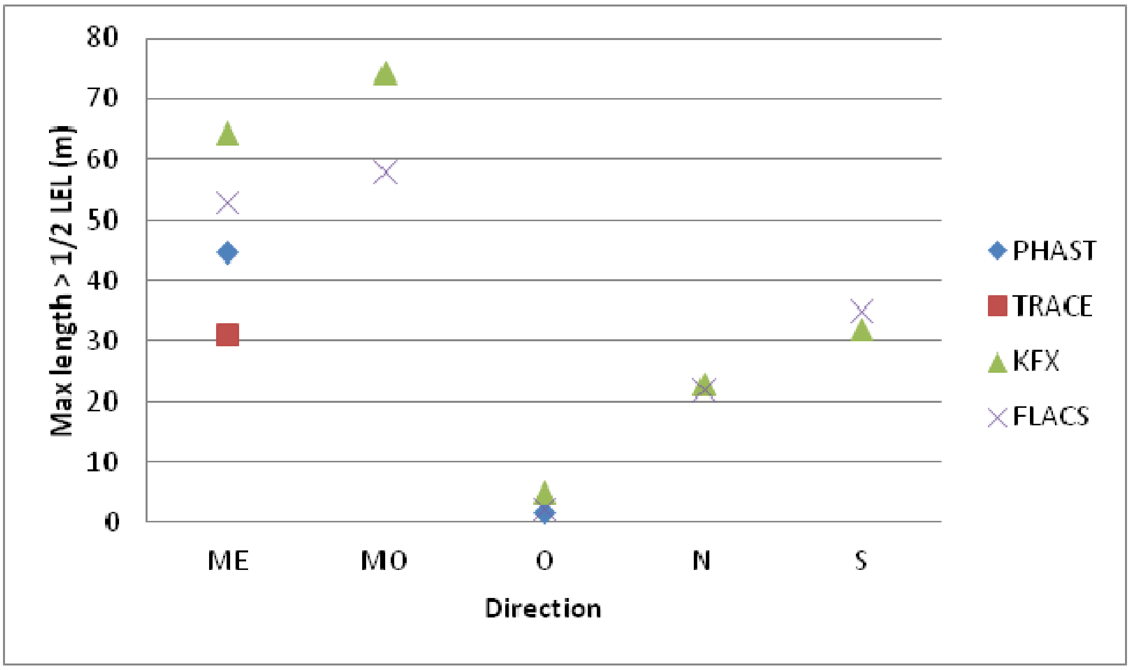

Figure 2.25: ½ LFL plume length of CH4 between CFD tools and integral tools for various leak rates

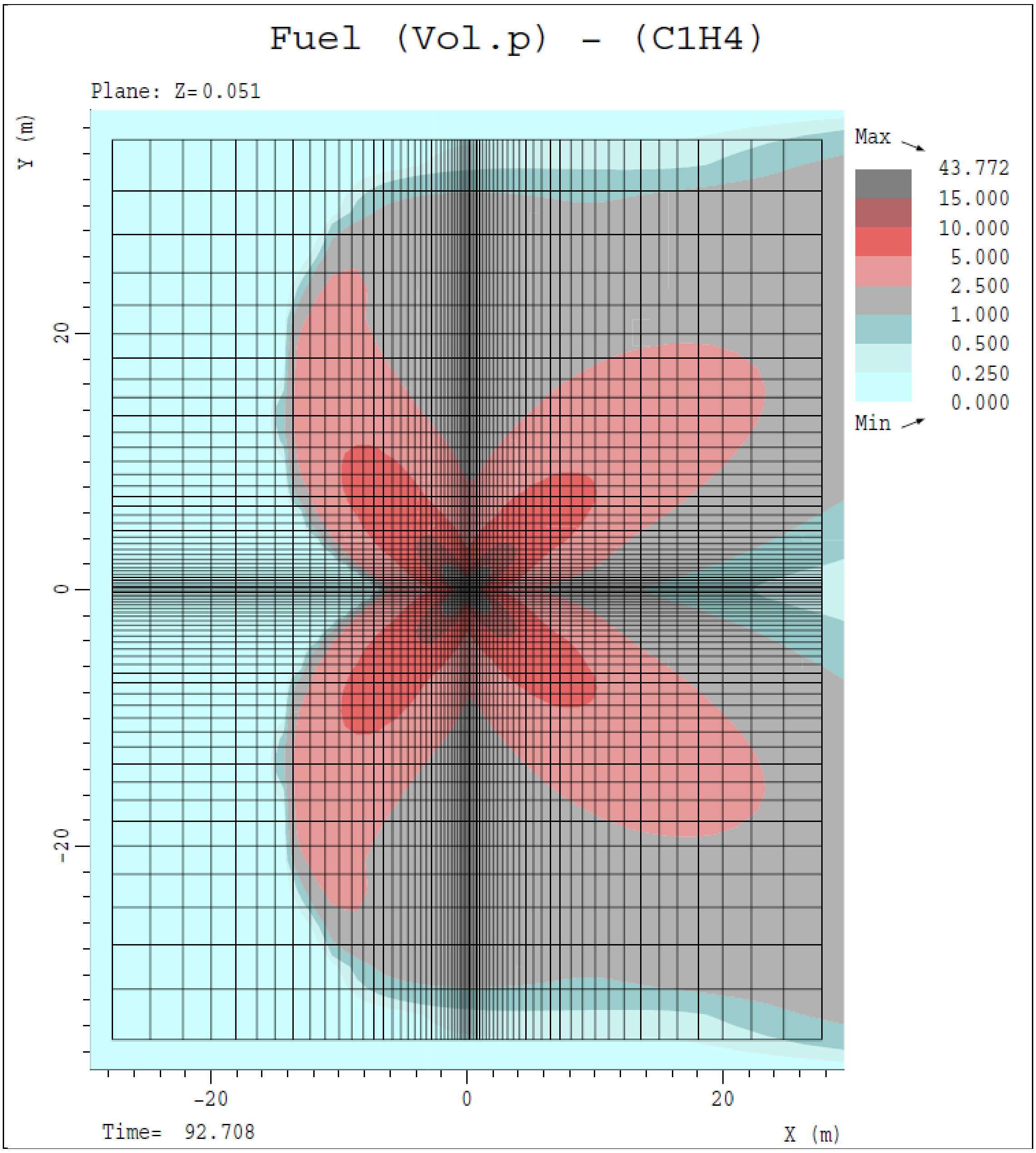

Figure 2.26: Concentration plots illustrating numerical diffusion for downwind jet leak in KFX simulation (top view)

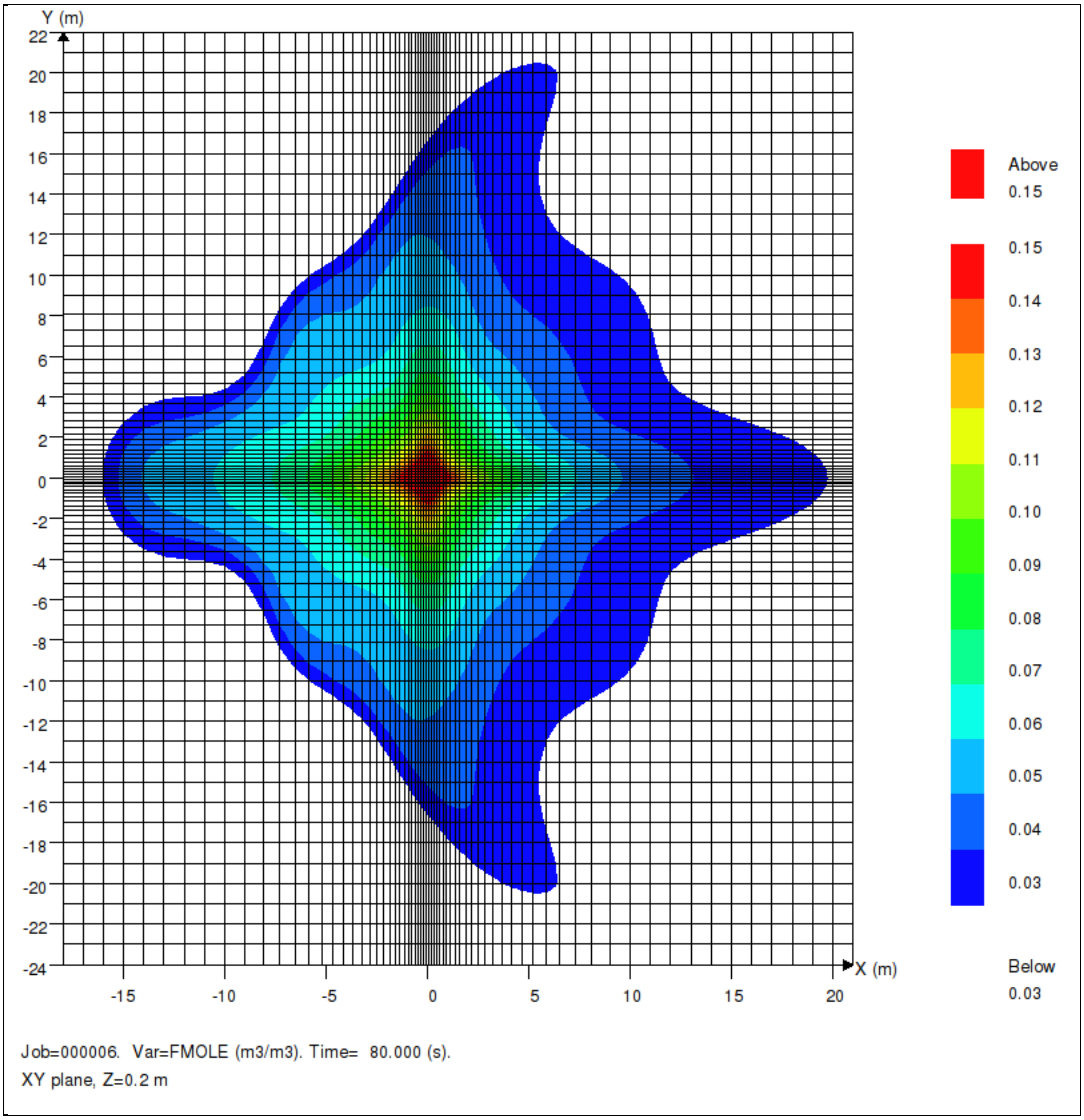

Figure 2.27: Concentration plots illustrating numerical diffusion for downwind jet leak in FLACS simulation (top view)

2.5.4 Effect of surface roughness

Both CFD tools and integral tools are used to simulate the effects of surface roughness in the jet simulation. Surface roughness values are given as scaled roughness (Z0) 0.2 m and 0.8 m. Rest of the parameters are same like base case simulations. The results are shown as plume length in tables and graphs. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limits (½ LFL).

From the results it can be concluded that the effect of surface roughness is very marginal and it did not affect the plume lengths significantly. The primary reason is the jet is elevated at 2 m above the ground, where the convection strength from jet is much stronger when compared to the diffusions caused by surface roughness.

In general, plume lengths for LFL and UFL agrees very well among the tools. But ½ LFL lengths differ a lot. KFX shows a larger plume length when compared to FLACS. The possible reasons can be due to differences in air entrainments and turbulent viscosity predictions among the CFD tools.

Table 2.16: Comparison of plume length between Integral and CFD tools for Z0 = 0.2 m

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	52.3	64.5	43.1	32
LFL	20	17	18.4	17
UFL	6.5	8.4	6.4	7

Table 2.17: Comparison of plume length between integral and CFD tools for roughness Z0 0.8 m

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	50.5	63.5	40.4	32
LFL	19.7	17	17.2	17
UFL	6.5	8.5	6.3	7

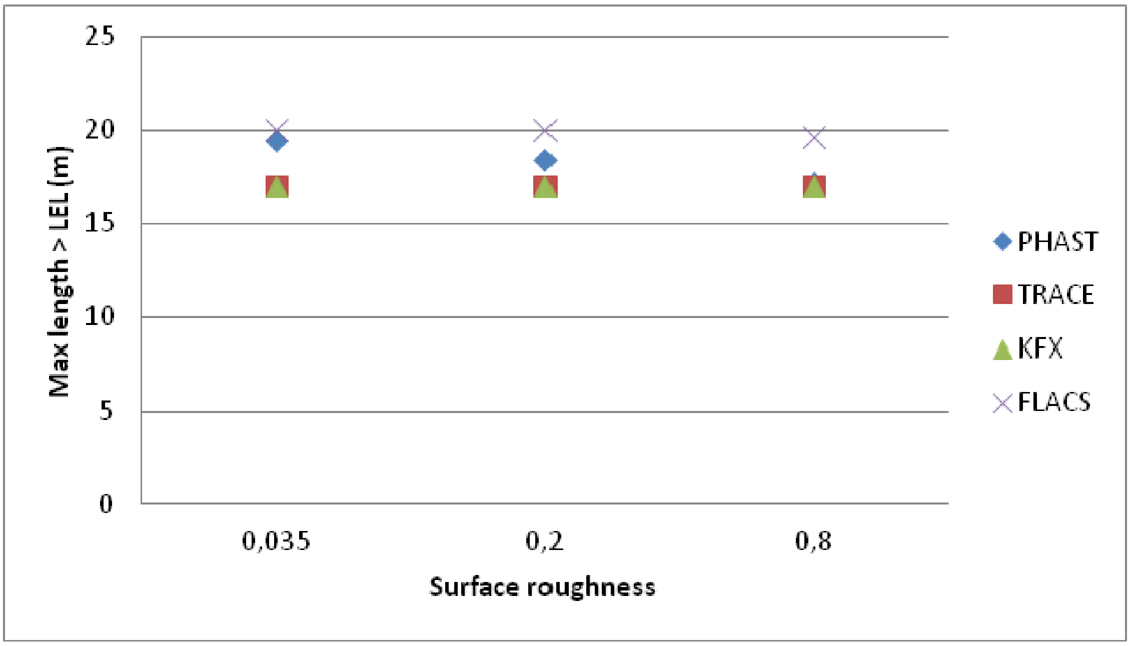

Figure 2.28: LFL plume length of CH_4 between CFD tools and integral tools for various surface roughness

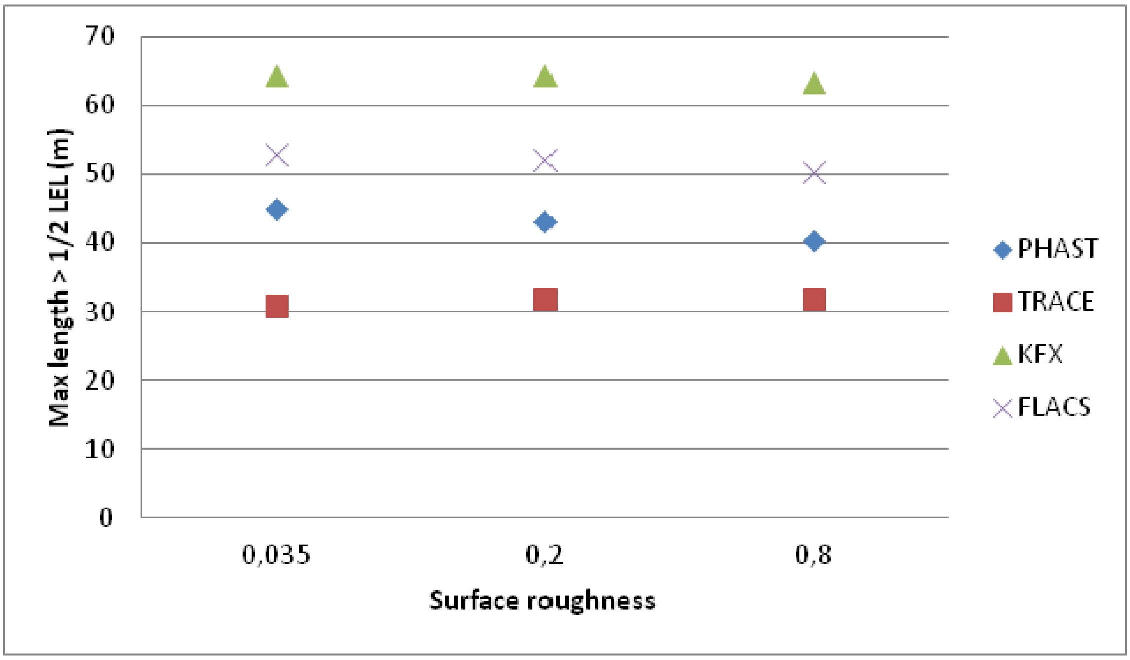

Figure 2.29: ½LFL plume length of CH4 between CFD tools and integral tools for various surface roughness

2.5.5 Effect of wind speed

Both CFD tools and integral tools are used to simulate the effects of wind speed in the jet simulation. Two wind speeds are chosen for this analysis 6 m/s and 12 m/s. Rest of the parameters are same like base case simulations. The results are shown as plume length with contour plots. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limits (½ LFL).

From the results it can be concluded that for larger wind speed, plume lengths are smaller due to enhanced mixing and results in short plume length. It is to be noted that UFL remains unchanged for TRACE, FLACS and KFX for all wind speeds. Only PHAST shows a decline in UFL length against wind speed. Only for ½ LFL plume length KFX shows the declining trend. One possible reason could be that the jet momentum is much stronger in KFX due to additional air entrainment and becomes insensitive to wind speed in the region closer to the jet. The wind velocity will only have a significant effect in the region of the jet where the jet momentum is comparable to the wind momentum – and this occurs further out in a jet with larger initial momentum.

