



Gas dispersion model DRIFT 3.6.14: modelling the dispersion of flammable vapour

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HSE uses gas dispersion modelling in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazards sites. To update its dispersion modelling capability, HSE commissioned ESR Technology to develop a new version of the gas dispersion model DRIFT. The new version, DRIFT 3, includes a significant number of modelling enhancements over the version previously used within HSE (DRIFT 2.31). These include the extension of the model to treat buoyant plumes and time varying releases. Before DRIFT 3 is adopted for use by HSE, it must undergo thorough evaluation and assessment for a range of release scenarios. The initial phases of the DRIFT 3 testing programme used DRIFT 3.6.4 and are described in reports RR1100 and RR1101. Further testing is described in four reports including this one: RR1165, RR1166, RR1167 and RR1168. The four reports cover the evaluation of the model and assessment for a range of scenarios using the enhanced version DRIFT 3.6.14.

This report describes an assessment of the performance of DRIFT 3.6.14 for modelling the dispersion of flammable vapour. The assessment is for three release scenarios: vapour evolved from pools of flammable liquids, flashing jet releases of flammable substances, and instantaneous flashing releases of flammable substances. These scenarios are typically used by HSE to assess Hazardous Substances Consent applications and set Land Use Planning zones around major hazards sites and pipelines. This report describes sensitivity tests which show that DRIFT 3.6.14 works reliably for these scenarios. As a result of this assessment and accompanying model evaluation (see RR1165), DRIFT 3.6.14 has been adopted by HSE to model the dispersion of flammable vapour for these three release scenarios.

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Gas dispersion model

DRIFT 3.6.14: modelling the dispersion of flammable vapour

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KEY MESSAGES

The Health and Safety Executive (HSE) uses gas dispersion modelling in its assessment of the hazards and risks posed to people in the vicinity by toxic and flammable substances stored at major hazards sites. A new version of the gas dispersion model DRIFT (Dispersion of Releases Involving Flammables or Toxics), DRIFT 3, was commissioned by HSE to update its dispersion modelling capability.

To ensure that DRIFT 3 is fit for purpose, a programme of work is being undertaken at HSE. This includes an evaluation of DRIFT 3's dispersion modelling capabilities and an assessment of the performance of DRIFT 3 for modelling the types of release scenario typically considered by HSE for Hazardous Substances Consent assessments.

This report presents an assessment of the use of DRIFT 3.6.14 for modelling the dispersion of flammable vapour from vessels and pipelines. The dispersion of such releases was previously modelled by HSE using DRIFT 2.31 or the CRUNCH dispersion model, a precursor to DRIFT that was originally developed in the early 1980s. The outputs of DRIFT 3.6.14 and either DRIFT 2.31 or CRUNCH have been compared for evaporating pools, continuous flashing releases and instantaneous flashing releases. The substances considered were LNG (liquefied natural gas), liquid hydrogen, LPG (liquefied petroleum gas), ethylene, isobutane, propane and *o*-cresol.

Sensitivity tests have been carried out to ensure that DRIFT 3 works reliably for the types of inputs typically used by HSE. Guidance is also provided on how DRIFT 3 should be used to model the dispersion of flammable vapour for the purposes of Hazardous Substances Consent assessment and Major Accident Hazard pipeline risk assessment.

As a result of this work, DRIFT 3.6.14 has now been adopted by HSE to model the dispersion of flammable vapour for vessel and pipeline releases.

This detailed technical report is aimed at technical specialists in consequence modelling and risk assessment.

EXECUTIVE SUMMARY

The Health and Safety Executive (HSE) uses gas dispersion modelling in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazards sites and transported in Major Accident Hazard (MAH) pipelines. To update its dispersion modelling capability, HSE commissioned ESR Technology to develop a new version of the gas dispersion model DRIFT (Dispersion of Releases Involving Flammables or Toxics). The new version of the model, DRIFT version 3 (DRIFT 3), includes a significant number of modelling enhancements over the version of DRIFT previously used by HSE (DRIFT 2.31).

Under the Planning (Hazardous Substances) Regulations, the presence of hazardous chemicals above specified threshold quantities requires Hazardous Substance Consent (HSC) from a Hazardous Substances Authority (HSA), which is usually the local Planning Authority. HSE is a statutory consultee on all Hazardous Substances Consent applications. Its role is to consider the hazards and residual risk which would be presented by the hazardous substance(s) to people in the vicinity, and on the basis of this to advise the HSA whether or not consent should be granted. The outputs of these assessments are also used to set Land Use Planning (LUP) zones around major hazards sites. DRIFT 3 will be used by HSE in this assessment process.

DRIFT 3 will also be used by HSE in the assessment of HSA/LUP zones in the vicinity of Major Accident Hazard (MAH) pipelines. HSE is a statutory consultee for MAH Pipelines, which fall under the Pipeline Safety Regulations (PSR). HSE considers the risks to people in the vicinity of the pipeline and provides advice accordingly.

The programme of work to ensure that DRIFT 3 is fit for purpose has included: an evaluation of DRIFT 3's dispersion modelling capabilities; and an assessment of the performance of DRIFT 3 for modelling the types of release scenario typically considered by HSE for Hazardous Substances Consent assessments and MAH pipeline risk assessments.

This report presents an assessment of the use of DRIFT 3.6.14 for modelling the dispersion of flammable vapour and is aimed at HSE risk assessment modelling specialists for major hazard and major accident hazard pipelines. The evolution of vapour from a range of sources was investigated, including:

- Pools formed from spills of flammable liquids;
- Flashing releases from holes in vessels and pipes containing flammable chemicals; and
- Catastrophic failures of storage vessels containing flammable chemicals.

The dispersion of such releases was previously modelled by HSE using DRIFT 2.31 or CRUNCH, a dispersion model for continuous releases of denser-than-air vapour. The output of DRIFT 3 and the previously used model has been compared and sensitivity studies on key input parameters have been carried out.