Table 2.18: Comparison of plume length between integral and CFD tools for wind 6 m/s

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	49	60	36.7	27
LFL	18.5	17.5	16.7	14
UFL	6.5	8.87	6.2	7

Table 2.19: Comparison of plume length between integral and CFD tools for wind 12 m/s

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	37.5	47.5	26.7	22
LFL	17.7	17.2	14.5	13
UFL	6.5	8.85	5.9	7

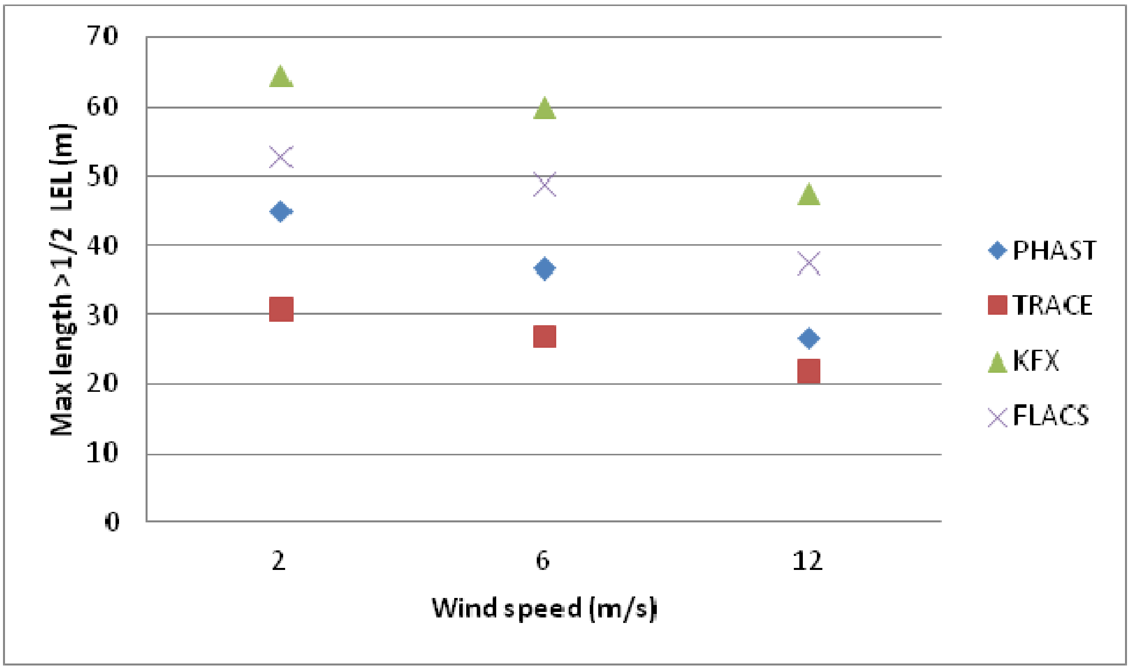

Figure 2.30: ½ LFL plume length of CH4 between CFD tools and integral tools for various wind speed

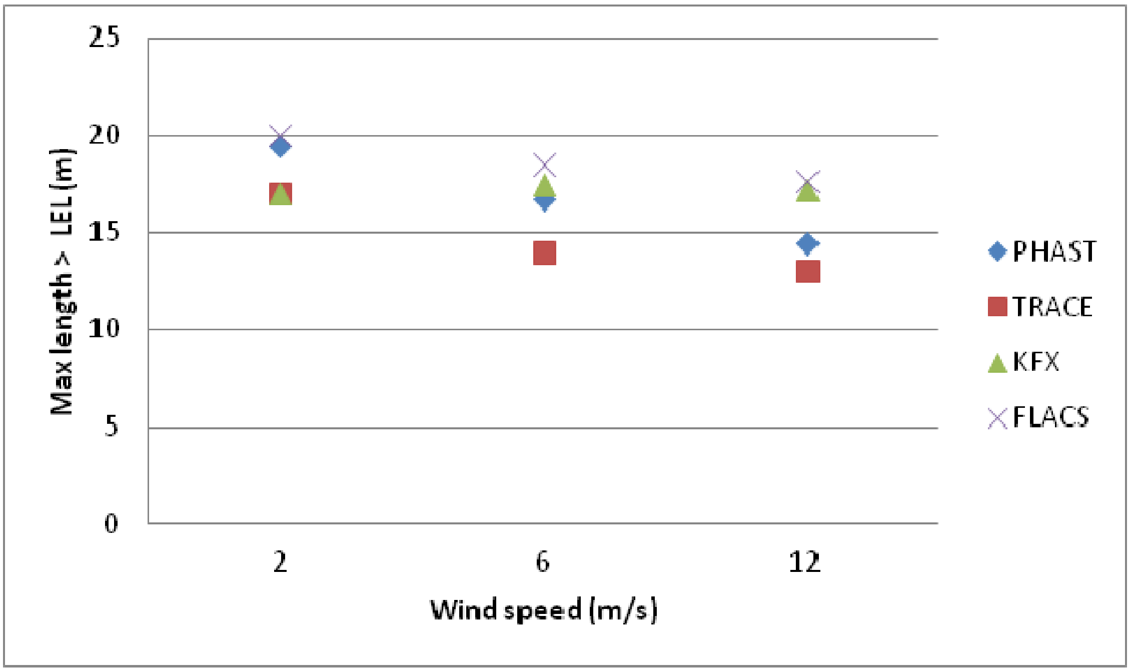

Figure 2.31: LFL plume length of CH4 between CFD tools and integral tools for various wind speed

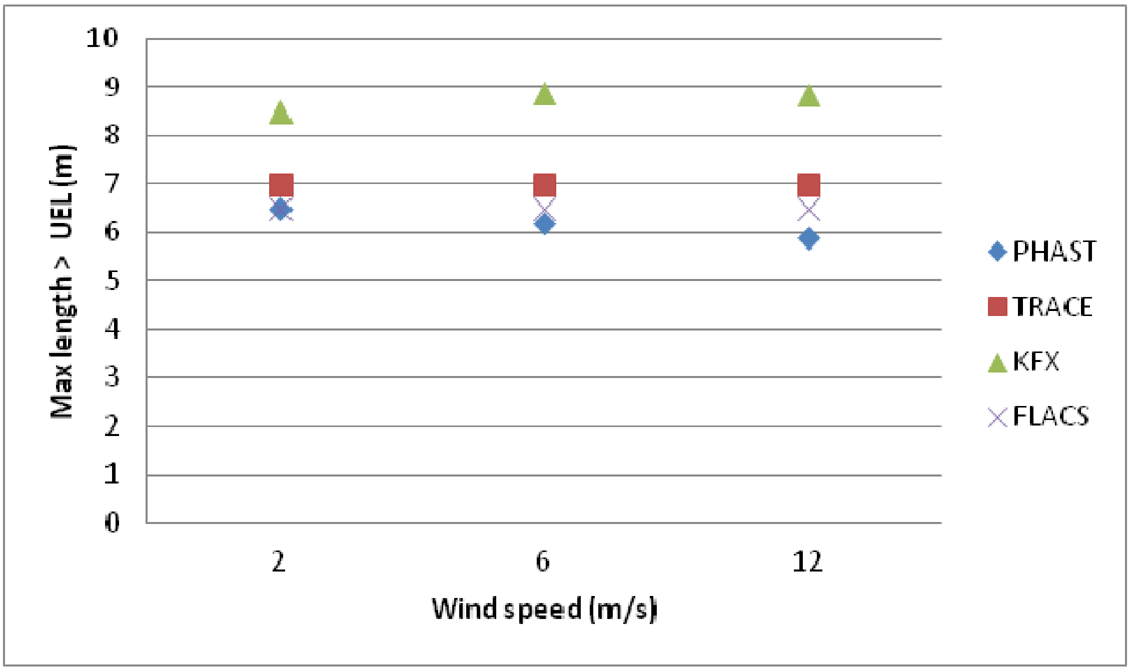

Figure 2.32: UFL plume length of CH4 between CFD tools and integral tools for various leak rates

2.5.6 Effect of wind stability

Both CFD tools and integral tools are used to simulate the effects of wind stability class models in the jet simulation. Wind class F (stable) and A (unstable) are chosen for this analysis. Rest of the parameters are same like base case simulations. The results are shown as plume length in tables and graphs. The plume lengths are given in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limits (½ LFL).

In general the integral tools, agreed to show the same trend i.e. the plume lengths are increasing for the wind stability class A, D and F in ascending manner although the difference between D and F is small or negligible. In general TRACE shows stronger variations than the other models. It is evident that stability class A has high turbulence levels and results in more turbulent diffusion. Diffusion tends to spread the concentrations in all directions and shortens the plume length by lowering the convection strength. So class A predicts a lower plume length when compared to other classes.

Stability class A cannot be modelled in the CFD tools KFX and FLACS, due to some modelling difficulties with standard k - epsilon models.

It is also to be noted that CFD tools remains insensitive for stability class D and F for such low wind speed 2m/s for the jet release closer to the ground (2 m above). From the Figure 2.33 and Figure 2.34 the curve is almost flat for the wind class D and F.

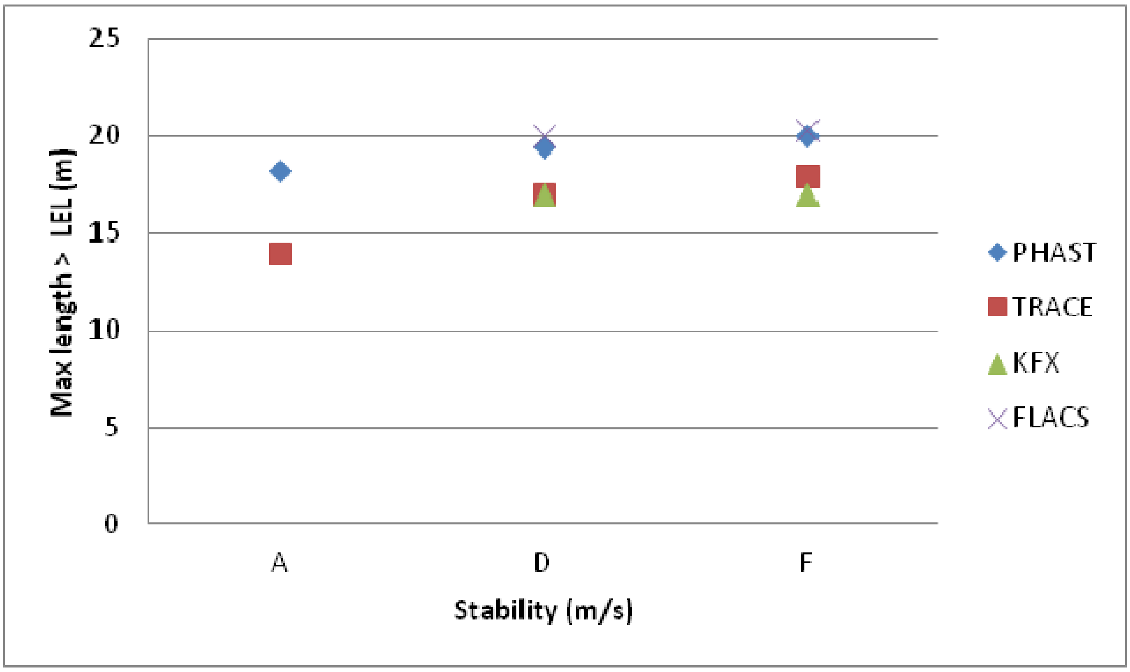

Figure 2.33: LFL plume length of CH_4 between CFD tools and integral tools for various stability class models

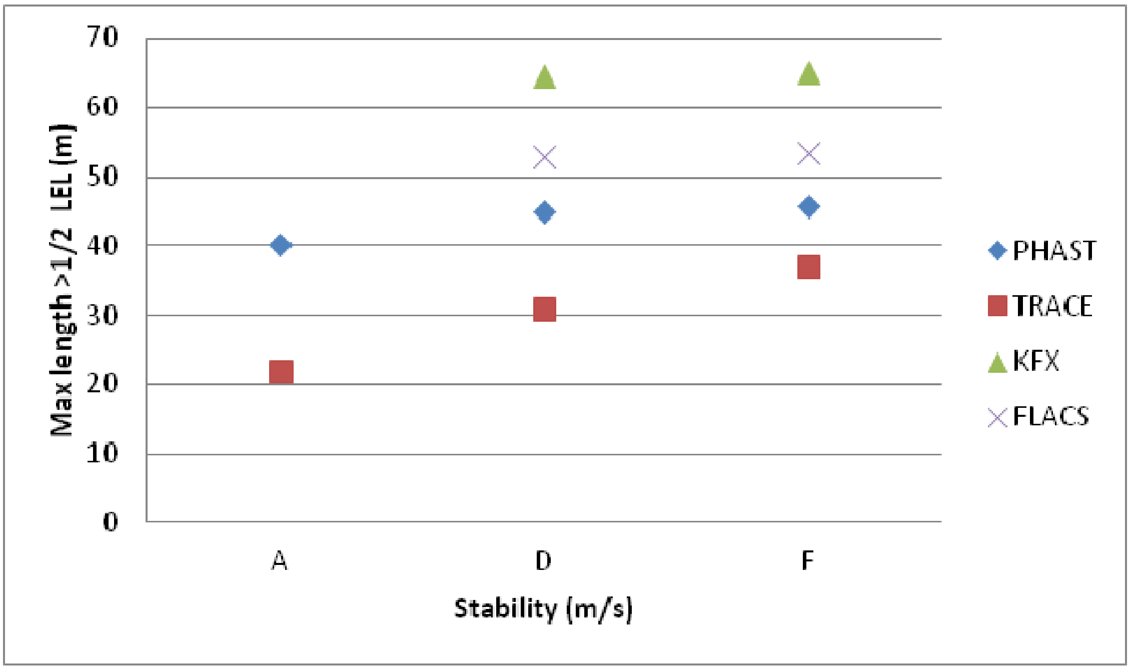

Figure 2.34: ½ LFL plume length of CH4 between CFD tools and integral tools for various leak rates

Table 2.20: Comparison of plume length between Integral and CFD tools for wind stability class A

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	NA	NA	40.3	22
LFL	NA	NA	18.2	14
UFL	NA	NA	6.7	7

Table 2.21: Comparison of plume length between integral and CFD tools for wind stability class F

Plume length [m]	FLACS	KFX	PHAST	TRACE
½ LFL	53.5	65	46	37
LFL	20.3	17	20	18
UFL	6.5	8.5	6.5	8

2.5.7 Effect of sloping terrain

Only KFX and FLACS are used to simulate the effects of sloping terrain for the jet simulation (this is not possible with integral tools). 5 % slope is considered for this simulation. It is modelled by tuning the acceleration vectors gx and gz to induce some horizontal body forces in all the cells. The remaining parameters are the same as for the base case simulations. Standard k-epsilon turbulence model with wall functions are used in both the CFD codes.

Due to large momentum from jet, the plume lengths are remains unchanged for 5 % slope. For this case, results from base case jet simulations can be referred.

2.5.8 Effect of obstructions

Only KFX and FLACS are used to simulate the effects of obstruction in the jet simulation (this is not possible with integral tools). Near field and far field obstructions are simulated with two different geometries. For the near field obstruction, a 3 x 3 x 4 m obstacle is positioned at 3 m away from the jet. For the far field obstruction, a 10 x 10 x 10 m obstacle is positioned at 20 m away from the jet. Rest of the simulation parameters is same as in the base case simulation. Standard k-epsilon turbulence model with wall functions are used in both the CFD codes. The results are shown as plume lengths with contour plots. They are shown in Lower flammability limit (LFL), Upper flammability limit (UFL) and ½ Lower flammability limit (½ LFL) for all 3 cases separately.

Both KFX and FLACS show a good agreement for distant obstacle test case. For near field obstacle, FLACS predicts a larger plume length when compared to KFX. The differences in the air entrainment and turbulence models can cause these effects.

Table 2.22: Comparison of plume length for near field and far field obstacle

Plume length [m]	3m distant jet		20 m distant jet	
	FLACS	KFX	FLACS	KFX
½ LFL	29	15	20	20.5
LFL	12.7	5	20	17
UFL	3	3	6.5	9

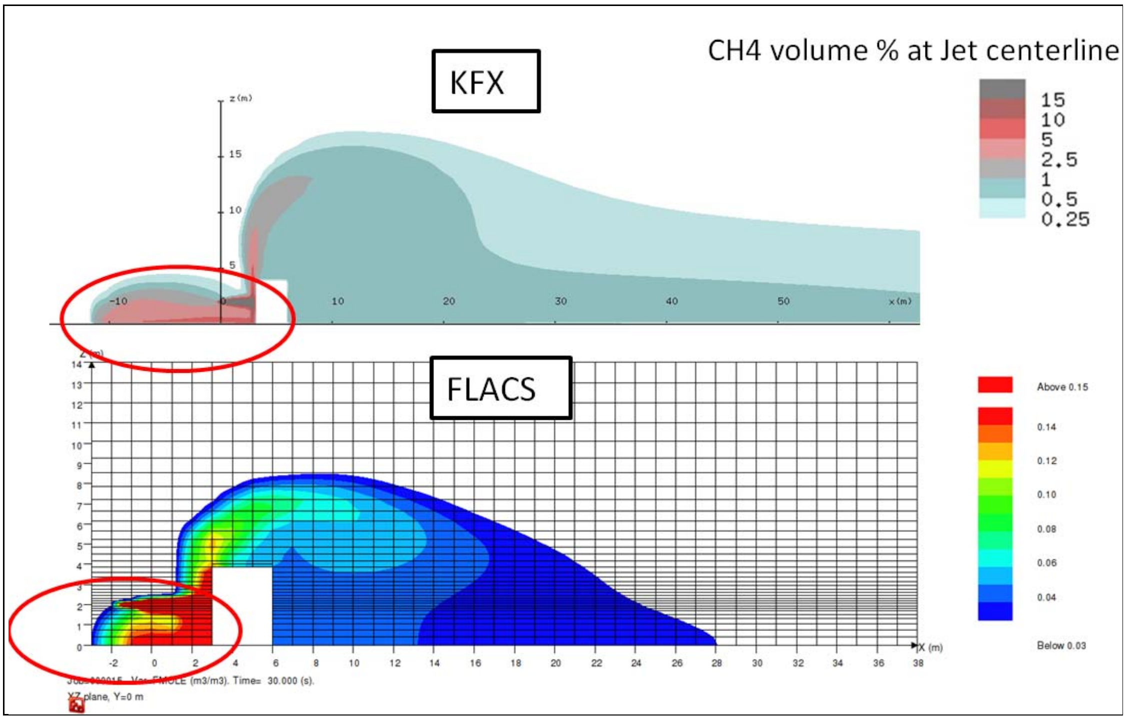

Figure 2.35: Concentration plots of CH4 between KFX and FLACS at jet centreline (½ LFL: 2.5 %, LFL: 5 %, UFL: 15 %) for near field obstacle test case

Reflections towards the upstream are much higher in KFX than in FLACS. It is circled in red envelope. From the plan view in Figure 2.36. It can be shown that the UFL cloud shape agrees well in both the tools. For the distant obstacle test case, the ½ LFL cloud is totally stopped by the large obstacle in both the tools. It can be seen in Figure 2.37.

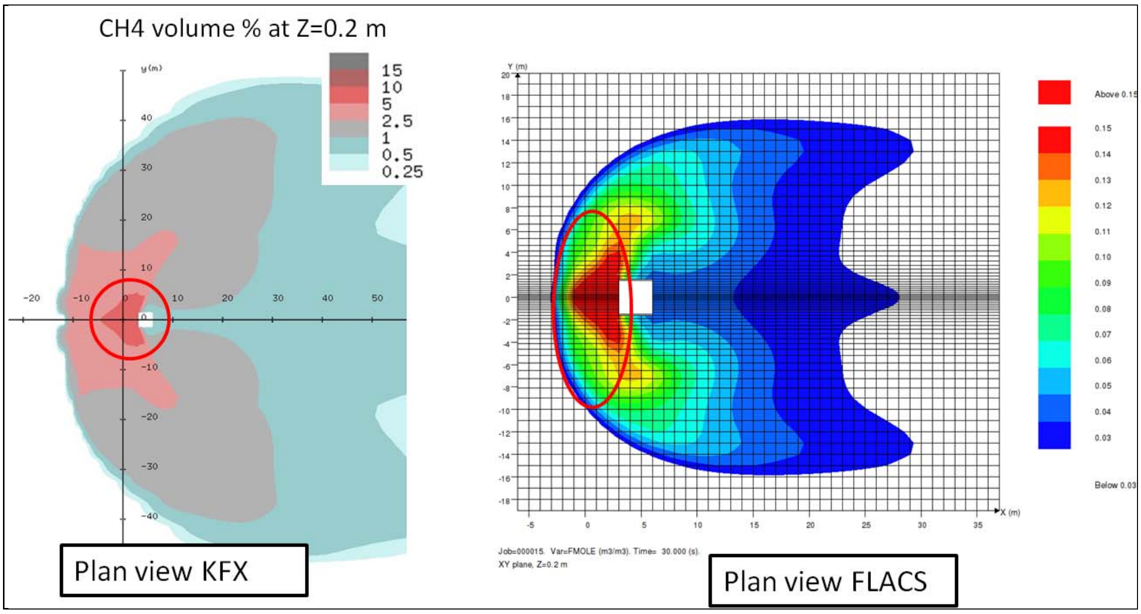

Figure 2.36: Concentration plots of CH_4 between KFX and FLACS viewed from above at z=0.2 m (½ LFL: 2.5 %, LFL: 5 %, UFL: 15 %) for near field obstacle test case

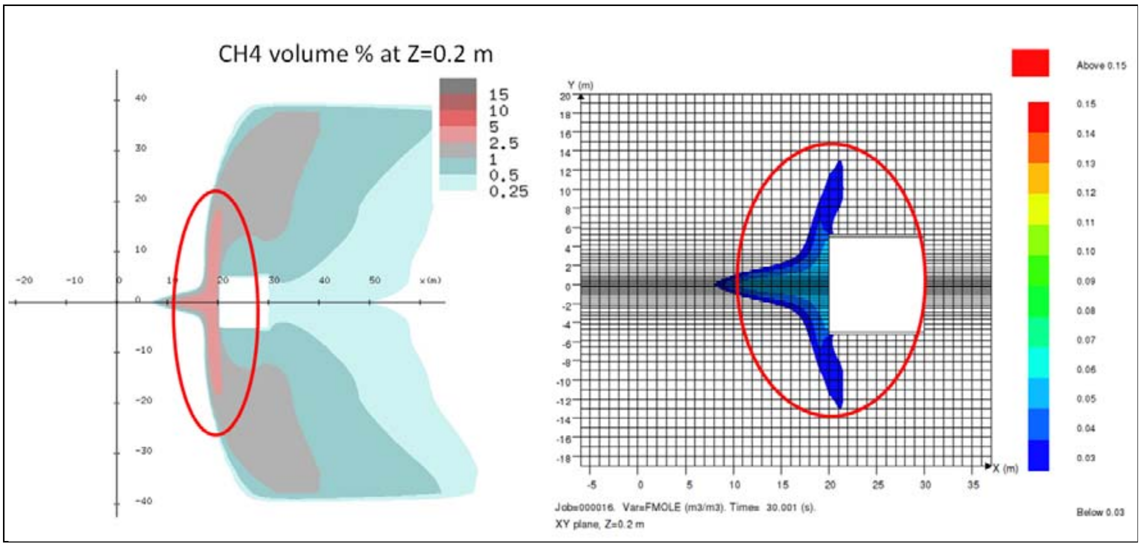

Figure 2.37: Concentration plots of CH_4 between KFX and FLACS viewed from above at Z=0.2 m for distant obstacle test case (½ LFL: 2.5 %, LFL: 5 %, UFL: 15 %) for far field obstacle test case

2.6 Concluding remarks

2.6.1 Comparison of models

2.6.1.1 Base case

For the pool scenario, Phast, FLACS and KFX all agree on the LFL with distance within 50-65 m while TRACE predicts about the double distance. For the jet scenario, all models agree on a distance of 17-20 m.

2.6.1.2 Sensitivities

In most of the sensitivities the models show the same trends but with different strengths.

Larger leaks results in larger spread in the results.

FLACS and KFX generally predict similar results but deviate for the largest release scenarios for both pool and jet. For the 50 kg/s jet release FLACS predicts significantly shorter distances than KFX. The jet as leak source is modelled differently in FLACS and KFX. In the region very close to the leak opening the jet is supersonic and is treated differently in the two codes. Depending on the modeller, different ways of handling air entrainment may give different results. On the other hand, for the corresponding 53 kg/s pool release KFX predicts almost half the LEL distance of FLACS. This may be due to different ways of modelling the boundary conditions close to the ground in FLACS and KFX. FLACS has limitations in use when effects close to the ground are important - currently considered to be conservative (overestimate distances).

Neither KFX nor FLACS should be used for very unstable atmospheric conditions as Pasquill A due to limitations in the standard k-ε model. For downward jet releases close to the ground the simulation grid must be carefully selected to minimise numerical diffusion.

CFD models are complex. There are several differences within the tools (source term, turbulence model and wind profile model), and in addition there will be several possibilities for the user use the tools differently (grid, temperatures, etc.). As a result, the observed discrepancy between the two CFD tools on gas dispersion is within the limit of what is expected when comparing two tools that are originally developed for explosion and fire simulations.

Phast shows relatively good agreement with CFD models for scenarios with no geometry, i.e. buildings or terrain effects. The exception is a downward jet and stable atmosphere, both cases in which Phast predicts significantly longer distances than the CFD models as well as high roughness where the UFL distance for the pool increases as opposed to the other models.

Trace generally predicts longer distances for the pool scenarios than the other models, especially for the largest pool. The exception is high wind speeds where TRACE predicts shorter LEL distances than the other models.

Trace and Phast should not be used for downward leaks close above the ground. For such scenarios CFD scenarios with carefully selected simulation grids should be used.

Integral models like Phast and TRACE cannot account for the effect of local geometry or terrain like valleys, sloping ground etc. CFD models should be used for such scenarios.

2.6.2 Conclusions from test scenarios

Pool vs. jet release

A given leak rate released as evaporation from a pool gave 2-3 times longer LEL distances than the same leak rate released as a jet. Indeed the gas jet has a high velocity, but as consequence of this velocity a high level of turbulence is produced that effectively mixes air into the jet and dilutes the gas concentration. The gas from the pool is basically transported by the wind at a low velocity resulting in much lower turbulence and corresponding less mixing of air and dilution of the cloud, hence the longer distance to LEL.

Effect of wind speed

For a jet release the effect of wind speed is small, basically because the dispersion at the LEL distance is dominated by the jet higher velocity at that point.

For pool leaks an increase in wind speed reduces the LEL distance as the wind determines the dispersion from the start. Increased wind produces more turbulence that dilutes the cloud more efficiently as discussed above.

Effect of ground roughness

Increased ground roughness has practically no effect on the jet, but reduces the LEL distances for the pool scenarios as the release is at ground level which in combination with the low transport velocity (e.g. the wind) makes the dispersion more sensitive to the ground conditions.

Effect of atmospheric stability

Atmospheric stability had practically no effect on the jet release whereas the LEL distances for the pool scenario increase the more stable the atmosphere is due to reduced turbulent mixing of air into the cloud. Note that KFX and FLACS should not be used for very unstable conditions (Pasquill A).

Effect of jet directions

A jet directed downwards colliding with the ground actually results in more or less the same LEL distance as a horizontal jet for a wind velocity of 2 m/s (except for Phast, however, use of the Phast model for downward directed leaks is not recommended since this model has not been sufficiently validated). This may be different for higher wind velocities.

Wind in the opposite direction of the jet has little effect on the LEL distance - if anything it increases the LEL distance slightly, an effect which is more pronounced for the 0.5 LEL distance. The wind is not strong enough to transport gas to the area behind the leak source.

The downwind scenario produces a gas cloud that has more or less the same extension in all directions, although a little shorter upwind and a little longer downwind although shorter than the downwind directed jet. However, due to sensitivity to numerical diffusion in this scenario the actual distances should not be trusted.

Effect of slope

The scenario with a horizontal pool on the top of a 5 % slope showed a 20 % increase in LEL distance due to the heavy methane gas drifting downwards the slope. Note that in a real case with the liquid LNG being released in a slope the pool may run down the slope before evaporating resulting in even longer LEL distances than in the test scenario.

The slope had no effect on the jet distances as those are basically determined by the jet impulse.

Effect of a building obstructing the jet

A small building close to the jet partly stops the jet and directs it side- and upwards over the building. The distance to LEL id significantly reduced compared to the free jet. When a larger building is located at 20 m which is about the LEL distance in the free jet case, the effect of the building is to stop the cloud. The LEL distance is naturally the same as for the unobstructed jet, but the building stops further dispersion of lower concentrations.

3. TYPICAL SAFETY DISTANCES (DSB CASES)

3.1 Introduction

Scandpower has been asked to suggest some typical safety distances from a number of typical facilities. These facilities are (the case numbers presented are the case numbers provided in the list of test cases issued by DSB):

"Case 5.2": LPG-consumer terminal - small above ground - gas
"Case 5.3": LPG-consumer terminal - medium above ground - gas/liquid
"Case 5.4": LPG-storage facility - large above ground - liquid
"Case 5.5": LPG-consumer terminal - small below ground - gas
"Case 5.6": LPG-consumer terminal - medium below ground - liquid
"Case 5.7": LPG-filling station for gas bottles
"Case 5.11": LNG-consumer terminal
"Case 5.12": LNG-terminal with ship transport
"Case 5.14": Pressure reduction stations (Hp/Mp)
"Case 5.16": Pressures reduction stations (Mp/Lp)
"Case NH3": Ammonium plants
"Case ISO propanol": Tank facility - Iso-propanol
"Case Tank facility - diesel": Tank facility - diesel

These distances may then be used as input for a discussion by DSB to suggest safety distances that a contractor shall comply with when designing a facility.

3.2 Methodology

3.2.1 Scenario identification and the simplified ISO-risk model

The simulated scenarios have been defined by DSB with the intention to estimate typical safety distances associated with target frequencies. DSB has requested ISO-risk curves with frequencies from 1E-4 per year to 1E-7 per year.

ISO-risk curves for a facility can be calculated by combining all possible hazardous events with their respective frequencies, ignition probability, wind direction, wind speed, fatality probability and hazard distances. The end result will be a curve that represents the probability for fatality at different locations (distances from the plant).

The ISO-risk curves estimated for a generic type of facility will not be valid for all similar facilities, since many of the key risk parameters will vary with the different facilities (their activity level, locations and so forth). A simplified model is therefore used to produce typical ISO curves in this report; only the hazardous event with the most severe consequences is included at each given frequency level. For example, if the distance to a fatal thermal radiation level for a jet fire is greater than the distance of dispersion for a fatal gas cloud for a scenario predicted to occur with an annual frequency of 1E-5, only the jet fire is included for the 1E-5 frequency level. This approach is intended to be a coarse best estimate approach.

The first step in the applied model is defining leak frequencies (i.e. the likelihood of a leakage to occur). This is based on input detailed in a report prepared by Scandpower and A-tek for DSB in 2007, called "Risikoanalyse av gassanlegg", Ref. /11/. However, this report does not include all facility types that DSB want to analyse, and is therefore limited with respect to scenario descriptions. A number of previously issued Scandpower reports, generic sources and engineering judgments have also been used to identify the representative risk scenarios. The end result of this activity is a list of non-ignited scenarios with a frequency between 1E-3 per year and 1E-6 per year (which, after multiplying with the ignition probability and wind distribution, will approximate the target 1E-4 through 1E-7 events).

In order to obtain similar circumstances for the different facilities, all scenarios were placed at the same location in each respective facility (in the centre of the ISO-risk curve, corresponding to centre of the plant). These frequencies were then combined with the proposed ignition probabilities (see Chapter 3.2.2) and an equal wind distribution (with a 25 % probability for wind in all four applied directions) resulting in an ISO-risk curve for the given facility. The wind factor was used for gas dispersion and jet-fire, but not for pool-fires because the hazard distance is not influenced by the wind as much as the gas dispersion. The jet-fire frequency is multiplied by 1/4 because of the 4 different directions the flame can be directed, not considering up and down.

The fatality rates in the simplified model have been decided by use of the following criteria:

- **Ignited gas cloud:**
  - All persons inside the LFL-contour will perish. All other will survive
- **Jet-fire:**
  - All persons inside the 15 kW/m^2 contour will perish. All other will survive
- **Pool-fire:**
  - All persons inside the 15 kW/m^2 contour will perish. All other will survive
- **BLEVE:**
  - All persons inside the 25 kW/m^2 will perish. All other will survive

3.2.1.1 BLEVE

Boiling Liquid Expanding Vapour Explosion (BLEVE) results in an explosion with a overpressure in the order of 0.05 bar at the source and a fireball with a large diameter. The preceding event for the fireball may be a pool fire enveloping a pressurised storage tank containing liquefied gas or a jet fire impinging on the storage tank. After a certain amount of time, the tank will rupture due to the intense heating.

A fraction of liquefied super heated fuel subsequently released will evaporate immediately and take part in a fireball that has the shape of a hemispherical burning cloud or ball of fire which emits heat radiation over a relatively short period of time.

As an average fatality limit, the diameter of the fireball cannot be used, since the heat flux at the surface of the fireball can be up to 290 kW/m^2. In this study the 25 kW/m^2 contour is used as a fatality limit due to the short exposure time, in comparison to the jet- and pool-fires. However, the longest hazard distances might be found by projectiles that are thrown out.

There are many methods on how to calculate a maximum diameter of the fireball. In the Fire Handbook, Ref. /12/, several methods are described, but in this report, the following formula is used from the handbook is used:

$$D_m = 6.36\ m^{1/3}$$

Where *D* is the diameter of the BLEVE and *m* is the mass of the liquefied gas participating in the combustion. The formula is used since the formula is independent of the fuel type.

In this report the BLEVE event has not been used as a scenario for most of the above ground scenarios. This is because they are simple facilities, with little possible escalation scenarios. It is also possible to protect the tank from other flammable materials in small facilities.

In larger facilities there are more sources that can lead to an escalation and hence, a BLEVE. If the BLEVE is included it will typically influence the ISO-risk curve for 1E-6, as shown in Figure 3.8.

3.2.2 Ignition modelling

In order to establish a robust evaluation of ignition probabilities for the different leak sizes, Scandpower has compared three different Ignition models

- TNO model
- DNV model
- Hydro model

The TNO and DNV models are based on physically part counting and analysis of ignition sources. The Hydro model is generic in the sense that it is based on the area of a gas cloud, and whether or not the area in which the gas cloud is dispersing through is EX-classified or unclassified.

The different models are explained in detail in the following chapters.

3.2.2.1 TNO-model

$$P(t) = P_{present} \times (1 - e^{-wt})$$

(P(present))	-	Probability that the source is present when the cloud passes
(w)	-	Ignition efficiency
(s)	-	Time

This model counts mainly large sources, like furnaces and boilers. All electrical equipment related to these are therefore assumed to be included in the given ignition efficiency. See Table 3.1 for all ignition sources.

Table 3.1: Ignition sources in the TNO-model

Source	Probability for ignition when exposed one minute	Ignition efficiency (w)
Motor vehicle	0.4	0.0085
Flare	1	1
Outdoor furnace	0.9	0.04
Indoor furnace	0.45	0.00077
Outdoor boiler	0.45	0.00077
Indoor boiler	0.23	0.0048
Ship	0.5	0.0116
Ship transporting flammable materials	0.3	0.006
Fishing vessel	0.2	0.0037
Pleasure craft	0.1	0.0018
Diesel train	0.4	0.0085
Electric train	0.8	0.027
Transmission line (per 100 meter)	0.2	0.0037
Chemical plant (per plant)	0.9	0.04
Oil refinery (per refinery)	0.9	0.04
Heavy industry	0.7	0.02
Person (per person)	0.01	0.00018

3.2.2.2 DNV-model

The DNV-model is given by the following equation:

$$P = A*B*C + D*C + E*B*C + F$$

where:

P Probability for ignition
A AADT - Number of vehicle movements each second
B Exposure times
C Fraction of internal area affected by the gas cloud
D Total ignition intensity for continuous sources
E Total ignition intensity for discrete sources
F Immediate ignition

Total ignition intensity is calculated by multiplying the amount of equipment per m^2 area with the ignition intensity and the correction factor per ignition source.

Table 3.2: Ignition source in the DNV-model

Tennkilde	Basis intensity		Correction factor			
	Continuous	Discrete	Technology	Manning	Age	Correction factor
Electrical equipment	2.60E-06	2.70E-08	1	1	1	1
Pump	9.60E-05	2.10E-07	1	1	1	1
Compressor	2.30E-03	5.10E-06	1	1	1	1
Other	3.90E-06	1.90E-08	1	1	1	1
Personnel	3.00E-06	4.00E-08	1	1	1	1

3.2.2.3 Hydro-model

The Hydro-model was developed by Norsk Hydro and is used in their handbook. This model has been used on different onshore facilities in Norway.

The basis assumption in this model is that the ignition probability of a gas cloud is dependent of the cloud size. The basis used is a gas cloud on 600 m^2 that is given a certain ignition probability. The ignition probability is dependent on whether the gas cloud is within an EX-classified zone or not.

$$P_{Ign} = I_{Ign} \cdot (1 - e^{\left(\frac{P_{ing,600} \cdot A}{A_{600}}\right)})$$

P_{ign} Probability for ignition
I_{ign} Probability for immediate ignition
$P_{ing,\,600}$ Probability for ignition of reference cloud
» 600 m^2
» EX-zone - 0.05
» Outside - 0.2
A Area of cloud
A_{600} Area of reference cloud - defined as 600

The results from the model is show in the figure below.

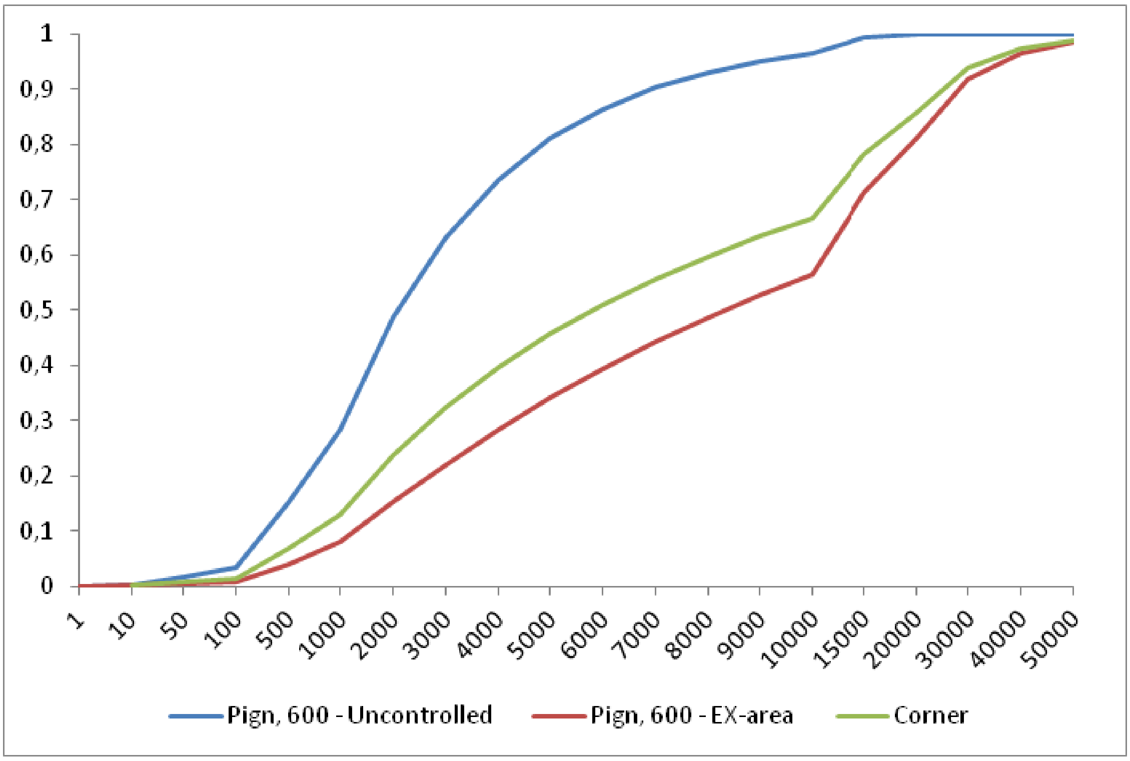

Figure 3.1: Hydro model (x-axis is distance from leak, y-axis is ignition probability)

As seen in the figure above, the ignition probability will eventually reach 1.0 (guaranteed ignition) for a sufficiently large gas cloud (approximately 50,000 m^2). There is however, a large difference in the ignition probability for smaller gas clouds if the cloud is inside an EX-zone or not.