Objectives

The main objectives of this work were:

- To ensure that DRIFT 3 works reliably for the types of inputs typically used by HSE for the assessment of Hazardous Substance Consent applications relating to flammable substances, and for Pipeline Safety Regulations (PSR) assessment purposes;
- To determine an appropriate methodology for modelling the hazards posed by pools of flammable substances using ESR's GASP (Gas Accumulation over Spreading Pools) model and DRIFT 3;
- To determine an appropriate methodology for modelling the hazards posed by flashing jet releases of flammable substances using a suitable release rate model and DRIFT 3; and
- To determine an appropriate methodology for modelling the hazards posed by flashing releases of flammable substances from catastrophic vessel failure using the ACE (Airborne Concentration Estimate) source term model and DRIFT 3.

Main Findings

Methodologies for modelling the dispersion of flammable vapour using DRIFT 3 have been developed, in consultation with the developers of the model and specialist inspectors and researchers within HSE. These modelling recommendations are based on the operation of DRIFT 3.6.14. In most cases, differences between the modelling methodologies used in previous versions of DRIFT and DRIFT 3.6.14 reflect an improvement in the ability of DRIFT to model real physical processes, such as gravitational spreading of the cloud over the source, plume meander and the effect of finite release duration.

DRIFT 3.6.14 outputs shorter, narrower Lower Flammable Limit (LFL) isopleths than DRIFT 2.31, although there are some exceptions to this general observation. It also outputs shorter hazard ranges to the LFL than the CRUNCH model, particularly in stable atmospheric and low wind speed weather conditions.

Findings specific to the type of release being investigated are given subsequently.

Evaporating pools

The evaporation of a pool from a spill of flammable material can form a flammable cloud which disperses away from the initial release site and the pool itself.

DRIFT 3.6.14 contains three methods for calculating the dispersion of continuous releases. These are:

- A steady continuous model, which assumes a continuous release of a substance;
- A finite duration model, which contains the same basic equations as the steady continuous model but treats the cloud differently in post-processing; and
- A time varying model, which divides the release up into a specified number of time segments. This enables different aspects of the release to be modelled in more detail.

The time varying model in DRIFT 3 has not undergone thorough evaluation and also does not produce a solution for all scenarios. For these reasons, it has not yet been approved for use by HSE. HSE has therefore developed a methodology to determine the source term to be used in conjunction with the finite duration model in DRIFT 3. This methodology has been developed to deal with cases where the vaporisation rate outputs from GASP vary significantly over the duration of the release. This is the case in some of the evaporating pool scenarios investigated.

For some substances released as a result of process vessel failure, such as liquefied hydrogen and *o*-cresol at elevated temperatures and pressures, the cloud becomes buoyant and the hazard ranges depend on whether the centreline height of the cloud is used or a user specified height. The centreline height produces the largest hazard ranges but may not accurately reflect the true hazard to a person in the vicinity of a release.

Flashing releases from holes in vessels, pipework and pipelines

In these scenarios, a continuous release of a flammable substance from a vessel or pipeline results in a flammable cloud being formed that disperses away from the release point. The cloud has the potential to ignite and flash back to the original release point.

For the ethylene and propane pipelines considered in this study, one of the sensitivities investigated has been the effects on the results from variation of the release temperature. It has been found that, as the temperature increases, the downwind distances decrease. This is due to the decrease in density of the cloud as the release temperature increases, which increases the amount of mixing with the surrounding atmosphere.

Flashing releases from catastrophic vessel failure

In these scenarios, the contents of a vessel are lost near-instantaneously, forming a flammable cloud. In some cases, rainout can occur, leading to pool formation, as well as a cloud.

HSE uses the Airborne Concentration Estimation (ACE) model to generate the source terms for DRIFT 3 for near-instantaneous flashing releases of a substance following a catastrophic failure of a storage or process vessel.

It was found that the resultant pool caused by rainout from the initial release can lead to hazard ranges of a similar magnitude to the initial cloud generated from the substance flashing from the vessel failure. It is therefore important to consider both the cloud and the pool when performing a Hazardous Substances Consent assessment.

Outcomes

As a result of this work, DRIFT 3.6.14 has now been adopted by HSE to model:

- The dispersion of vapour evolved from pools of flammable substances;
- The dispersion of vapour from flashing releases of flammable substances from holes; and
- The dispersion of vapour from flashing releases of flammable substances from catastrophic vessel failure.

Specific details of the modelling for each type of release are given subsequently.

Evaporating pools

The finite duration model in DRIFT 3 is the most appropriate option for modelling evaporating pools of flammable liquids.

The centreline height output option in DRIFT 3 is used in all cases for the hazard range, including when the cloud becomes buoyant. It is possible that an observer on the ground will be beneath a flammable cloud. If the cloud ignites, the observer could be harmed by the resultant fire. The option of using the centreline height provides the more cautious approach and captures this scenario.

For an evaporating pool where GASP results do not vary significantly over time, a mean vaporisation rate for the duration of the release can be used as input to DRIFT 3 to model the release scenario.

For an evaporating pool where the GASP results indicate that the vaporisation rate varies significantly over time then the methodology developed by HSE for generating a source term is used. This method takes into consideration a potentially large initial vaporisation rate that then quickly reduces over a short duration to a steady vaporisation rate for the remainder of the pool duration. The use of a mean vaporisation rate in such a case does not account for any initial peak vaporisation rate in the release and therefore is not suitable for these cases.

Flashing releases from holes from vessels, pipework and pipelines

For all cases of flashing releases from vessel, pipework or pipeline holes, the finite duration option in DRIFT 3.6.14 is the most appropriate option to use.

DRIFT 3.6.14 has replaced CRUNCH for the modelling of the dispersion of releases from pipelines.

For buried pipelines, a release height of 0 m is assumed, given that DRIFT cannot model releases below ground and the subsequent crater. This represents the closest approximation to a release that is deflected by the crater and then runs along the ground.

Flashing releases from catastrophic vessel failure

The instantaneous model is the most appropriate option in DRIFT 3.6.14 when modelling near-instantaneous flashing releases following a catastrophic failure of a vessel.

For these scenarios, any pool that is formed by rainout of the substance from the cloud is considered in conjunction with the initial cloud. The methodology followed for this element of the release is the same as that for evaporating pools.

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1 INTRODUCTION

The gas dispersion model DRIFT (Dispersion of Releases Involving Flammables or Toxics) was originally developed in the late 1980s, to model ground-based clouds released instantaneously or as a steady continuous source [1, 2]. DRIFT was developed for the Health and Safety Executive (HSE) by ESR Technology. ESR Technology has recently released a new version of the model, DRIFT 3.

HSE will use DRIFT 3 in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazards sites. Under the Planning (Hazardous Substances) Regulations [3], the presence of hazardous chemicals above specified threshold quantities requires consent from a Hazardous Substances Authority (HSA), which is usually the local Planning Authority. HSE is a statutory consultee on all Hazardous Substances Consent applications. Its role is to consider the hazards and residual risk which would be presented by the hazardous substance(s) to people in the vicinity, and on the basis of this to advise the HSA whether or not consent should be granted [4]. The outputs of these assessments are also used to set Land Use Planning (LUP) zones around major hazards sites [5].

DRIFT 3 will also be used for the assessment of LUP zones in the vicinity of Major Accident Hazard (MAH) pipelines. HSE is a statutory consultee for MAH pipelines, which fall under the Pipeline Safety Regulations (PSR) [6]. HSE considers the risks to people in the vicinity of the pipeline, and provides advice accordingly. The consultation regulations apply to new pipelines, modifications to existing pipelines, and to new developments in the vicinity of an existing pipeline.

DRIFT 3 includes a significant number of modelling enhancements over the version of DRIFT previously used by HSE (DRIFT 2.31) [7, 8]. These include extensions to the model to allow it to be applied to buoyant plumes and time varying releases. An overview of these enhancements is given in Section 1.1 of this report.

To ensure that DRIFT 3 is fit for purpose, a programme of work is being undertaken at HSE. This includes an evaluation of DRIFT 3's dispersion modelling capabilities and an assessment of the performance of DRIFT 3 for modelling the types of release scenario typically considered by HSE for Hazardous Substances Consent assessments and MAH pipeline risk assessments.

This report presents an assessment of the use of DRIFT 3.6.14 for modelling the dispersion of flammable vapour. This has included vapour evolved from pools of flammable liquids, the dispersion of flashing releases of flammable vapour from holes in vessels and pipes and from an instantaneous release from a catastrophic failure of vessels storing flammable substances. The dispersion of such releases was previously modelled by HSE using DRIFT 2.31, or, in some cases, CRUNCH [9], a precursor to DRIFT that was originally developed in the early 1980s. The outputs of DRIFT 3 and the previously used model have been compared and sensitivity studies on key input parameters have been carried out.

In this report, the new revised version of DRIFT is referred to as either DRIFT 3 or DRIFT version 3. When the output from a specific version of DRIFT 3 is presented, the exact version number is given.

1.1 MODEL ENHANCEMENTS IN DRIFT 3

A number of additions and modelling enhancements have been implemented in DRIFT 3, expanding the scope and potential uses of the model. A comprehensive account of these changes is given by Tickle and Carlisle [7, 8]. The model enhancements include:

- The inclusion of finite duration and time varying releases in addition to the instantaneous and steady continuous releases available in DRIFT 2;
- The option to calculate initial dilution over the source and upwind spreading;

- The extension of the model to include buoyant lift off and buoyant rise;
- Allowance for the effect of the vertical variation of atmospheric pressure, temperature and humidity on the cloud thermodynamics (necessitated by the extension of the model to include buoyant plumes);
- Inclusion of a lateral meander model, which accounts for the dilution caused by fluctuations in wind direction, and a vertical meander model, which accounts for the effects of updraughts and downdraughts in unstable atmospheric conditions;
- Incorporation of a momentum jet model. The jet model is based on the stand-alone model EJECT [10], which was used in conjunction with DRIFT 2.31;
- The generalisation of the model to include multi-component mixtures;
- The facility to read in data from SPI (Substance Property Information) files [11]. HSE's substance property database is in the form of SPI files. SPI files are text files containing spot values of physical properties at specified temperatures and equation coefficients which allow the calculation of various substance physical properties at a range of temperatures. SPI files are used by the majority of HSE's in-house models;
- The facility to run DRIFT 3 either via the GUI (Graphical User Interface) or via a COM (Component Object Model) interface [12]; and
- An improved and updated user interface. Plume footprints are plotted automatically within DRIFT 3, whereas when DRIFT 2.31 is used, a separate spreadsheet tool is required to plot the plume footprints.

The initial phases of HSE's testing programme were carried out using DRIFT 3.6.4. Since the completion of that work, DRIFT 3 has been further updated, and the most recent version of DRIFT currently available to HSE is DRIFT 3.6.14. Model enhancements implemented in DRIFT 3.6.5 and later versions include:

- Removal of the requirement for a user running DRIFT 3 in a Windows 7 environment to have administrator privileges, whilst maintaining compatibility with Windows XP;
- Removal of the empirical time delay for gravity spreading for non-stationary initial clouds. The new non-stationary cloud option is generally considered appropriate for clouds expected to be initially moving (e.g. due to momentum associated with any ambient air entrained prior to the DRIFT 3 run);
- Inclusion of a 'stationary initial cloud' option on the release tab. This option allows for comparison with the Thorney Island trials (see for example [13]) or other instantaneous release experiments which start from rest (zero centroid velocity and zero initial radial speed). The empirical time delay discussed in the previous point is maintained for these clouds (this is required for agreement with Thorney Island instantaneous trials);
- Modifications to allow initialisation in the case of an instantaneous cloud that is initially deeper than the mixing layer height. The mixing layer height defines the depth of the turbulent atmospheric boundary layer within which dispersion typically occurs: above this height, mixing is suppressed by the presence of a temperature inversion [14]. The new initialisation process keeps the cloud within the mixing layer and grows the lateral dimensions; and
- Improvements to the mathematical implementation of the time varying model, including modifications to the way in which lateral meander time averaging is applied.