3.2.2.4 Recommended ignition probability

The three models has been analyzed and tested on some typical cases. Based on tests, Scandpower experience and engineering judgment, the following ignition probabilities are identified for use in the present simplified study:

Hazard distance LFL < 10 meter:	Ignition probability 0.03 %
Hazard distance LFL between 10 and 50 meter:	Ignition probability 20 %
Hazard distance LFL > 50 meter:	Ignition probability 75 %

3.2.2.5 Comparison

The selected simplified ignition probability model has been compared to the three reference models for a typical LNG-facility.

The LNG-facility included the following equipment/ignition sources

- 1 truck
- 1 transmission line
- 1 person
- 1 outdoor furnace
- 1 compressor

- 2 pumps
- 5 continuous electrical sources
- large EX-controlled zone

The ignition sources were counted, the EX-zones defined and four releases where calculated:

0.1 kg/s - 30 sec duration
1 kg/s - 30 sec duration
12.5 kg/s - 30 sec duration
12.5 kg/s - 600 sec duration

This resulted is presented in Figure 3.2.

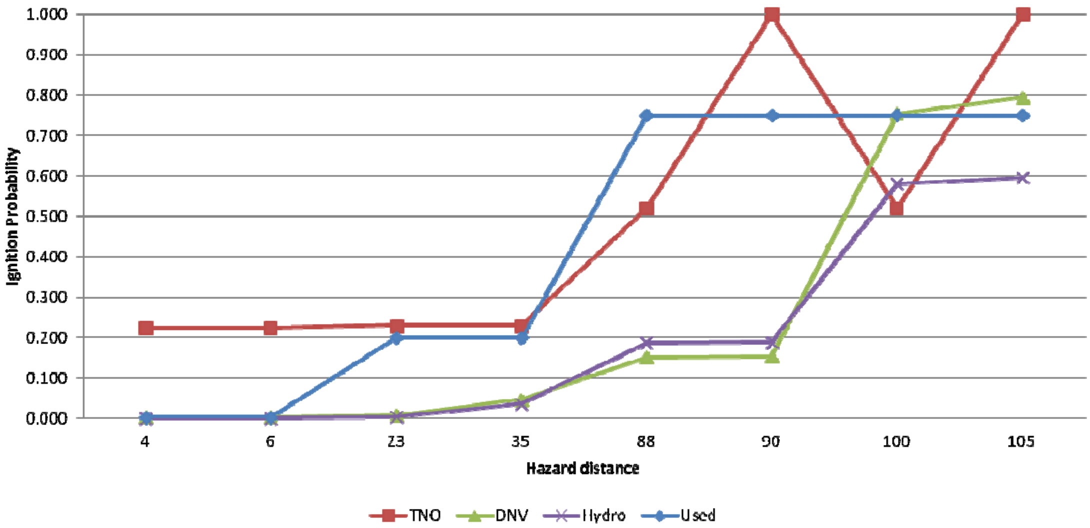

Figure 3.2: Comparison of different ignition models for the typical LNG-facility

As seen in the figure, the TNO-model gives a high ignition probability for the small releases. This is mainly due to the presence of an LNG-truck that gives a high ignition probability. It should be noted that the non-linear axis of the figure is a result of the different models being evaluated against specific scenarios.

The reason for the higher probability for the 90 meter distances than the 100 meter distance in the TNO model is that the duration and hence, the exposure time, is longer for the 90 meter release in the test case. For the ignition sources presented in the TNO-model for this facility, the ignition probability converges towards 1 at approximately 160 seconds.

3.3 Results

In this chapter, the results from the DSB cases are summarised in the form of dispersion distances, and where applicable distances to radiation levels. All simulations have been performed in PHAST. Using PHAST is, based on the findings from the test matrix, concluded to be sufficiently accurate for this exercise where the geometry and terrain is not known (and hence, cannot be assessed). Dispersion distances are in this study given as distances to gas concentrations corresponding to the Upper Flammability Limit (UFL), the Lower Flammability Limit (LFL) and half of the Lower Flammability Limit (1/2 LFL). For fire simulations distances are given to the following levels: 30 kW/m^2, 15 kW/m^2 and 5 kW/m^2.

3.3.1 Consequence modelling

The following general inputs have been included in the simulations:

- Wind speed of 2 m/s
- Pasquill Stability Class D
- Surface roughness is set 35 mm
- Outlet velocity limited to 350 m/s (in order to correspond to CFD simulations)
- Release height set at 2 m
- All releases, expect momentary releases, are directed horizontally
- Averaging time is set to 18.75 seconds (recommended by PHAST) for all flammable simulations. For toxic simulations, the averaging time is set to 600 sec (also recommended by PHAST). Averaging time is a parameter used in integral tools in order to account for:
    - ∗ The effect of wind meander, resulting in wider less dense clouds for large averaging times. This effect occurs for both continuous and time-varying dispersion.
    - ∗ Additional time-averaging at a specific position, resulting from time-dependent concentrations at this point (as a result of the effect of varying release rate).

Table 3.3 summarises the flammability limits used for the different substances simulated:

Table 3.3: Summary of flammability limits used for the simulated substances, volume basis as a measure of concentration in air

1/2LFL	LFL	UFL
Propane		
1 % or 10,000 ppm	2 % or 20,000 ppm	9.5 % or 95,000 ppm
Methane		
2.5 % or 25,000 ppm	5 % or 50,000 ppm	15 % or 150,000 ppm
Iso-propanol		
1 % or 10,000 ppm	2 % or 20,000 ppm	12 % or 120,000 ppm
n-Dodecane (Diesel)		
0.3 % or 3,000 ppm	0.6 % or 6,000 ppm	4.9 % or 49,000 ppm
Ammonia		
8 % or 80,000 ppm	16 % or 160,000 ppm	25 % or 250,000 ppm

In order to also account for the toxic properties of ammonia, simulations have also been performed with the following toxic limits:

- 300 ppm - IDLH level (Immediately Dangerous to Life and Health)
- 5,000 ppm - LC_{LO} (lowest concentration causing death)
- 10,000 ppm - Dobbel LC_{LO}

In some instances momentary releases are simulated. These are releases of a certain amount that are released momentarily and without any momentum. As these releases lack momentum the dispersion of these releases can in some cases (especially if a pool is also formed) drift both downwind and upwind. As a result of this the width of the gas cloud may be a better representation of how far a gas cloud will travel rather than the length, as the length is only counted from the origin of the release and therefore does not include the upwind dispersion. An asterix (*) is used to clarify which scenarios are momentary in the result presentation. Note that the width quoted in the result tables in the following chapter is the entire width of the gas cloud.

3.3.2 Case 5.2: LPG-consumer terminal - small above ground - gas

The following scenarios were run with focus on dispersion results:

Table 3.4: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage in gas phase that is detected and shutdown without delay	0.3 kg/s for 5 seconds, gas release
1E-4	Medium leakage in gas phase that is detected and shutdown with some delay	1 kg/s for 30 seconds, gas release
1E-5	Instant release of all volume in hose	18 kg momentary release, gas release
1E-6	Release of all volume in hose from a small hole	18 kg during the course of 30 seconds, gas release

All scenarios were run with a reservoir pressure of 5 bar(g) and temperature of 15 °C. 100 % propane was used to model LPG.

Dispersion results are presented in Table 3.5 and

Table 3.6.

Table 3.5: Case 5.2 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	9.6	1.96	5.2	2	1.1	2
1E-4	15.9	1.9	9.4	2	2.1	2
1E-5*	9.7	1.5	4.1	2	1.9	2
1E-6	12.3	1.95	7.4	2	1.5	2

Table 3.6: Case 5.2 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	0.8	0.4	0.1
1E-4	1.4	0.7	0.15
1E-5*	9	6.8	3
1E-6	1	0.5	0.1

The results are also presented in Figure 3.3.

The results show an increase in dispersion distance and width from case 1E-3 to 1E-4, which is as expected due to the increase in release rate. The 1E-6 case shows the same dispersion pattern as the first two cases, as this is also a jet release. The reason the distances do not increase is due to the release rate being 0.6 kg/s (18 kg divided by 30 seconds), and as such the dispersion results should be between the first two cases. The dispersion profile for case 1E-5 differs from the other cases and this can be explained by the fact that this release is a momentary release, i.e. not a jet release as the other cases. As such the 1E-5 case does not have the same momentum as the others, and instead the entire mass is released in air and creates a gas cloud that is significantly wider than the jet releases. However, as can be seen for the 1E-5 case the length of the gas cloud is greater than half of the width, and as such the length is the dominating dispersion distance.

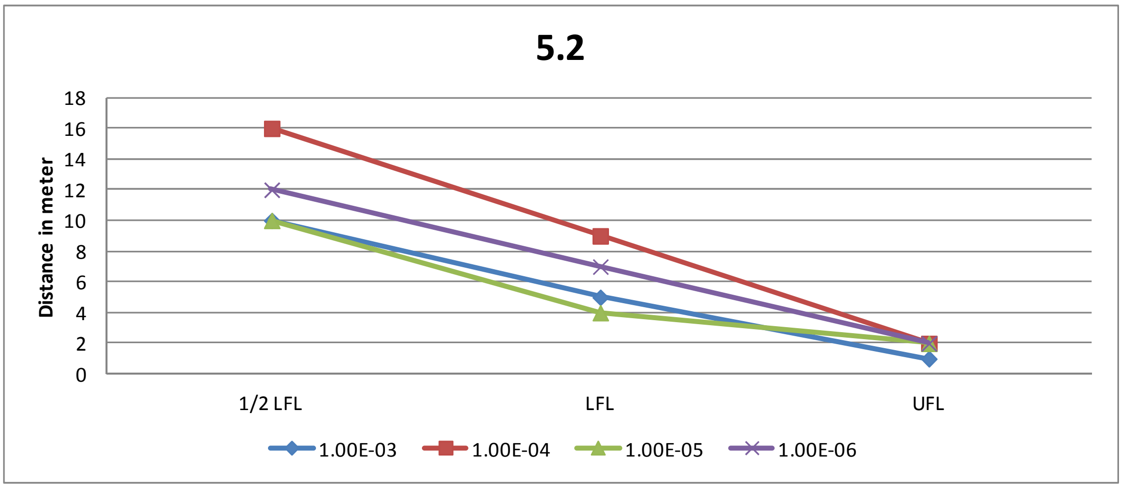

Figure 3.3: 1/2LFL, LFL and UFL calculated for Case 5.2

3.3.2.1 ISO-risk curve

The following ISO-risk curve has been calculated based on the results and the method shown earlier.

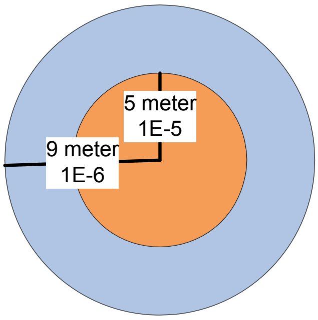

Figure 3.4: ISO-risk curve for LPG-consumer terminal - small above ground - gas

As shown in the figure, the 1E-7 curve is not calculated, as this is not longer than the 1E-6 curve.

3.3.3 Case 5.3: LPG-consumer terminal - medium above ground - gas/liquid

The following scenarios were run with focus on dispersion results:

Table 3.7: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage in gas phase that is detected and shutdown without delay	0.14 kg/s for 5 seconds, gas release
1E-4	Small leakage in gas phase that is detected and shutdown after a long time	0.14 kg/s for 5 minutes, gas release
1E-5	Instant release of all volume in hose	27.5 kg momentary release, liquid release
1E-6	Release of all volume in hose from a hole	5 kg/s for 10 minutes, liquid release

All gaseous scenarios were run with a reservoir pressure of 5 bar(g) and temperature of 15 °C. For liquid scenarios the reservoir temperature was the same, however the pressure used was 12 bar(g).100 % propane was used to model LPG.

Dispersion results are presented in Table 3.8 and Table 3.9.

Table 3.8: Case 5.3 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	6.8	2	3.7	2	0.7	2
1E-4	6.8	2	3.7	2	0.7	2
1E-5*	31.2	0	8.5	1	2.4	2
1E-6	59.7	0.15	27.3	1.3	7	2

Table 3.9: Case 5.3 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	0.5	0.25	0.05
1E-4	0.5	0.25	0.05
1E-5*	17.6	10.4	4
1E-6	7.6	2.2	0.4

The results are also presented in Figure 3.5.

The results show no increase in dispersion distances or width for the gaseous cases (the first two). This is due to the release rate being the same for both cases. Even though the release duration is increased (from 5 seconds to 5 minutes) it shows that the release has already reached steady state within the first five seconds and thus the effect of an increased duration is negligible. In general, the liquid releases show longer dispersion effects since the release amounts are larger. The 1E-6 case shows a similar dispersion pattern to the gaseous releases (thin cloud) as they all are jet releases. The 1E-5 case (momentary release) again shows a much wider release pattern, due to the lack of momentum.

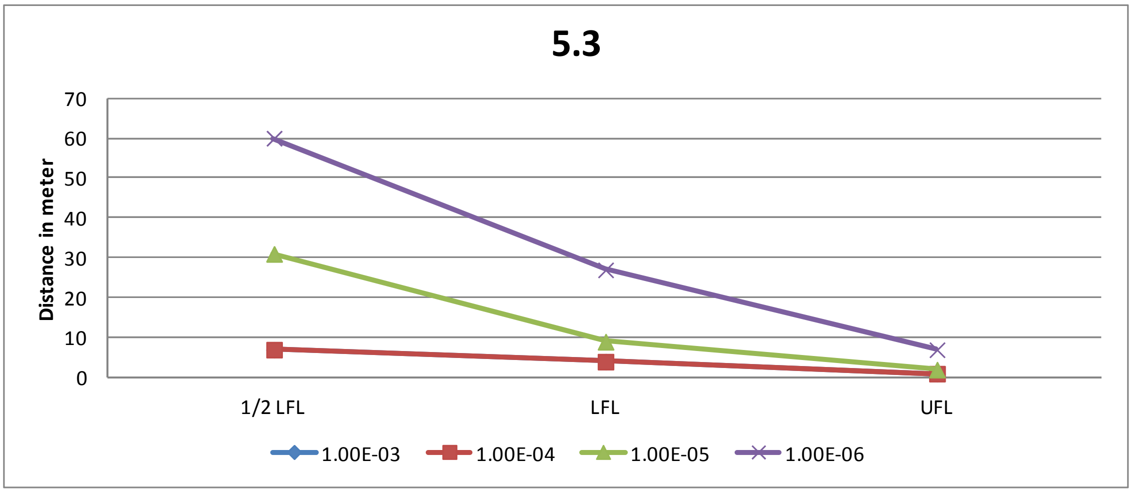

Figure 3.5: 1/2LFL, LFL and UFL calculated for Case 5.3

3.3.3.1 ISO-risk curve

The following ISO-risk curve has been calculated based on the results and the method shown earlier.

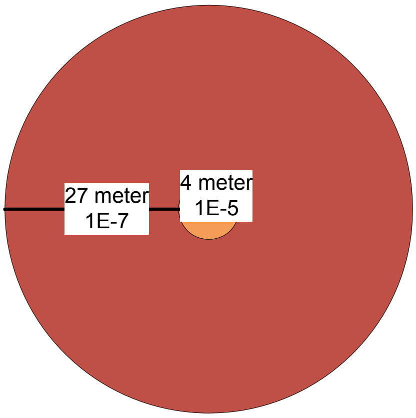

Figure 3.6: ISO-risk curve for LPG-consumer terminal - medium above ground - gas/liquid

As can be seen in the figure, the ISO-risk curve for 1E-6 or 1E-4 is not included, as there is no identified 1E-4 scenario that is bigger than the 1E-5 scenario, and that the 1E-6 curve also is shorter than the 1E-7, and hence is not shown.

It should be noted that the 5.3 case (above ground LPG) and the 5.6 case (below ground LPG) are of similar size (medium), but the safety distances given in this report is different in the two cases. This is because they represent two different process facilities with different accumulation of accidental frequencies. As a result, the 1E-5 case for case 5.3 is a low rate-long duration (0.14 kg/s for 300 seconds) event, whereas the 1E-5 event for 5.6 is a high rate-short duration (2.4 kg/s for 4 seconds) event. The calculated safety distances are therefore different. If the scenarios used to define the 1E-4 to 1E-7 events had been defined from the safety distance (and not from the leak rates, which has been done in this study), the safety distances for case 5.3 and 5.6 may have been more similar. This should be taken as another indication that the typical safety distances presented in this report may not be valid for all plants, and dedicated risk analyses should be performed for all individual facilities.

3.3.4 Case 5.4: LPG-storage facility - large above ground - liquid

This is a large facility, and during the hazard identification performed for the terminal, a large number of scenarios where identified. The following scenarios were therefore run with focus on dispersion results:

Table 3.10: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage from pipes around the tank that is not shutdown. Small leakage from hose that is not shutdown	10 kg/s for 600 seconds, liquid release
1E-4	Medium leakage from hose (loading/ unloading) that detected and shutdown with some delay	12 kg/s for 90 seconds, liquid release
1E-4	Large leakage from tank	16 bar(g) in tank, 4 m liquid head, release diameter 80mm, inventory of 1,000 kg, liquid release, no bund. Resulting in a release rate of 127 kg/s
1E-5	Small leakage in pipe inside facility that is not shut down	3 kg/s for 1,800 seconds, liquid release
1E-6	Rupture of pipeline inside facility that is not closed down	35 kg/s for 600 seconds, liquid release
1E-6	Medium leakage from hose (loading/ unloading) that is not stopped	12 kg/s for 600 seconds, liquid release
1E-6	Boiling Liquid Expanding Vapour Explosion (BLEVE) from tank	BLEVE of 2,525 m^3 (80 % full, 1E6 kg)

All scenarios were run with a reservoir pressure of 12 bar(g) and temperature of 15 °C, unless otherwise indicated. The BLEVE is calculated with a burst pressure of 25 barg. 100 % propane was used to model LPG.

Dispersion results are presented in Table 3.11 and Table 3.12.

Table 3.11: Case 5.4 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	93.4	0	42.4	1	9.6	2
1E-4 hose	104.8	0	47.6	0.9	11	1.95
1E-4 tank	272.6	0	179.7	0	34.8	1.7
1E-5	43.1	0.6	20	1.5	5.6	2
1E-6 Pipe	187.8	0	89.1	0	17.6	1.9
1E-6 hose	104.8	0	47.6	0.93	11	1.94

Table 3.12: Case 5.4 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	13.4	4	0.6
1E-4 hose	15.6	4.6	0.7
1E-4 tank	72	38	3
1E-5	5	1.9	0.4
1E-6 Pipe	36	10	3
1E-6 hose	15.6	4.6	0.8

The results are also presented in Figure 3.7.

The BLEVE was calculated to have a maximum diameter of 319 meters, with a by the use of the formula found in Chapter 3.2.1.1. The maximum distance to 25 kW/m^2 is in Phast found to be 650 meters.

The results again show the expected, which is that the dispersion effect is larger for increasing release rate, though this may be difficult to see due to the presented order of the scenarios. However, this is for instance clear for the 3 different hose scenarios (1E-3, 1E-4 hose and 1E-6 hose) and the 2 pipe scenarios (1E-5 and 1E-6 pipe) modelled. The tank scenario (1E-4 tank) is the only scenario that shows a much wider pattern (and also far longer). This can be partly explained by the high release rate, but also due to the propane in the tank emptying and thereby causing a secondary dispersion source as the gas cloud disperses after the initial release has ended. For all other scenarios steady state is achieved within the time frame of the leak and as such they exhibit a jet profile in the dispersion pattern.