In addition, improvements to how GASP (Gas Accumulation over Spreading Pools) generates DRIFT input files (DIN files) for use within DRIFT 3 have recently been made. GASP [15] is a source term model that calculates the evaporation rate from pools and also how the pool diameter varies with time.

1.2 OVERVIEW OF DRIFT 3 VALIDATION AND VERIFICATION

The initial validation and verification of DRIFT 3 was carried out by the developers of the model at ESR Technology. Comparisons of the DRIFT 3 and DRIFT 2 outputs with experimental data are presented by Tickle [16]. The primary aim of the Tickle paper was to confirm that the two versions broadly agree rather than to carry out a comprehensive validation study of DRIFT. Areas where DRIFT 3 produces significantly different predictions from DRIFT 2 are highlighted.

Tickle et al. [17] present comparisons of DRIFT 3 model predictions with experimental measurements of hydrogen fluoride releases obtained during the EU (European Union) URAHFREP (Understanding dispersion of industrial Releases of Anhydrous Hydrogen Fluoride and the associated Risk to the Environment and People) research project. The URAHFREP project studied HF thermodynamics and lift off of initially ground-based buoyant clouds. The focus of these comparisons was the validation and verification of the buoyant lift off and rise related enhancements to the DRIFT model. The comparisons indicate that DRIFT 3 generally gives a good representation of the effect of buoyancy on maximum concentration, and the buoyancy at which lift off occurs, although the ground-level concentration may be over-predicted when the cloud has significantly lifted from the ground.

The programme of work being undertaken at HSE has been designed to complement the ESR Technology studies. This programme of work considers both the validation of DRIFT 3 against experimental data and the effect of changes to the model on its predictions for the types of release scenario typically modelled by HSE for Hazardous Substances Consent assessments and MAH pipeline risk assessments. To date, the following topics have been covered:

- Evaluation of DRIFT's dispersion modelling capabilities

Coldrick and Webber [18] describe the evaluation of DRIFT 3.6.4 against a Model Evaluation Protocol (MEP) for dense gas dispersion models. The protocol was developed by Ivings et al. [19] for the US National Fire Protection Association (NFPA) and comprises scientific evaluation, model verification and model validation using a database of wind tunnel and field scale experimental data. The results of these stages are recorded in a comprehensive model evaluation report which includes qualitative and quantitative criteria for model acceptance. Coldrick and Webber include additional validation of DRIFT 3.6.4 against a series of passive dispersion experiments. Following the release of DRIFT 3.6.14, Cruse and Coldrick [20] carried out a further validation and comparison exercise in which results from DRIFT 3.6.14 were compared with those obtained in the evaluation of DRIFT 3.6.4. Cruse and Coldrick also present an assessment of the performance of DRIFT 3.6.14 for modelling the dispersion of vapour from pools of toxic liquids. As a result of this evaluation and assessment, DRIFT 3.6.14 was adopted by HSE to model the dispersion of vapour evolved from pools of toxic liquids [20].

- Assessment of the use of DRIFT for modelling the dispersion of vapour from pools of toxic liquids

Cruse et al. [21] present an assessment of the use of DRIFT 3.6.4 for modelling the dispersion of vapour from pools of toxic liquids. The dispersion of such releases was previously modelled by HSE using DRIFT 2.31. Methyl iodide and ethylene oxide test scenarios were used to assess the effect on the model predictions of the enhancements implemented between DRIFT 2.3.1 and DRIFT 3.6.4. The report also provides guidance on how DRIFT 3 should be used to model the dispersion of vapour from pools of toxic liquids.

- Assessment of the use of DRIFT for modelling releases of toxic pressure-liquefied gases

Lamb and Cruse [22] describe the assessment of the use of DRIFT 3.6.14 for modelling the dispersion of continuous releases of toxic pressure-liquefied gases. The dispersion of such releases was previously modelled by HSE using CRUNCH [9]. The outputs of DRIFT 3.6.14 and CRUNCH have been compared for a selection of chlorine, sulphur dioxide and ammonia release scenarios.

McGillivray and Cruse [23] present an assessment of the use of DRIFT 3.6.14 for modelling the dispersion of flashing instantaneous releases of toxic substances. The dispersion of such releases was previously modelled by HSE using DENZ [24]. The outputs of DRIFT 3.6.14 and DENZ were compared for a selection of chlorine, sulphur dioxide and ammonia release scenarios. Releases of substances heated above their normal boiling point in process vessels were also considered. Lamb and Cruse [22] and McGillivray and Cruse [23] also provide guidance on how DRIFT 3 should be used to model releases of toxic pressure-liquefied gases.

- Assessment of the use of DRIFT for modelling flammable releases

This report presents an assessment of the use of DRIFT 3.6.14 for modelling the dispersion of flammable vapour, considering both releases of flammable pressure-liquefied gases and the dispersion of vapour from pools of flammable liquids. The dispersion of vapour from pools of flammable liquids was previously modelled by HSE in DRIFT 2.31. Liquefied hydrogen and liquefied natural gas (LNG) test cases have been used to assess the effect on the model predictions of changing from DRIFT 2.31 to DRIFT 3.6.14. Continuous flashing releases of flammable substances were previously modelled by HSE using either DRIFT 2.31 (holes in vessels or pipework) or CRUNCH [9] (holes in pipelines). The CRUNCH and DRIFT 3.6.14 predictions have been compared for releases from ethylene and liquefied petroleum gas (LPG) pipelines. Instantaneous flashing releases of flammable substances were previously modelled by HSE in DRIFT 2.31. The effect on the model predictions of changing from DRIFT 2.31 to DRIFT 3.6.14 has been assessed for a selection of isobutane and propane release scenarios. This report also provides guidance on how DRIFT 3 should be used to model the dispersion of flammable vapour.

An assessment of the use of DRIFT 3 for modelling passive releases, including spray releases, is also planned.

1.3 DISPERSION MODELLING USING DRIFT 3

DRIFT 3 has a series of input tabs, onto which information about the conditions of the release, the source geometry and the atmospheric conditions should be entered. These inputs can either be imported from a source term model or directly input by the user.

The user can also input harm criteria of interest, which are used to determine the hazard ranges for the release. For flammable substances the harm criterion is expressed as a fraction of the Lower Flammable Limit (LFL), whereas for toxic substances a concentration or dose of interest should be entered. Within HSE, the target level of interest for flammable substances is normally the LFL.

A large range of outputs is available in DRIFT 3, in both tabular and graphical format. The main outputs of interest to HSE are:

- The variation with downwind distance of the width of the isopleth enclosing the area within which the target level of interest is exceeded; and
- The maximum downwind dispersion distance to the target level of interest.

Further guidance on the model input parameters and on how to run the model and extract results is provided in the DRIFT User Guide [25].

A Hazardous Substances Consent assessment relating to flammable substances considers a number of possible flammable hazards. One hazard that is considered in these assessments is known as a flash fire. A flash fire occurs when a release of flammable material forms a cloud that ignites at some distance from the source of the release. The fire then “flashes” through the flammable region of the cloud. For flash fires, the calculation of LFL isopleths for an appropriate range of release scenarios and weather conditions is required. The downwind extent and maximum half-width of the isopleths are used as inputs to an HSE model, FLIC (FLash fire Ignition Calculator), together with weather data and failure frequencies. FLIC calculates the risk at all points on a grid specified by the user and colour codes the grid according to the risk criterion for each LUP zone. The zones are defined as a risk of receiving a HSE dangerous dose of greater than 10 cpm/yr (chances per million per year) for the inner zone, between 1 cpm/yr and 10 cpm/yr for the middle zone and between 0.3 cpm/yr and 1 cpm/yr for the outer zone. The LUP zones can be plotted on a map and this is used to inform HSE’s Hazardous Substances Consent advice to Hazardous Substances Authorities. The intention is to use DRIFT 3 to calculate the LFL isopleth dimensions used in the risk calculation process.

DRIFT 3 will also be used for the assessment of LUP zones in the vicinity of Major Accident Hazard (MAH) pipelines which fall under the Pipeline Safety Regulations (PSR) [6]. HSE uses a code, MISHAP [26] to model the risks from MAH pipelines. For substances other than natural gas, MISHAP models the effects of flash fire on pipeline failure. The intention is to use DRIFT 3 for the flash fire calculations in MISHAP, in conjunction with weather data, failure frequencies and the outputs from other consequence models to generate LUP zones around the pipeline.

1.4 HSE’S MODELLING METHODOLOGY FOR THE DISPERSION OF FLAMMABLE RELEASES

HSE considers the dispersion of three types of flammable release. These are:

- Evaporating pools from spills of flammable liquids;
- Flashing releases from vessel, pipework, or pipeline holes; and
- Flashing releases from an instantaneous release from a catastrophic failure of a vessel or pipeline.

HSE models the spreading and vaporisation of pools resulting from accidental releases of flammable liquids using the program GASP (Gas Accumulation over Spreading Pools) [15]. The subsequent dispersion of the vapour evolved from the pool has previously been modelled using DRIFT 2.31.

GASP was developed for HSE by ESR Technology. It requires the user to define the nature of the liquid release, the ambient conditions, and the terrain onto which the liquid is spilt. Supplied with this information, GASP can calculate the time evolution of many quantities (including the pool size, pool temperature, vaporisation rate, and the total mass of vapour generated), which are then saved in a format that can be used in DRIFT.

Flashing releases of flammable substances from holes in vessels, pipework, or pipelines are modelled by HSE using an appropriate release rate model to provide the source terms for the dispersion model. For pipelines, the program PipeTech [27] is used to model the release rates for all substances other than natural gas, for which HSE’s in-house model LOSSP is used. Prior to 2014, however, LOSSP or HSE’s other in-house model, LOSSESP were used [26], depending on whether the substance was a gas or a liquid. PipeTech was only used for releases of substances other than natural gas from pipeline ruptures. For other types of release, HSE’s in-house suite of programs to calculate outflow from vessels and pipes, STREAM, is often used. The subsequent dispersion has previously been modelled using DRIFT 2.31 for static sites and CRUNCH [9] for pipelines.

The initial stages of a flashing instantaneous release from a catastrophic failure of a vessel storing a pressure liquefied gas are modelled using ACE (Airborne Concentration Estimate) [28, 29, 30], although

older assessments used the in-house HSE model IRATE. A review by Tickle [31] highlighted areas for improvement within IRATE. One example is that IRATE assumes that the entire inventory becomes airborne and neglects the potential for rainout and pool formation, which are likely to occur in reality. ACE is based on more rigorous science than IRATE and can account for rainout and pool formation. DRIFT 2.31 has previously been used to model the subsequent dispersion based on the ACE or IRATE outputs.

This report describes testing where the results generated from the previous HSE methodologies, using the DRIFT 2.31 or CRUNCH dispersion models, are compared with the results generated from the use of the DRIFT 3.6.14 model. The relevant input assumptions identified earlier in HSE's testing programme [21, 22, 23] have been used during this study. A summary of the recommended standard inputs is given in each of the subsequent sections for each type of release.

1.5 OBJECTIVES

The main objectives of this work were:

- To determine an appropriate methodology for modelling the hazards posed by pools of flammable substances using GASP and DRIFT 3;
- To determine an appropriate methodology for modelling the hazards posed by flashing jet releases of flammable substances using a suitable release rate model and DRIFT 3;
- To determine an appropriate methodology for modelling the hazards posed by flashing releases from an instantaneous release following catastrophic failure of vessels storing pressure liquefied flammable substances using ACE and DRIFT 3; and
- To perform sensitivity tests to ensure that DRIFT 3 works reliably for the types of inputs typically used by HSE for PSR assessment purposes and for the assessment of Hazardous Substances Consent applications relating to flammable substances.