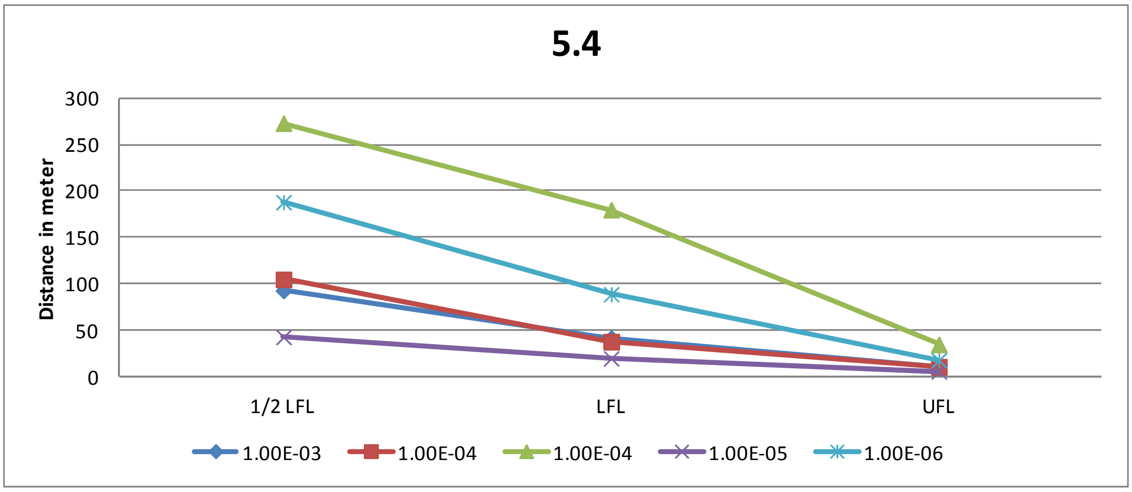

Figure 3.7: 1/2LFL, LFL and UFL calculated for Case 5.4

3.3.4.1 ISO-risk curve

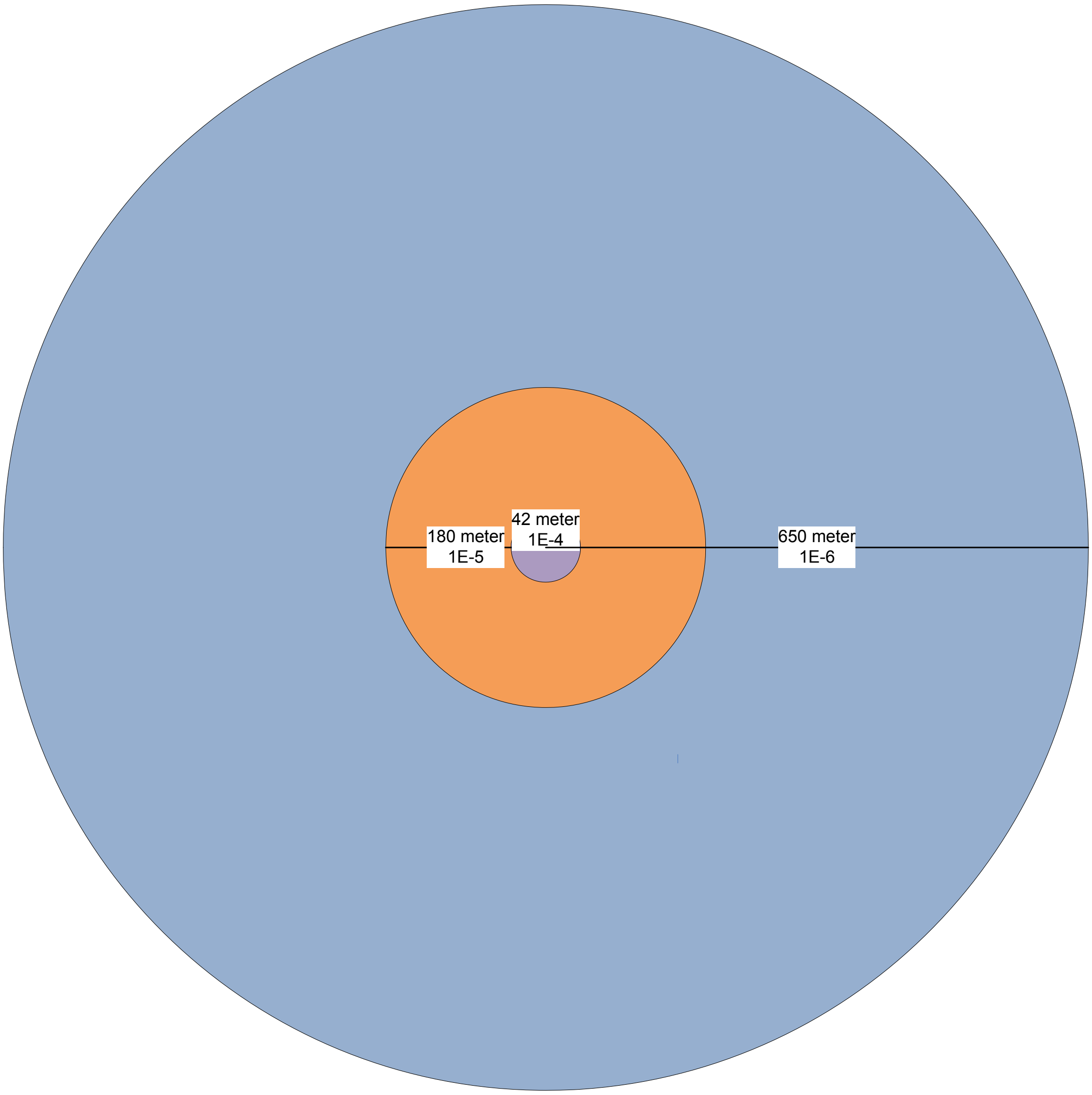

Figure 3.8: ISO-risk curve for LPG-storage facility - large above ground - liquid

As shown in the figure and tables above, the risk from the storage facilities is dominated by events caused by the tank, especially the BLEVE, but also large release. These are events that are heavily influenced by the design of the tank, and the safety measures in the facility.

3.3.5 Case 5.5: LPG-consumer terminal - small below ground - gas

The following scenarios were run with focus on dispersion results:

Table 3.13: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage in gas phase that is detected and shutdown without delay	0.3 kg/s for 5 seconds, gas release
1E-4	Medium leakage in gas phase that is detected and shutdown with some delay	1 kg/s for 30 seconds, gas release
1E-5	Instant release of all volume in hose	18 kg momentary release, gas release
1E-6	Instant release of all volume in hose from a small hole	18 kg during the course of 30 seconds, gas release

All scenarios were run with a reservoir pressure of 5 bar(g) and temperature of 15 °C. 100 % propane was used to model LPG.

Dispersion results are presented in Table 3.14 and Table 3.15.

Table 3.14: Case 5.5 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	9.6	1.96	5.2	2	1.1	2
1E-4	15.9	1.9	9.4	2	2.1	2
1E-5*	9.7	1.5	4.1	2	1.9	2
1E-6	12.3	1.95	7.4	2	1.5	2

Table 3.15: Case 5.5 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	0.8	0.4	0.1
1E-4	1.4	0.7	0.15
1E-5*	9	6.8	3
1E-6	1	0.5	0.1

The results are also presented in Figure 3.9.

See Chapter 3.3.2 for a discussion of the results, as the scenario in this case are the same as those used in case 5.2.

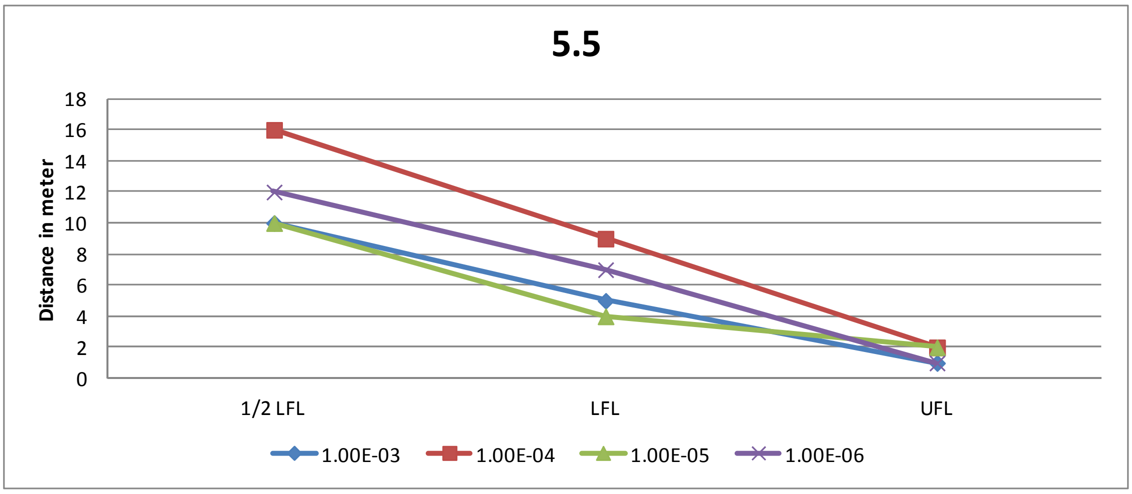

Figure 3.9: 1/2LFL, LFL and UFL calculated for Case 5.5

3.3.5.1 ISO-risk curves

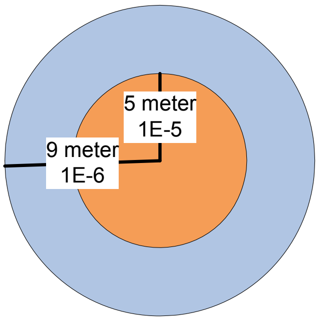

Figure 3.10: ISO-risk curve LPG-consumer terminal - small below ground - gas

As shown in the figure, the 1E-7 curve is not calculated, as this the same as the 1E-6 curve.

3.3.6 Case 5.6: LPG-consumer terminal, medium below ground - liquid

The following scenarios were run with focus on dispersion and fire results:

Table 3.16: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage in liquid phase that is detected and shutdown without delay	0.3 kg/s for 5 seconds, liquid release
1E-4	Large leakage in liquid phase that is detected and shutdown without delay	2,4 kg/s for 4 seconds, liquid release
1E-5	Instant release of all volume in hose	27.5 kg momentary release, liquid release
1E-6	Release of all volume in hose from a hole	5 kg/s for 10 minutes, liquid release

All scenarios were run with a reservoir pressure of 12 bar(g) and temperature of 15 °C. 100 % propane was used to model LPG.

Dispersion results are presented in Table 3.17 and Table 3.18.

Table 3.17: Case 5.6 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	11.3	1.7	6.7	1.9	1.7	2
1E-4	37.3	0.8	17.5	1.6	4.8	2
1E-5*	31.2	0	8.5	1	2.4	2
1E-6	59.7	0.15	27.3	1.3	7	2

Table 3.18: Case 5.6 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	1	0.5	0.1
1E-4	4	1.4	0.3
1E-5*	17.6	10.4	4
1E-6	7.6	2.2	0.4

The results are also presented in Figure 3.11.

For all jet releases (i.e. all of the scenarios except the 1E-5 case) the dispersion pattern is consistent; a thin jet profile that increases in size (both length and width) with respect to increasing release rate. For the momentary release (1E-5 case) the dispersion pattern is again different; producing a significantly wider gas cloud.

Table 3.19 presents the results related to heat flux radiation distances as a result of jet fires (no pool fires arise since pool formation does not occur):

Table 3.19: Case 5.6 - Heat flux radiation distances as a result of jet fires

Case	Max distance to 5 kW/m^2 (m)	Max distance to 15 kW/m^2 (m)	Max distance to 30 kW/m^2 (m)
1E-3	13.5	10.5	8.9
1E-4	36.3	29.3	26.2
1E-5*	-	-	-
1E-6	51	41.1	36.8

The results for jet fires are as expected; the heat flux radiation distances increase with increasing release rate. For case 1E-5 a jet fire does not occur since the release is momentary (i.e. there is no jet).

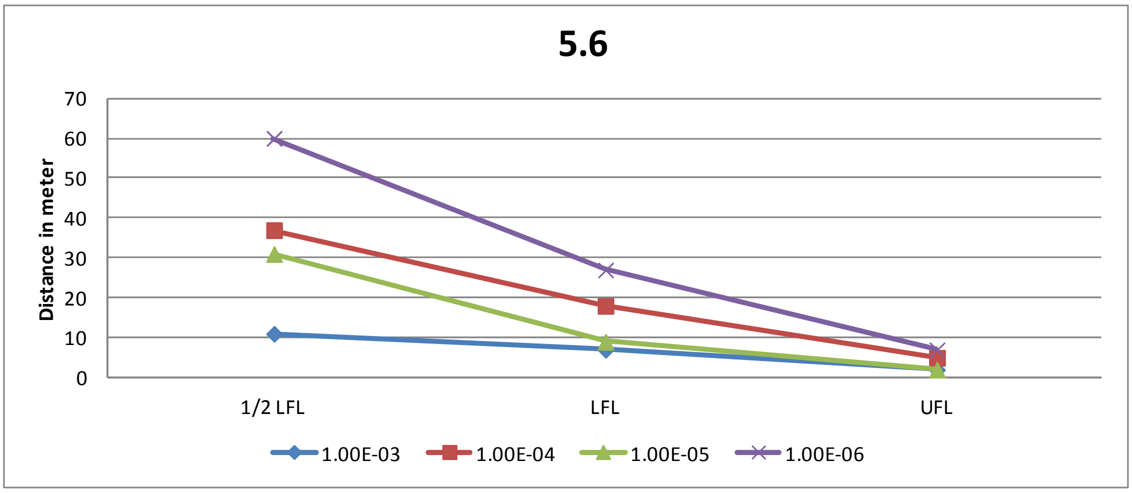

Figure 3.11: 1/2LFL, LFL and UFL calculated for Case 5.6

3.3.6.1 ISO-risk curve

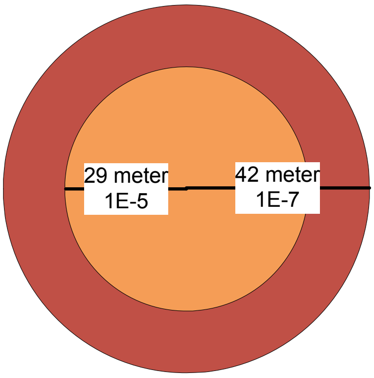

Figure 3.12: ISO-risk curves LPG-consumer terminal, medium below ground - liquid

The ISO-risk curve is only shown for the two frequencies 1E-5 and 1E-7, as no 1E-4 curve is calculated and 1E-5 goes longer than the 1E-6. These safety distances are given by the jet-fires, as the hazard distance from these fires are longer than for the dispersion.

3.3.7 Case 5.7: LPG-filling station for gas bottles - liquid

The following scenarios were run with focus on dispersion and fire results:

Table 3.20: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage in liquid phase that is detected and shutdown without delay	0.3 kg/s for 5 seconds, liquid release
1E-4	Medium leakage in liquid phase that is detected and shutdown with some delay	0.5 kg/s for 40 seconds, liquid release
1E-5	Instant release of all volume in hose	27.5 kg momentary release, liquid release
1E-6	Release of all volume in hose from a hole	5 kg/s for 10 minutes, liquid release

All scenarios were run with a reservoir pressure of 12 bar(g) and temperature of 15 °C. 100 % propane was used to model LPG.

Dispersion results are presented in Table 3.21 and Table 3.22.

Table 3.21: Case 5.7 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	11.3	1.7	6.7	1.9	1.7	2
1E-4	13.6	1.6	8.9	1.9	2.2	2
1E-5*	31.2	0	8.5	1	2.4	2
1E-6	59.7	0.15	27.3	1.3	7	2

Table 3.22: Case 5.7 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	1	0.5	0.1
1E-4	1.2	0.6	0.1
1E-5*	17.6	10.4	4
1E-6	7.6	2.2	0.4

The results are also presented in Figure 3.13.

For all jet releases (i.e. all of the scenarios except the 1E-5 case) the dispersion pattern is consistent; a thin jet profile that increases in size (both length and width) with respect to increasing release rate. For the momentary release (1E-5 case) the dispersion pattern is again different; producing a significantly wider gas cloud.

Table 3.23 presents the results related to heat flux radiation distances as a result of jet fires (no pool fires arise since pool formation does not occur):

Table 3.23: Case 5.7 - Heat flux radiation distances as a result of jet fires

Case	Max distance to 5 kW/m^2 (m)	Max distance to 15 kW/m^2 (m)	Max distance to 30 kW/m^2 (m)
1E-3	13.5	10.5	8.9
1E-4	17.3	13.7	11.8
1E-5*	-	-	-
1E-6	51	41.1	36.8

The results for jet fires are as expected; the heat flux radiation distances increase with increasing release rate. For case 1E-5 a jet fire does not occur since the release is momentary (i.e. there is no jet).

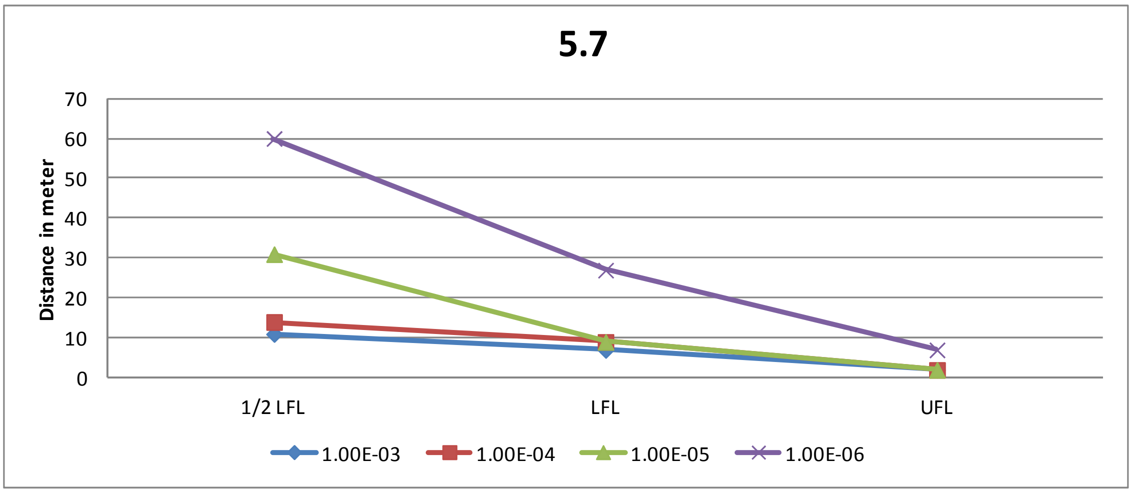

Figure 3.13: 1/2LFL, LFL and UFL calculated for Case 5.7

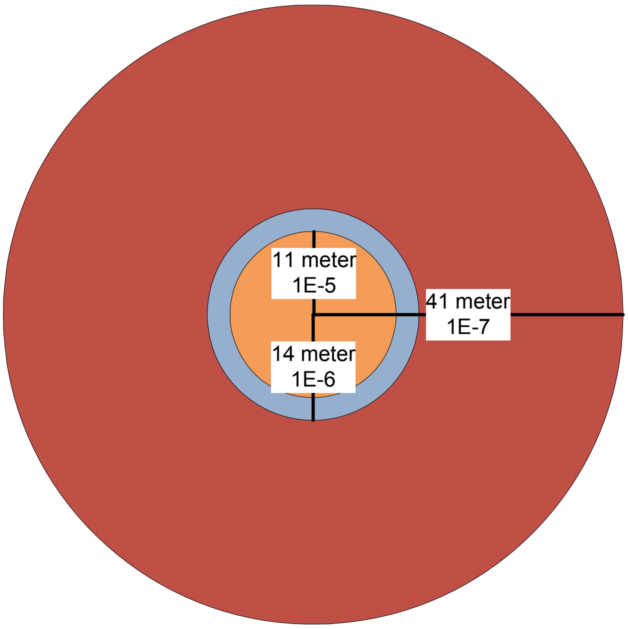

Figure 3.14: ISO-risk curve LPG-filling station for gas bottles - liquid

The ISO-risk curves safety distances are dominated by the jet-fires. A BLEVE is not included in the results, as the risk for this is regarded as negligible because of the safe design of the tank, and other little flammable material in the area.