A further aim of this work was to determine the effect that adopting DRIFT 3 would have on land-use-planning decisions. This was achieved by using DRIFT 3 to reassess Hazardous Substances Consent applications or pipeline assessments under PSR, that were originally assessed using DRIFT 2.31 or CRUNCH, and comparing the resulting hazard ranges or LUP distances.

1.6 STRUCTURE OF REPORT

This report presents a comparison of the results generated using DRIFT 3.6.14 with the results obtained using DRIFT 2.31, the version previously used within HSE for flammable substance assessments. A comparison is also given of the results obtained using DRIFT 3.6.14 with the results from the CRUNCH dispersion model, for assessing accidental releases from pipelines transporting flammable substances. This report is structured as follows:

- Section 2 considers the impacts of the new model on the assessment of evaporating pools from spills of flammable liquids. Consent applications for LNG (liquefied natural gas) and liquid hydrogen that were originally assessed using GASP and DRIFT 2.31 are reassessed using GASP and DRIFT 3.6.14. The hazard ranges, given by the crosswind variation with downwind distance to the LFL (Lower Flammable Limit) envelope, obtained in the original assessments have been compared to those obtained from the reassessments. This is to determine the impact that adopting DRIFT 3 would have on HSE's land-use-planning advice. Possible reasons for the differences between the predicted hazard ranges are discussed, such as the use of different mathematical models, release types, and modelling assumptions.

- Section 3 describes the impact of the new model on the assessment of flashing jet releases of flammable substances. A PSR assessment for a flashing release from a hole in an ethylene pipeline is reassessed using DRIFT 3.6.14 where the PipeTech and LOSSP models are used to calculate the flow rates. A similar assessment for an LPG pipeline is reassessed using DRIFT 3.6.14 where PipeTech and LOSSESP are used to calculate the flow rates. A compressor station siting policy assessment that was originally modelled using DRIFT 3.6.5 has been modelled using DRIFT 3.6.14.
- Section 4 considers flashing releases from an instantaneous release from catastrophic failure of vessels storing pressure liquefied flammable substances. It gives the details of reassessments of consent applications for *o*-cresol, isobutane and propane. In the original assessments, IRATE was used to model the source terms with DRIFT 2 or DRIFT 3.6.4 used to model the toxic effects of an accidental release. In the reassessments, comparisons have been performed using both IRATE and ACE 3.11 to provide the inputs to DRIFT 3.6.14.
- The conclusions from this work are presented in Section 5.

2 MODELLING EVAPORATING POOLS FROM SPILLS OF FLAMMABLE SUBSTANCES

2.1 INTRODUCTION

The hazards posed by the evolution of vapour from a pool of flammable liquid and its subsequent dispersion were previously assessed by HSE using GASP and DRIFT 2.31. Two consent applications for which this methodology was used have been reassessed using DRIFT 3.6.14. The hazard ranges obtained in the original assessments and the reassessments have been compared to determine the impact that adopting DRIFT 3 would have on HSE's land-use-planning advice. Possible reasons for the differences between the predicted hazard ranges, such as the use of different mathematical models, release types and modelling assumptions, are discussed.

When comparing plots of DRIFT 2.31 results to DRIFT 3.6.14 results, it should be noted that, for DRIFT 2.31, the maximum downwind and crosswind extents are used to form an isopleth of two half ellipses, which are joined along their major axes. The DRIFT 3.6.14 plots, in contrast, display the calculated crosswind extents at each downwind distance and represent the actual shape of the cloud predicted by the model as opposed to an idealised shape.

2.2 METHODOLOGY

Recent consent applications for liquefied natural gas (LNG) and liquefied hydrogen have been reassessed using DRIFT 3.6.14.

Each scenario was initially reassessed in DRIFT 3.6.14 using input values chosen to replicate the assumptions used in DRIFT 2.31 as closely as possible. One exception to test improved modelling in DRIFT 3 is that the release type has been set to the finite duration option for the runs carried out using DRIFT 3. This option is unavailable in DRIFT 2.31, where only the steady continuous option (a steady state release) can be modelled for a continuous release from a vessel or pipework. The basic equations are the same for the steady continuous model and the finite duration model but the cloud is treated differently in post-processing by DRIFT 3. The finite duration model includes dilution of the leading and trailing edges of the plume, which means that the cloud spreads longitudinally as it travels downwind rather than remaining as a steady state plume with passage time equal to the release duration. In effect, the finite duration model can be thought of as gradually eroding a steady continuous 'core'. The effect of this is that, in the far field (i.e. some distance from the source) the concentration predicted by the finite duration model will decay more rapidly than that predicted by the continuous model.

DRIFT 3.6.14 also contains a time varying model that can model different stages of the release, such as an initial peak in the vaporisation rate. This is not considered in the finite duration model, which uses a mean vaporisation rate across the duration of the run. The time varying model in DRIFT 3.6.14 has not yet undergone thorough evaluation and also does not produce a solution for all scenarios. For these reasons, it is not currently used in Hazardous Substances Consent assessments, but it may be used for comparison purposes.

To replicate the DRIFT 2.31 settings, the pool roughness length in GASP was set to 0 m. Additional runs were undertaken using DRIFT 3.6.14 where the pool roughness length was set to 0.00023 m, which is the recommended value for use in GASP for HSE assessments. The use of the recommended pool roughness length is discussed further in Section 2.4.2.

The remaining assumptions made for the DRIFT 3 modelling are those detailed by Cruse et al. [21]. The recommended input values are listed in Table 1.