3.3.8 Case 5.11: LNG-consumer terminal

The following scenarios were run with focus on dispersion results:

Table 3.24: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage in liquid phase that is detected and shutdown without delay	0.3 kg/s for 5 seconds, liquid release
1E-4	Small leakage in hose or facility that is detected and shutdown with some delay	3 kg/s for 30 seconds, liquid release
1E-5	Rupture of hose (loading/unloading) that is detected and shutdown with some delay	40 kg/s for 30 seconds, liquid release
1E-6	Tank collapse with bunding	500 m^3 momentary release into 400 m^2 bund (circular) with height 1 m

All scenarios were run with a reservoir pressure of 5 bar(g) and temperature of -160 °C. 100 % methane was used to model LNG.

Dispersion results are presented in Table 3.25 and Table 3.26.

Table 3.25: Case 5.11 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	18.5	0	8.8	1	4.8	1.8
1E-4	115.7	0	55.9	0	14.3	0.5
1E-5	428	0	203.6	0	69.7	0
1E-6*	321.6	0	193.7	0	130.3	0

Table 3.26: Case 5.11 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	2.3	0.8	0.3
1E-4	32	10	1
1E-5	192	66	13
1E-6*	320	272	180

The results are also presented in Figure 3.15.

For all jet releases (i.e. all of the scenarios except the 1E-6 case) the dispersion pattern is consistent; a thin jet profile that increases in size (both length and width) with respect to increasing release rate. However, for scenario 1E-5 there is evidence for a much wider gas cloud and this can be explained by the fact that a pool is formed for this scenario. Pool formation does not occur for the first two scenarios. For the momentary release (1E-6 case) the dispersion pattern is again different; producing a significantly wider gas cloud (for some concentration levels the gas cloud's width is greater than its length). In addition the release also produces a pool which is inhibited to grow because of a bund. This may assist in explaining why the width is in some instances greater than the length and also why the dispersion distances for the 1E-5 scenario is greater than the 1E-6 case.

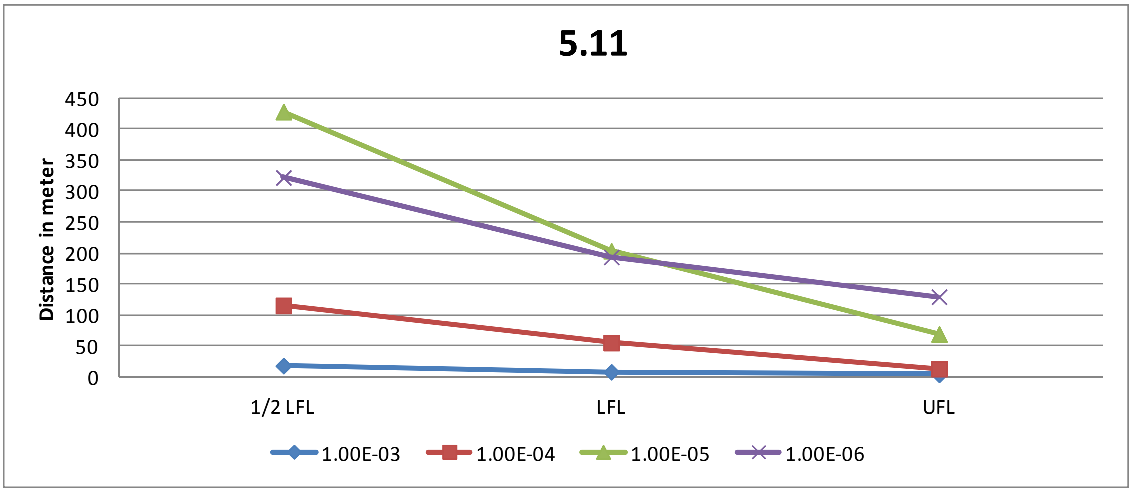

Figure 3.15: 1/2LFL, LFL and UFL calculated for Case 5.11

3.3.8.1 ISO-risk curves

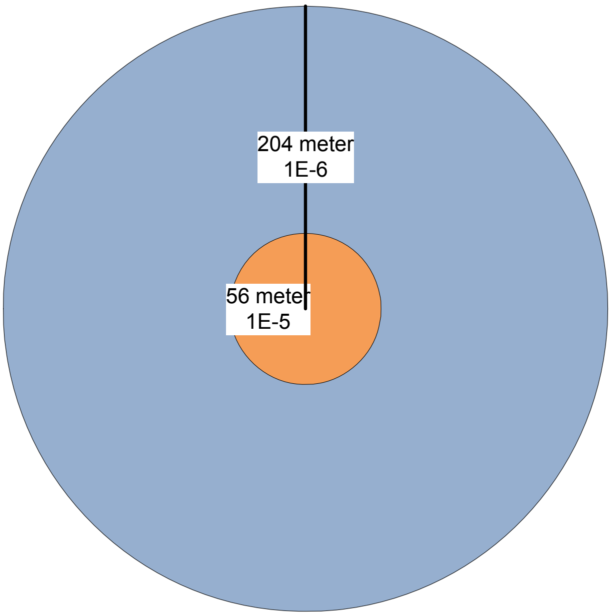

Figure 3.16: ISO-risk curve LNG-consumer terminal

The ISO-risk shows that there is a big difference between the 1E-5 and 1E-6 curve at this terminal. The 1E-6 release is dependent on the design and operation of the LNG-terminal, and is not valid for all facilities. This can either be a major event, if the tank has no bunding, or a small event, if the tank is designed with full containment etc.

3.3.9 Case 5.12: LNG-terminal with ship transport

The following scenarios were run with focus on dispersion and fire results:

Table 3.27: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage in liquid phase that is detected and shutdown without delay	0.3 kg/s for 5 seconds, liquid release
1E-4	Small leakage in hose or facility that is detected and shutdown with some delay	3 kg/s for 30 seconds, liquid release
1E-5	Large leakage of hose (loading/unloading) that is detected and shutdown with minimal delay. Using a PERC system.	25 kg/s for 20 seconds, liquid release
1E-6	Rupture of hose (loading/unloading) or pipeline that is detected and shutdown with some delay	117 kg/s for 30 seconds, liquid release
1E-6	Tank collapse with bunding	500 m^3 momentary release into 400 m^2 bund (circular) with height 1 m

All scenarios were run with a reservoir pressure of 5 bar(g) and temperature of -160 °C. 100 % methane was used to model LNG.

Dispersion results are presented in Table 3.28 and Table 3.29.

Table 3.28: Case 5.12 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	18.5	0.04	8.8	1.1	4.8	1.8
1E-4	115.7	0	55.9	0	14.3	0.5
1E-5	340	0	165.8	0	54.8	0
1E-6	712	0	327	0	114.1	0
1E-6 tank*	321.6	0	193.7	0	130.3	0

Table 3.29: Case 5.12 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	2.3	0.8	0.3
1E-4	32	10	1
1E-5	143	49	9
1E-6	368	128	26
1E-6 tank*	320	272	180

The results are also presented in Figure 3.17.

For all jet releases (i.e. all of the scenarios except the 1E-6 tank case) the dispersion pattern is consistent; a thin jet profile that increases in size (both length and width) with respect to increasing release rate. However, for scenarios 1E-5 and 1E-6 there is evidence for a much wider gas cloud and this can be explained by the fact that a pool is formed for these scenarios. Pool formation does not occur for the first two scenarios. For the momentary release (1E-6 tank case) the dispersion pattern is again different; producing a significantly wider gas cloud (for some concentration levels the gas cloud's width is greater than its length). In addition the release also produces a pool which is inhibited to grow because of a bund. This may assist in explaining why the width in some instances is greater than the length and also why the dispersion distances for the 1E-5 (not all concentration limits) and 1E-6 scenarios are greater than the 1E-6 tank case.

Table 3.30 presents the results related to heat flux radiation distances as a result of jet fires:

Table 3.30: Case 5.12 - Heat flux radiation distances as a result of jet fires

Case	Max distance to 5 kW/m^2 (m)	Max distance to 15 kW/m^2 (m)	Max distance to 30 kW/m^2 (m)
1E-3	17.4	14	13.2
1E-4	50.2	41.3	37.0
1E-5	129.1	105.5	94.6
1E-6	225.5	207.5	185.7
1E-6 tank*	-	-	-

The results for jet fires are as expected; the heat flux radiation distances increase with increasing release rate. For case 1E-6 tank a jet fire does not occur since the release is momentary (i.e. there is no jet).

Table 3.31 presents the results related to heat flux radiation distances as a result of pool fires.

Table 3.31: Case 5.12 - Heat flux radiation distances as a result of pool fires

Case	Max distance to 5 kW/m^2 (m)	Max distance to 15 kW/m^2 (m)	Max distance to 30 kW/m^2 (m)
1E-3	-	-	-
1E-4	-	-	-
1E-5	31.4	-	-
1E-6	82.1	69.7	62.9
1E-6 tank*	115.8	72.6	51.1

The results for pool fires are as expected; the heat flux radiation distances increase with increasing pool size (for instance 1E-6 tank has a pool radius of 11.3 and 1E-6 has a pool radius of 2.6 m). For the first two cases pool fires do not arise as pool formation does not occur.

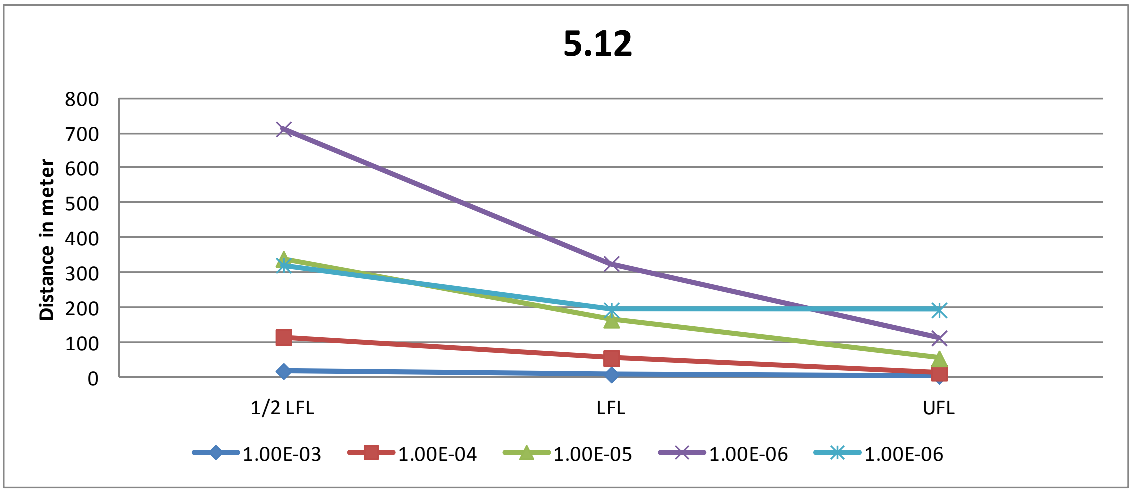

Figure 3.17 1/2LFL, LFL and UFL calculated for Case 5.12

3.3.9.1 ISO-risk curves

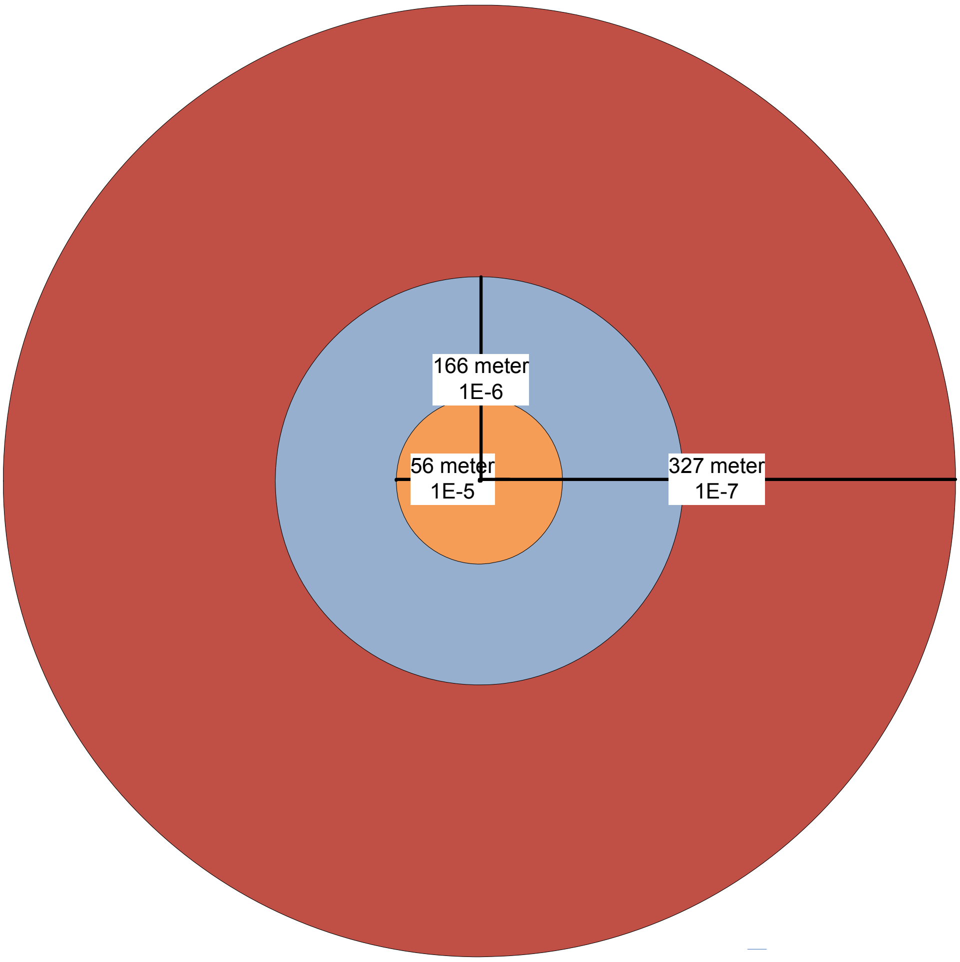

Figure 3.18: ISO-risk curve LNG-terminal with ship transport

The LNG-terminal with ship transport gives large hazard distances for all frequencies, and is dominated by the dispersion scenarios. This is because of the high rates and volumes involved when importing from ships.

3.3.10 Case 5.14: Pressure reduction stations (Hp/Mp) - Methane

The following scenarios were run with focus on dispersion results:

Table 3.32: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage from 10 bar(g) part of station	2.54 kg/s until steady state is achieved, gas release, 10 bar(g) (MP)
1E-4	Medium leakage from the 190 bar(g) part of the station	Hole diameter 10.5 mm until steady state is achieved, gas release 190 bar(g) (HP)
1E-5	Large leakage/rupture of pipe from the 190 bar(g) part of the station	132 kg/s at 190 bar(g) (HP)
1E-6	Explosion	The station is assumed to have sufficient relief panels, so an explosion will give very low hazard distances. Not investigated further

All scenarios were run with a reservoir temperature of 15 °C. 100 % methane was used.

Dispersion results are presented in Table 3.33 and Table 3.34.

Table 3.33: Case 5.14 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	26.7	2.3	14	2.05	4.5	2
1E-4 HP	31.8 m	2 m	15.1 m	2 m	5 m	2 m
1E-5 HP	333 m	2.5 m	138.9 m	2.6 m	34.3 m	2 m

Table 3.34: Case 5.14 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3 MP	2.5	1.1	0.4
1E-4 HP	2.7 m	1.3 m	0.4 m
1E-5- HP	23 m	11 m	3 m

The results are also presented in Figure 3.19.

For all jet releases the dispersion pattern is consistent; a thin jet profile that increases in size (both length and width) with respect to increasing release rate. From results this may however not be clear. This is due to the fact that 1E-4 MP is actually a smaller release than 1E-3 MP. The release rates for these scenarios are 0.14 kg/s and 2.54 kg/s for 1E-4 MP and 1E-3 MP respectively. For the high pressure cases the release rates are as follows: 2.54 kg/s and 3.04 kg/s for 1E-3 HP and 1E-4 HP respectively.