Table 1 Recommended input values for use in DRIFT 3 for evaporating pools of flammable chemicals

Input	Recommended value in DRIFT 3
Release type	Finite duration
Phase	As imported from DIN file or GASP file
Substance, temperature and contaminant fraction	As imported from DIN file or GASP file
Release rate	As imported from DIN file or GASP file, except for 'peaky' releases of substances. In such cases, refer to the method described in Section 2.2.
Release duration	For 'non-peaky' releases, the release duration should be set to 1800 s or the pool lifetime if shorter. For 'peaky' releases, the release duration should be set to the time that ensures mass is conserved.
Location	(0,0,0) (z = 0 m corresponds to ground level)
Source type	Low momentum area source
Source diameter	As imported from DIN file or GASP file
Include dilution over source	Yes
Weather scheme	Pasquill
Input inversion height	No (the model determines this from a look-up table when the Pasquill weather scheme is selected)
Temperature	288.15 K (D); 278.15 K (F)
Relative humidity	60%
Reference height	10 m
Roughness length	0.1 m (rural); 0.3 m (urban)
Wind angle from North ¹	270° (towards the positive x direction)
Pasquill stability	D (day) or F (night)
Wind speed ²	F2.4, D2.4, D4.3 & D6.7
User input flammability limits	No as these should be read in automatically from the SPI file
Levels of interest	Lower Flammable Limit (LFL)

¹In DRIFT 3, the wind direction is defined as the direction from which the wind is blowing. This is the convention used by the Met Office. In EJECT (the jet model used in conjunction with DRIFT 2.31), the wind direction is defined as the direction towards which the wind is blowing. DRIFT 3 automatically corrects for this when opening a legacy file.

²Historically, flammable assessments have been performed using D5 and F2 weather, where the letter represents the Pasquill stability class and the number is the wind speed in metres per second at a reference height of 10 m. The comparisons in this report have used these values.

For some scenarios, the maximum vaporisation rate output from GASP is at least twice the mean vaporisation rate calculated over the release duration. These releases tend to have a short duration rise to a peak vaporisation rate that then quickly falls to a continuous steady state vaporisation rate for the remainder of the release. This type of release source term is referred to as a 'peaky' release by HSE. This is to distinguish these scenarios from a release where the mean vaporisation rate remains relatively constant over the duration of the release, with only a slight increase seen in the initial stages; HSE describes such releases as 'non-peaky' releases.

When the HSE 'peaky' criteria were met, sensitivity tests were carried out using a 'peaky' methodology to determine the source term that should be used from the GASP outputs in the DRIFT 3 model. This 'peaky' methodology involves looking at the graphical output, given by GASP, showing the vaporisation rate over the duration modelled. This graphical output also shows a steady state mean vaporisation rate that would result in the same amount of material evolving from the pool over the entire release duration.

Using the GASP outputs, a user can calculate at what time (T_{2c}) the vaporisation rate falls below the steady state mean vaporisation rate after the initial peak. This allows the user to recalculate the DRIFT source term obtained from GASP. The T_{2c} time is used to calculate a revised mean vaporisation rate that conserves the total mass released (i.e. the total mass of release is divided by T_{2c}). The revised rate is checked against the peak vaporisation rate reported by GASP. If the revised rate is greater than the peak, it is capped at the peak vaporisation rate and the time is recalculated, using the peak vaporisation rate, to ensure that the mass is conserved. The revised mean flow rate and the revised time are used as the release rate and release duration inputs within DRIFT. Tests were also undertaken for these cases using the time varying model within DRIFT 3.6.14, which models the release by dividing the release into a specified number of time segments. Each of the segments is modelled using the finite duration model and the results are combined to produce the complete dispersion results. As explained previously, the time varying model is not currently recommended for use in Hazardous Substances Consent assessments.

Figure 1 illustrates how a 'peaky' release appears in GASP. The red line is the mean vaporisation rate and the point at which the curve crosses this point (approximately 500 s in this case) is T_{2c} . Figure 2 shows how a 'non-peaky' release can appear in GASP. The curve may not always be continually increasing, as in this example, but may gradually increase before gradually decreasing again. No sharp peak is seen, however, and the maximum vaporisation rate never reaches twice the mean vaporisation rate.