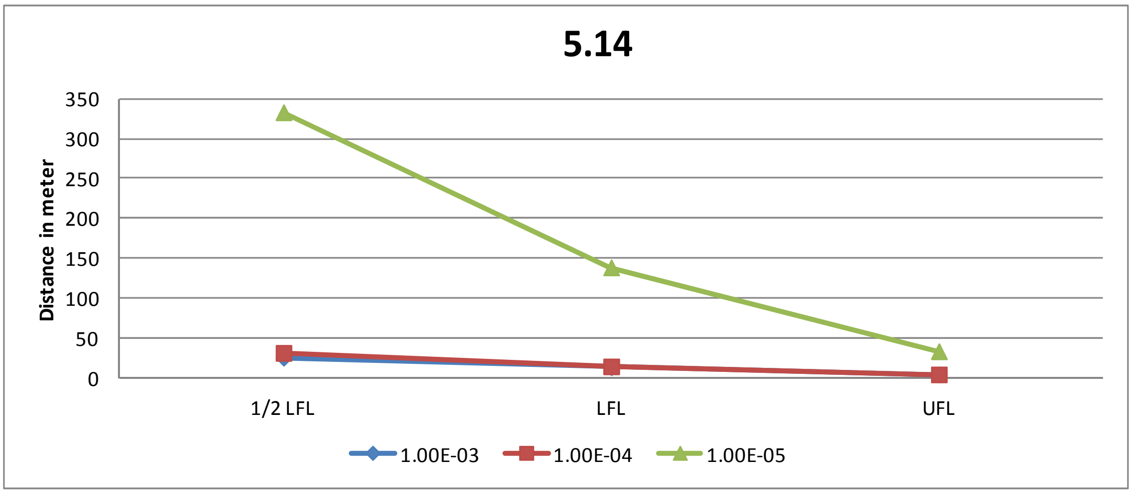

Figure 3.19: 1/2LFL, LFL and UFL calculated for Case 5.14

3.3.10.1 ISO-risk curves

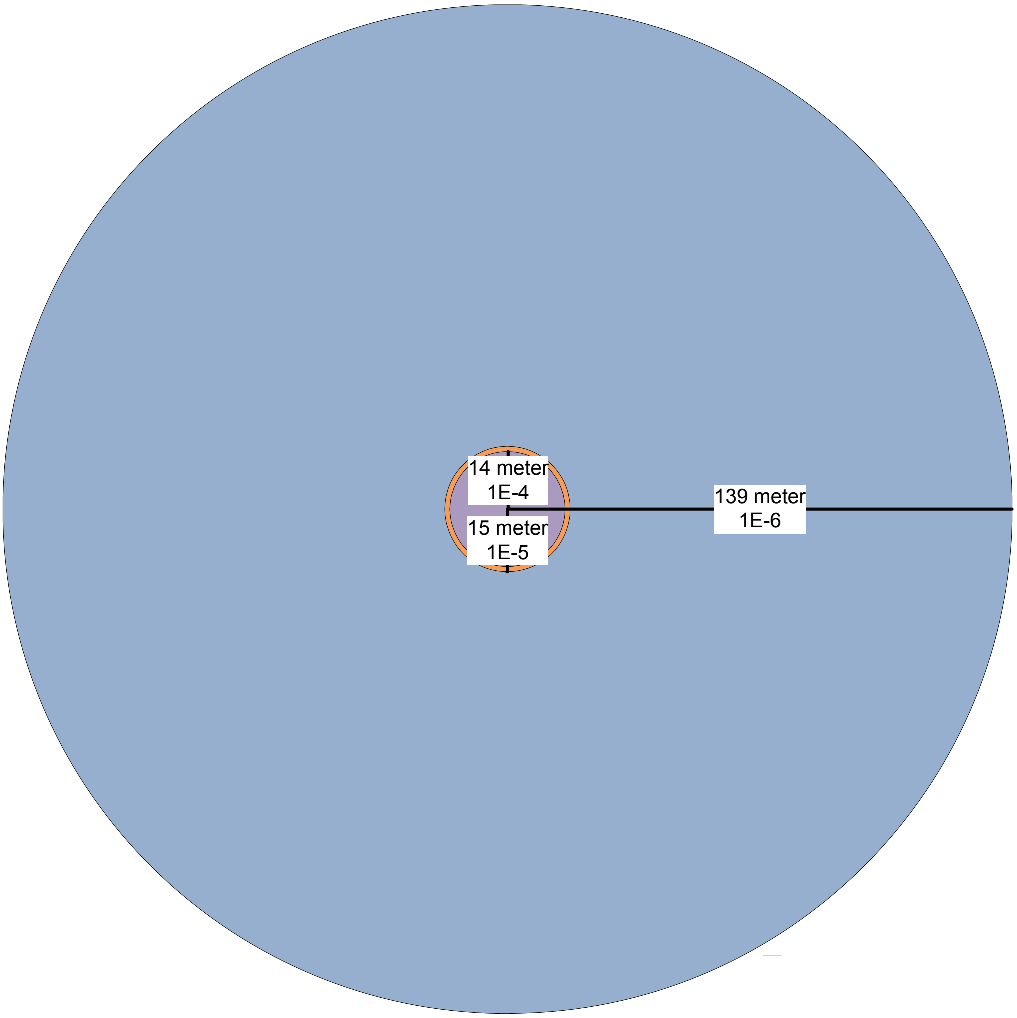

Figure 3.20: ISO-risk curve for HP/MP station

3.3.11 Case 5.16: Pressure reduction stations (Mp/Lp) - Methane

The following scenarios were run with focus on dispersion results:

Table 3.35: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage from 10 bar(g) part of station	0.18 kg/s until steady state is achieved, gas release, 10 bar(g) (MP)
1E-4	Medium leakage from the 10 bar(g) part of the station	Hole diameter 17.5 mm until steady state is achieved, gas release 10 bar(g) (MP)
1E-5	Large leakage/rupture of pipe from the 10 bar(g) part of the station	44 kg/s at 10 bar(g) (MP)
1E-6	Explosion	The station is assumed to have sufficient relief panels, so an explosion will give very low hazard distances. Not investigated further

All scenarios were run with a reservoir temperature of 15 °C. 100 % methane was used.

Dispersion results are presented in Table 3.36 and Table 3.37.

Table 3.36: Case 5.16 - Dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3 MP	7.9	2	4.1	2	1.2	2
1E-4 MP	10.5	2	5.6	2	1.7	2
1E-5 MP	134	9.8	71.2	3.7	17.5	2

Table 3.37: Case 5.16 - Dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3 MP	0.6	0.3	0.1
1E-4 MP	0.9	0.5	0.15
1E-5 MP	11.4	5.8	1.6

The results are also presented in Figure 3.21.

For all jet releases the dispersion pattern is consistent; a thin jet profile that increases in size (both length and width) with respect to increasing release rate. From results this may however not be clear. This is due to the fact that all of scenarios expect 1E-4 MP end up with the same release rate of 0.18 kg/s. The release rates for 1E-4 MP is 0.4 kg/s.

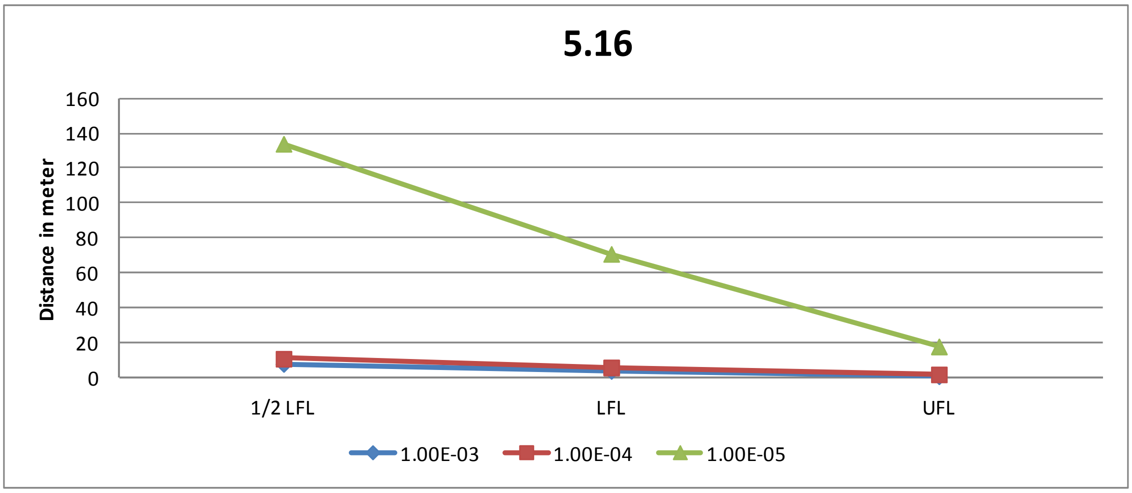

Figure 3.21: 1/2LFL, LFL and UFL calculated for Case 5.16

3.3.11.1 ISO-risk curves

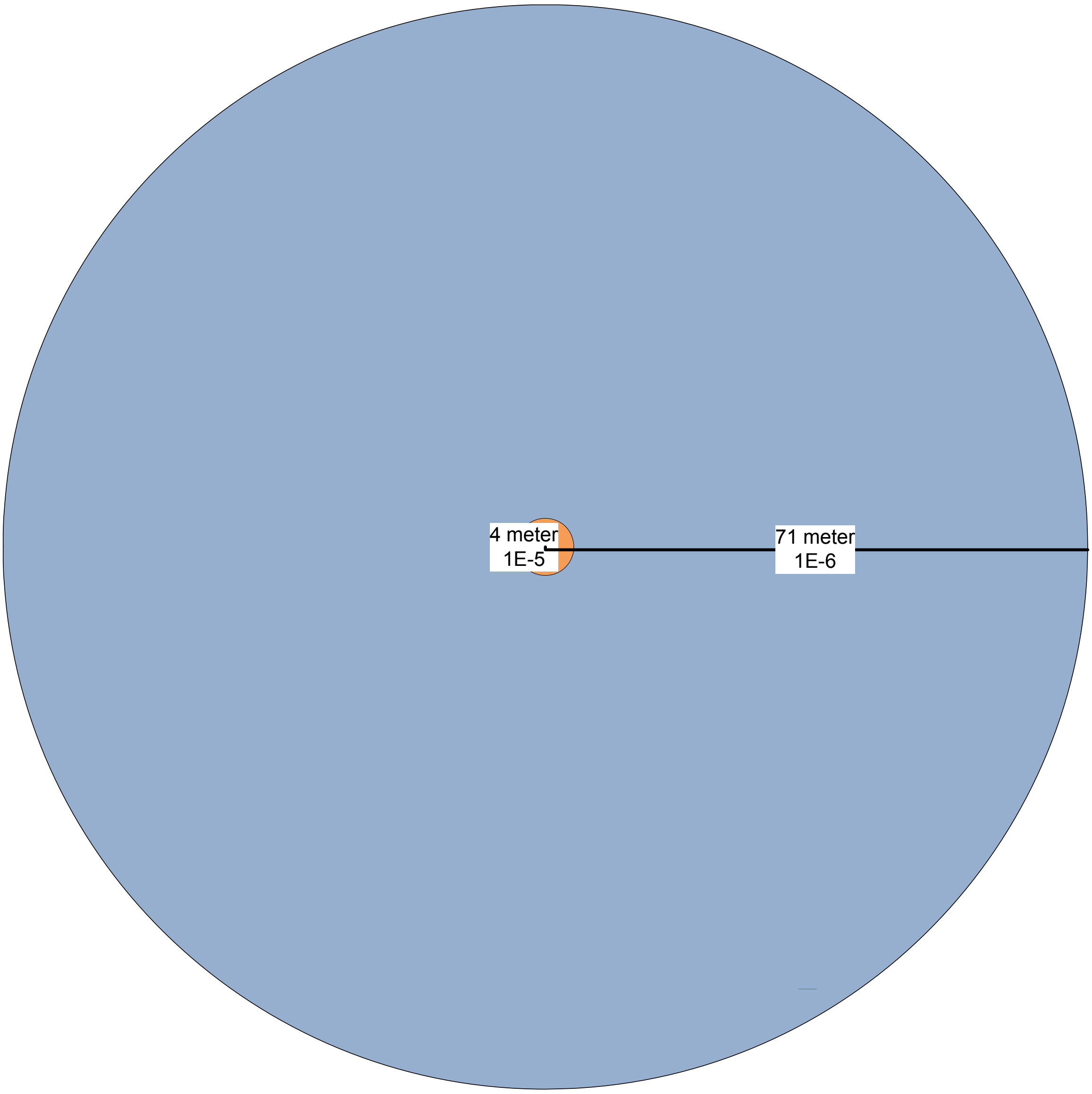

Figure 3.22: ISO-risk curve for the MP/LP station

3.3.12 Ammonia plants

The following scenarios were run with focus on dispersion results:

Table 3.38: Scenarios

Frequency	Description	Calculated release
1E-3	Small leakage in large ammonia facility	0.5 kg/s for 90 seconds, gas release
1E-4	Medium leakage in a large ammonia facility. Instant release of complete inventory of a small ammonia facility	0.4 m^3 momentary release, gas release
1E-5	Large leakage in a large ammonia facility. Instant release of complete inventory of a medium ammonia facility	1 m^3 momentary release, gas release
1E-6	Instant release of complete inventory of a large ammonia facility	5 m^3 momentary release, gas release

All scenarios were run with a reservoir pressure of 15 bar(g) and temperature of 10 °C.

Flammable dispersion results are presented in Table 3.36 and Table 3.37.

Table 3.39: Ammonia - Flammable dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	5.8	1.9	2.9	2	1.7	2
1E-4*	9	2	5.9	2	4.5	2
1E-5*	12.5	2	8.3	2	6.5	2
1E-6*	22.3	2	14.9	2	11.6	2

Table 3.40: Ammonia - Flammable dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	0.4	0.2	0.1
1E-4*	13.8	10.4	8.6
1E-5*	19.4	14.4	12
1E-6*	34	25.4	21.2

For the jet release (1E-3) the dispersion pattern is consistent with earlier results; a thin jet profile. The momentary release results (all other scenarios) show that the dispersion length and width increase with the amount released. For ammonia the width is consistently greater than the length of the ensuing gas cloud for all simulated scenarios.

Toxic dispersion results are presented in Table 3.41 and Table 3.42. These results show the same general trends as the flammable results.

Table 3.41: Ammonia - Toxic dispersion length and height results

Case	Max distance 300 ppm (m)	Height for max distance 300 ppm (m)	Max distance 5000 ppm (m)	Height for max distance 5,000 ppm (m)	Max distance 10,000 ppm (m)	Height for max distance 10,000 ppm (m)
1E-3	283	0	97	0	42	0
1E-4*	413	0	194	0	140	0
1E-5*	543	0	256	0	195	0
1E-6*	958	0	452	0	339	0

Table 3.42: Ammonia - Toxic dispersion width results

Case	Max width 300 ppm (m)	Max width 5,000 ppm (m)	Max width 10,000 ppm (m)
1E-3	144	21	6
1E-4*	380	148	106
1E-5*	546	214	150
1E-6*	1016	410	280

The results are also presented in Figure 3.23.

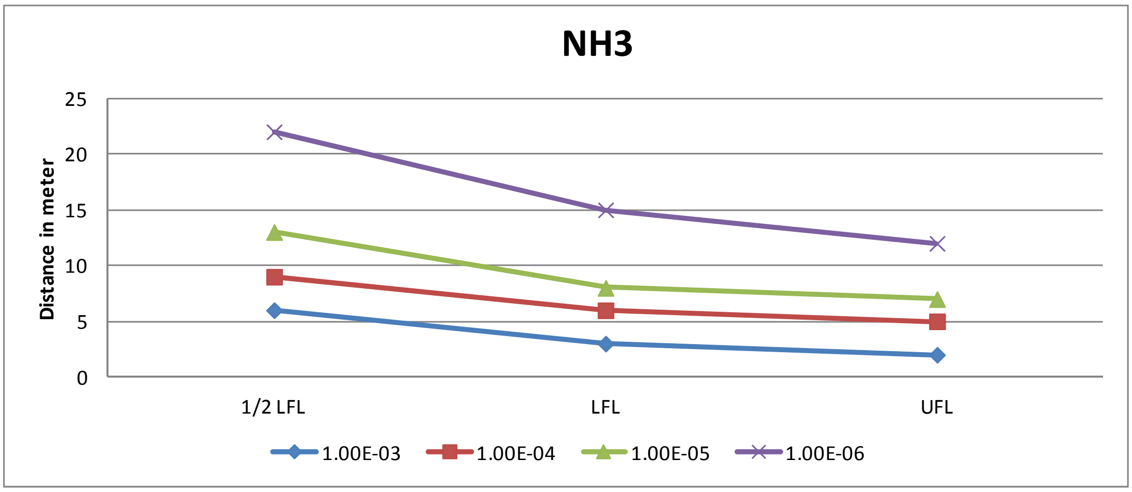

Figure 3.23: 1/2LFL, LFL and UFL calculated for Case NH3

3.3.12.1 ISO-risk curves

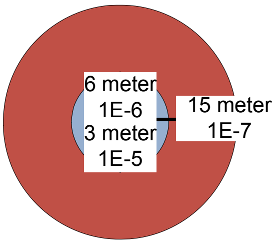

Figure 3.24: ISO-risk curves for ammonia. The hazard distances are due to flammability of the cloud

Flammability distances for ammonia are generally smaller than for other substances analysed in this report.

3.3.12.2 Toxicity

Ammonia is also toxic, and the expected evacuation distances from ammonia facilities are given below. These limits are set on the basis of the IDLH-value of 300 ppm. These frequencies cannot be compared to the ISO-risk values, since this is not set in relation to fatalities.

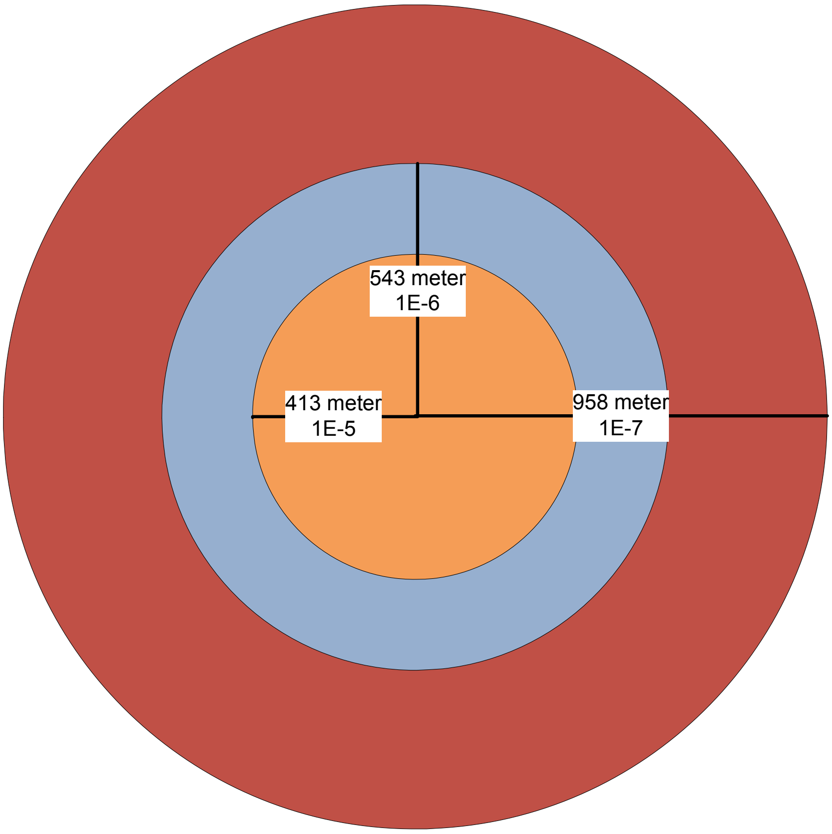

Figure 3.25: Toxicity for ammonia

3.3.13 Tank facility - Isopropanol

The following scenarios were run with focus on dispersion and fire results:

Table 3.43: Scenarios

Frequency	Description	Calculated release
1E-3	Leakage from pipeline inside facility that is not detected	3 kg/s for 10 minutes, liquid release
1E-4	Hole in tank that result in release of the entire tank into bund within 10 minutes.	3,000 m^3 release during 10 minutes, 1,000 m^2 bund (circular) with height 3 m, liquid release, 0.1 bar(g)
1E-5	Rupture of hose (loading/unloading) that is shutdown with some delay	10 kg/s for 30 seconds, liquid release
1E-6	Catastrophic rupture of tank into bund.	3,000 m^3 momentary release, 1,000 m^2 bund (circular) with height 1 m, liquid release, 0.3 bar(g)

All scenarios were run with a reservoir pressure of 5 bar(g) and temperature of 15 °C, unless otherwise specified.

Dispersion results are presented in Table 3.44 and Table 3.45.

Table 3.44: Iso-propanol - Flammable dispersion length and height results

Case	Max distance 1/2LFL (m)	Height for max distance 1/2LFL (m)	Max distance LFL (m)	Height for max distance LFL (m)	Max distance UFL (m)	Height for max distance UFL (m)
1E-3	14.7	0.6	14.3	0.6	7.5	1.7
1E-4	62.1	0	23.9	0	3.6	0
1E-5	16.6	0.7	16.4	0.7	12.7	1.2
1E-6*	105.7	0	30.9	1.8	30.6	1.8

Table 3.45: Iso-propanol - Flammable dispersion width results

Case	Max width 1/2LFL (m)	Max width LFL (m)	Max width UFL (m)
1E-3	3.2	2.5	0.5
1E-4	9	4	1.6
1E-5	4.2	3.5	0.8
1E-6*	110	50	50

The results are also presented in Figure 3.26.

For the jet release (all except 1E-6) the dispersion pattern is consistent with earlier results; a thin jet profile that increases in size (both length and width) with respect to increasing release rate. The reason for 1E-4 showing a greater gas cloud than the other 2 scenarios is because it has a release rate which is larger (approximately 3,900 kg/s). The momentary release result (1E-6) again shows that the resulting gas cloud's width is greater than its length. This may be explained due to the presence of a bund. The bund may also explain why the dispersion distances to LFL and UFL are the same, since the bund inhibits the growth of the pool produced.

Table 3.46 and Table 3.47 present the results related to heat flux radiation distances as a result of pool fires. PHAST calculates two different types of pool fires that result from iso-propanol releases. These are:

- An **early pool fire** is one that occurs immediately after rainout for a long-duration continuous release, before the cloud has started to disperse away from the pool.
- A **late pool fire** is one that occurs after the cloud has started dispersing away from the pool.

The pool fire results are thus presented as both late and early. In some instances the heat radiation from these pools are the same.

Table 3.46: Iso-propanol - Heat flux radiation distances as a result of early pool fires

Case	Max distance to 5 kW/m^2 (m)	Max distance to 15 kW/m^2 (m)	Max distance to 30 kW/m^2 (m)
1E-3	39.1	30.2	23.4
1E-4	80.6	53.2	38.6
1E-5	39.0	30.8	24.8
1E-6*	-	-	-

Table 3.47: Iso-propanol - Heat flux radiation distances as a result of late pool fires

Case	Max distance to 5 kW/m^2 (m)	Max distance to 15 kW/m^2 (m)	Max distance to 30 kW/m^2 (m)
1E-3	63.1	45.7	35.7
1E-4	80.6	53.2	38.6
1E-5	39.0	30.8	24.8
1E-6*	79.6	52.2	37.6

The results for pool fires are as expected; the heat flux radiation distances increase with increasing pool size (which increases with release amount). For cases 1E-4 and 1E-6 the released amount is the same, the only difference being the time frame during which the release occurs. This may explain the similarity in distances to the specified heat flux radiation levels.

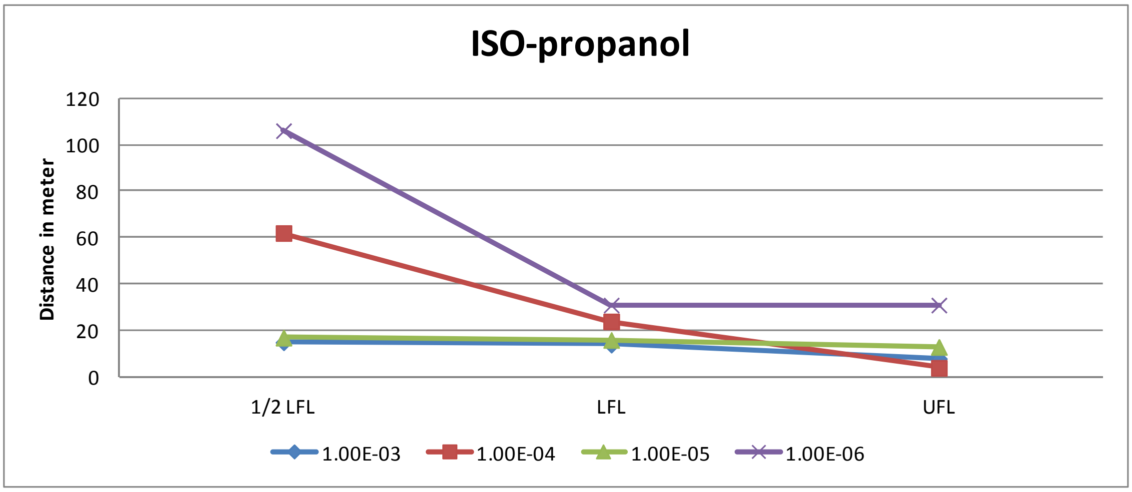

Figure 3.26: 1/2LFL, LFL and UFL calculated for Case ISO-propanol

3.3.13.1 ISO-risk curves

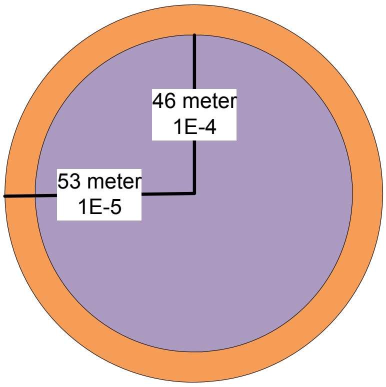

Figure 3.27: ISO-risk curves for Iso-propanol

The ISO-risk curves for the Iso-propanol facility shows that there is a large zone for the 1E-4, but that the realistic worst case scenario is a 1E-5 event. This is a fire in the bunding.

3.3.14 Tank facility - diesel

The following scenarios were run with focus on fire results:

Table 3.48: Scenarios

Frequency	Description	Calculated release
1E-3	Large leakage from hose (loading/ unloading), detected and shutdown with some delay	20 kg/s for 1.5 minutes, pumped liquid release
1E-4	Rupture of hose (loading/unloading), detected and shutdown with some delay	222 kg/s for 1.5 minutes, pumped liquid release
1E-5	Rupture of hose (loading/unloading), that is not detected and shutdown	222 kg/s for 10 minutes, pumped liquid release
1E-6	Catastrophic rupture of tank	3,000 m^3 momentary release, liquid release, 0.3 bar(g)

All scenarios were run with a reservoir pressure of 5 bar(g) and temperature of 15°C, unless otherwise specified. All scenarios were also modeled with a bund with the capability of handling the tank volume and 10 additional percent, in this case a total volume of 3,300 m^3 (1,000 m^2 circular area and 3.3 m in depth). Diesel has modelled by using 100 % n-dodecane ($C_{12}H_{26}$). Only fire scenarios were run.

Table 3.49 and Table 3.50 present the results related to heat flux radiation distances as a result of pool fires. PHAST calculates two different types of pool fires that seem to arise with n-dodecane. These are:

- An **early pool fire** is one that occurs immediately after rainout for a long-duration continuous release, before the cloud has started to disperse away from the pool.
- A **late pool fire** is one that occurs after the cloud has started dispersing away from the pool.

The pool fire results are thus presented as both late and early. In some instances the heat radiation from these pools are the same.

Table 3.49: Diesel - Heat flux radiation distances as a result of early pool fires

Case	Max distance to 5 kW/m^2 (m)	Max distance to 15 kW/m^2 (m)	Max distance to 30 kW/m^2 (m)
1E-3	53.8	33.2	-
1E-4	62.7	37.2	-
1E-5	62.7	37.2	-
1E-6*	-	-	-

Table 3.50: Diesel - Heat flux radiation distances as a result of late pool fires

Case	Max distance to 5 kW/m^2 (m)	Max distance to 15 kW/m^2 (m)	Max distance to 30 kW/m^2 (m)
1E-3	54.6	33.3	-
1E-4	62.7	37.2	-
1E-5	62.7	37.2	-
1E-6*	47.8	22.3	-

For all of the scenarios the maximum pool radius is 17.8 metres (i.e. maximum due to bund) except for the 1E-3 scenario, which has a maximum radius of 12.3 metres. As a result of this the heat radiation from the 1E-3 scenario is less than 1E-4 and 1E-5. For the 1E-6 case, since this is a momentary release, the pool is pretty much formed instantly as opposed to the other scenarios where a significant amount of time elapses before the maximum diameter is reached.

3.3.14.1 ISO-risk curve diesel facility

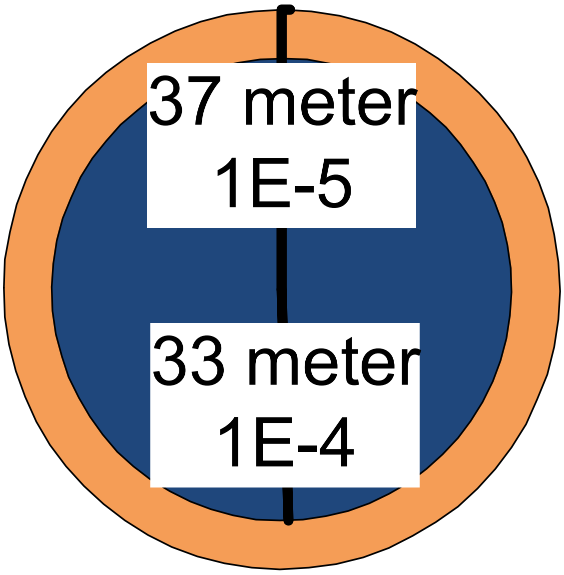

Figure 3.28: ISO-risk curve tank facility - diesel

3.4 Concluding remarks/recommendations

This section of the report aims at concluding the DSB case study performed in order to determine generic safety distances related to a number of typical facilities (such as small LPG-consumer terminals, LNG-consumer terminals, ammonia plats, etc).

The generic safety distances quoted and calculated in this report are indeed generic. It is therefore important that the calculated safety distances are not used uncritically. They are to be used only as a first **indication** of the risk levels around a facility, and not as a final risk assessment. With all industrial facilities (such as those included in this report) there will always be a number of facility-specific and location-specific risks that must be analysed and managed by means of a risk assessment. Utilizing the generic safety distances outlined in this report does not imply that an organization is exempt from performing a risk assessment of its facility.

Since the calculations performed in order to obtain the safety distances are generic they are also susceptible to a number of uncertainties. These are summarized below:

Ignition model

The choice of ignition model is important for the calculation of iso-risk curves. As can be seen from Chapter 3.2.2 the models predict different ignition probabilities for a given flammable gas cloud. As such this difference warrants the need for sensitivities to be performed to ensure that the conclusions drawn (i.e. if risk levels are considered acceptable) from the predicted risk levels are the same regardless of the model used.

In addition, for the generic cases run in this report, a number of assumptions have been made regarding the existence of ignition sources. These may not correspond to the actual circumstances at an actual facility and therefore may under- or overestimate the facility's safety distances. Ignition sources will be dependent on the number and type of activities performed at a facility, and by not including such parameters in a risk assessment one always runs the risk of ignoring a facility's specific risk driver.

Wind, weather and terrain data

The consequence simulations used as input for the calculation of the safety distances have been performed for a wind speed of 2 m/s, Pasquill Stability Class D and a surface roughness of 35 mm. A number of other wind and stability class combinations will be present for different locations, and it is again important to include such local parameters in order to be able to, as far as reasonably possible, predict risk levels tailor-made for the facility and its location in question.

Where terrain or building structures are suspected to influence the results, dispersion distances should be calculated using CFD models like KFX and FLACS.

Bunding

For a number of scenarios performed in the consequence modelling it has been assumed that a bund (impoundment pit or similar) is present that will contain a leaking medium and inhibit it from producing a pool greater than the size of the bund itself. This assumption was made in order to account for typical barriers in place to mitigate consequences of a leak; bunding being one such common barrier. Naturally, not all facilities will be equipped with such measures, and even if they are, the bunds may not be of the same size or type assumed in this report. Again it is important to consider the actual circumstances at the facility in question in order to be to present a risk picture that is as realistic as possible.

Activity

For many of the scenarios selected, the estimated leak frequencies (and hence the representative critical scenarios) are directly correlated to the activity. Hence, by increased activity at the facility, the risk will also increase.

For some of the hazards, like tank rupture etc. the risk is not dependent of the activity, but these scenarios do often have low frequencies, and there is often good barriers (for instance bundig) in place to reduce the consequence.

3.4.1 Comparison of safety distances

In this chapter the ISO-risk distances for different facilities are presented.

In Figure 3.29 and Figure 3.30 it can be seen that there are large differences between the different facilities with respect to the ISO-risk distances.

The largest safety distances are seen on an LPG-facility, and the scenarios that contribute to these distances are related to the tank. In LNG-facilities the tanks are assumed to be better protected, and the safety distance for 1E-5 events is therefore dominated by leakage from a loading/unloading hose.

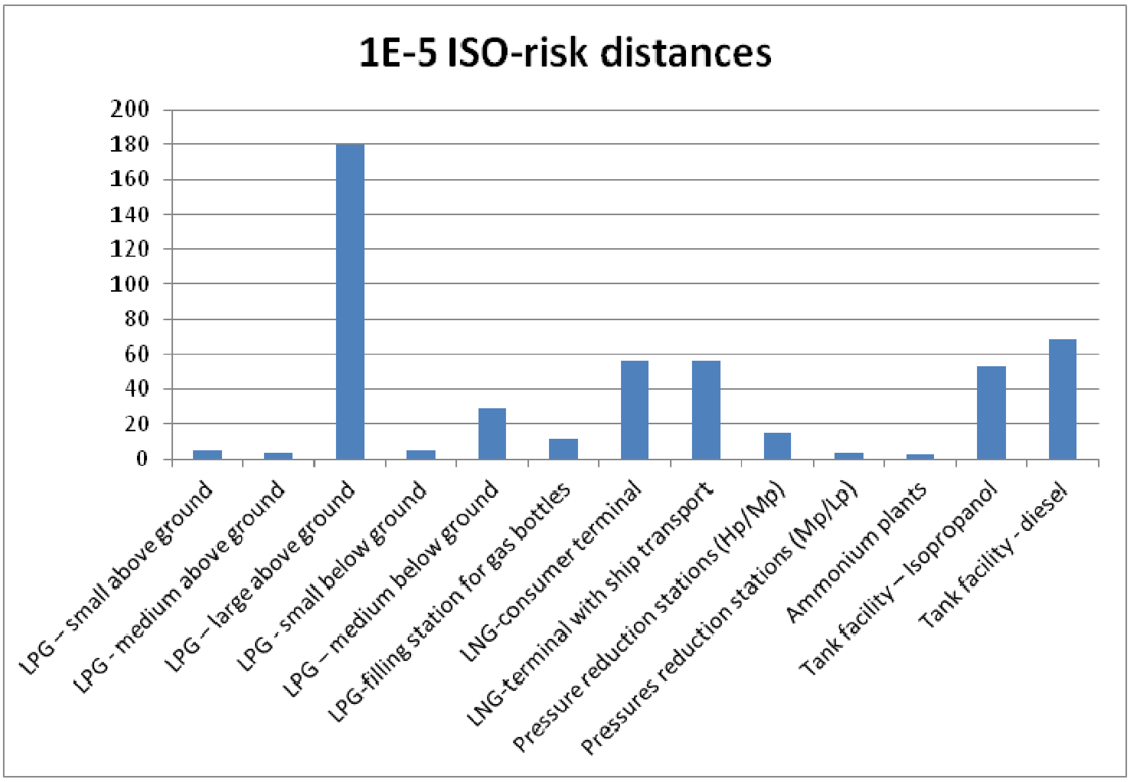

Figure 3.29: 1E-5 ISO-risk distances for different facilities

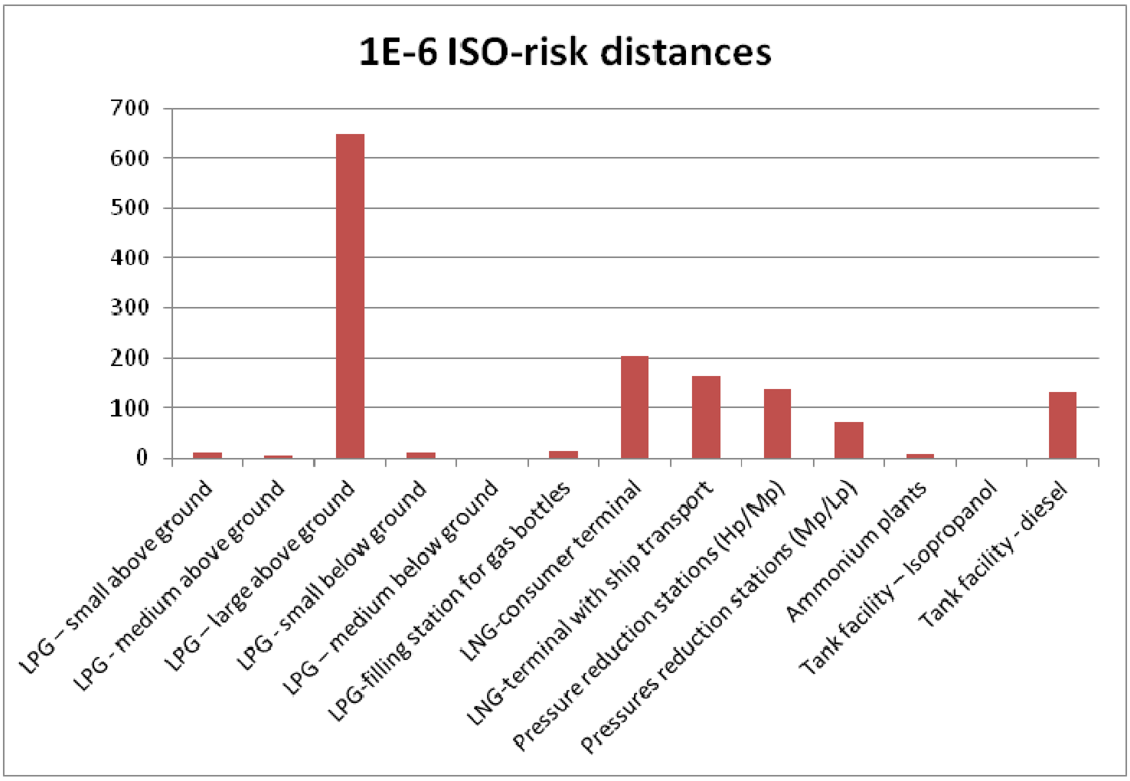

Figure 3.30: 1E-6 ISO-risk distances f or different facilities

4. REFERENCES

/1/ DNV website, PHAST, URL: http://www.dnv.com/services/software/ products/ safeti/safetiqra/phast.asp, accessed 28/11-2011.

/2/ Safer Systems website, TRACE, URL: http://www.safersystem.com/trace.htm, accessed 28/11-2011.

/3/ GexCon AS: "FLACS v9.1 User's Manual", September 2011.

/4/ Launder, B.E., Spalding, D.B.: "The numerical computation of turbulent flows", Comp. Meth. In App. Mech. And Eng., 3 (1974), 269-289.

/5/ http://www.gexcon.com/publications.

/6/ Hansen, O.R., Gavelli, F., Ichard, M. & David, S. G: "Validation of FLACS against experimental data sets from the model evaluation database for LNG vapor dispersion", Journal of Loss Prevention in the Process Industries, 23 (2010), 857-877.

/7 / "Special Interest Group on Quality and Trust in Industrial CFD: Best Practice Guidelines", European Research Community on Flow, Turbulence and Combustion (ERCOFTAC), Version 1 .0, January 2000.

/8 / Asmund Huser, Pål Jahre Bilsen , Helge Skåtun: "Application of k-e model to the stable ABL: Pollution in complex terrain", Journal of wind engineering and Industrial Aerodynamics 67 &68 (1997) 425-436.

/9/ "Kameleon FireEx Validation Handbook", Document No. R0922, 19 February 2010.

/10 / Eric De Carvalho, Total E& P Norge: "Gas dispersion simulations: Comparison of results between KFX and FLACS", KFX User Meeting, November 2010.

/11/ Scandpower AS: "Risikoanalyse av gassanlegg", Report No. 70.730.005/R1, 18 April 2007.

/12/ Scandpower and SINTEF: "Handbook for Fire Calculations and Fire Risk Assessment in the Process Industry", 17 September 2003.

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