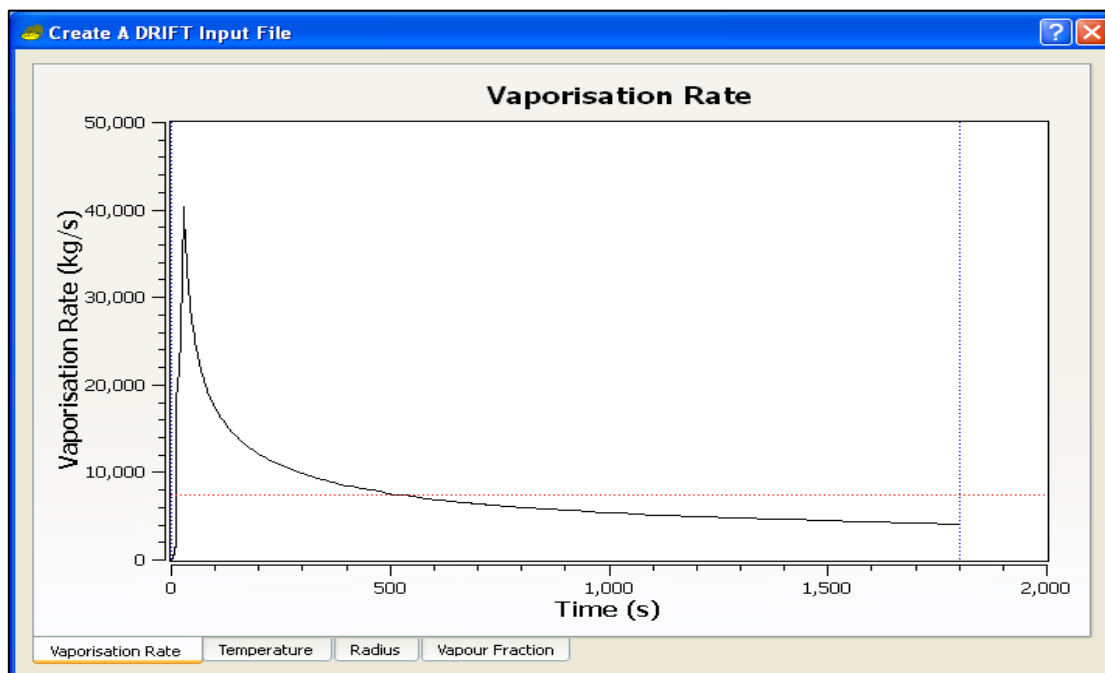


Figure 1 Example of a 'peaky' release from GASP

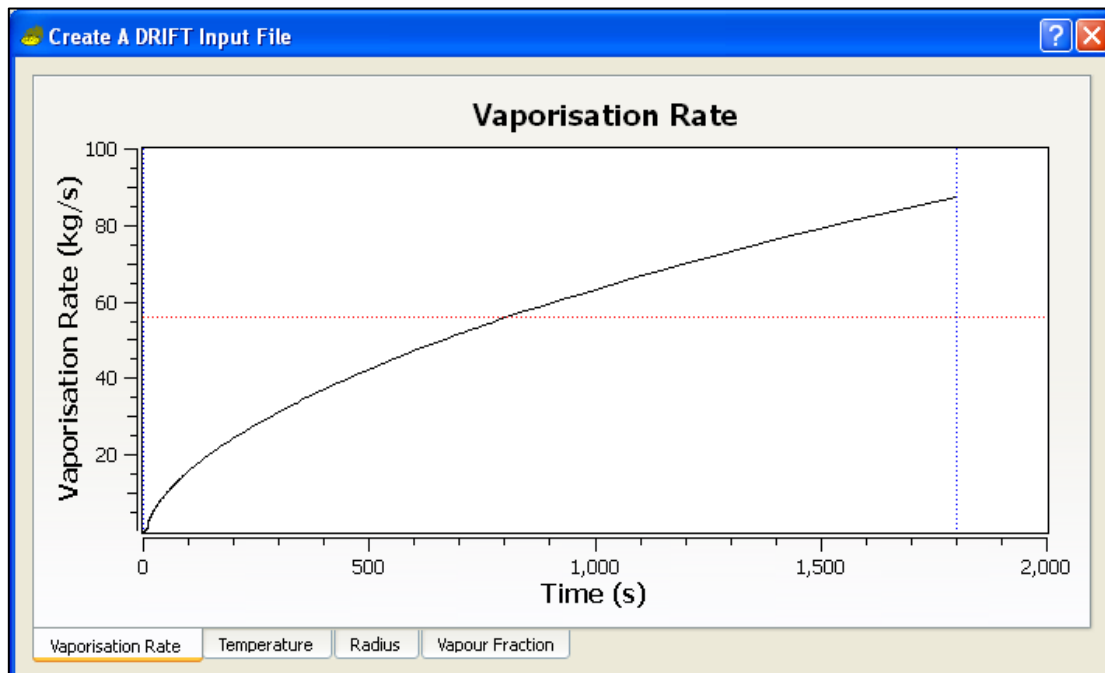


Figure 2 Example of a ‘non-peaky’ release from GASP

DRIFT 3 has the option of obtaining information from DRIFT input (DIN) files or using GASP output (GASP) files. Both of these file types can be output by GASP. If the release meets the criterion to be modelled using the ‘peaky’ methodology then the information must be read in via the DIN file and the release duration must be adjusted by the user to allow for the mass conservation of the release.

Results from DRIFT 3 are normally output along the centreline height. This is a line through the centre of the cloud, rather than at a specific receiver height, and the actual height may vary with horizontal distance, depending on the shape of the cloud. The reported downwind and crosswind extents are the distances along the centreline mapped to the horizontal plane representing the ground. These distances can be larger than if the outputs are reported at a specific receiver height. In certain circumstances, a different reporting height may be more appropriate. These cases have been highlighted in the report.

For some scenarios, a direct comparison between the DRIFT 2.31 and DRIFT 3.6.14 outputs was not possible. In DRIFT 2.31, the source dimension predicted by GASP is assumed to apply only in the crosswind direction, resulting in a line source. For a dense gas release with a low plume velocity, such a source is unstable (and unphysical) and DRIFT 2.31 cannot run using the source dimensions and vaporisation rate predicted by GASP. In such cases, DRIFT 2.31 can be forced to run by manually editing the plume velocity and the roughness length. In the original DRIFT 2.31 assessments considered here, this process was carried out for some of the releases. However, the edited source term may no longer be a good representation of the actual release. DRIFT 3 contains an improved sub-model for low momentum area sources, which includes the effects of upwind spreading. As a result, scenarios that would not run in DRIFT 2.31 usually run in DRIFT 3 without difficulty.

DRIFT 2.31 has generally been run using both the continuous and instantaneous options to model particular continuous release scenarios. This is because the steady continuous (steady state) model is more applicable in the near field (i.e. close to the release point), whilst the instantaneous model is more applicable in the far field (i.e. some distance from the release point). The choice of which model is appropriate is determined by the Britter McQuaid criteria [32]. It is not necessary to run both the continuous and instantaneous models in DRIFT 3 as the finite duration model in DRIFT 3 allows more realistic modelling of continuous releases. When the cloud travel time is much greater than the release duration, the concentration profiles of the finite duration model tend to those of the instantaneous model after the release has ceased. This condition is met if the observer is positioned far from the source. When there is a long release time

compared with the cloud travel time, the concentration profiles of the finite duration model tend to those of the steady continuous model. The finite duration model has been used for all DRIFT 3 runs in this section, unless stated otherwise.

A full list of the GASP and DRIFT input values used in the original assessments and the reassessments is provided in Section 6.1 in the Appendices. The values of the LFL for each substance are given in Section 6.4 in the Appendices.

2.3 LIQUEFIED HYDROGEN ASSESSMENT

A consent application for the storage of 8.5 tonnes of hydrogen in mobile cryogenic pressure containers was reassessed to test a liquefied flammable gas that is potentially buoyant. The liquefied hydrogen is contained in either a Hydra road tanker (a liquid hydrogen tanker which can off-load hydrogen in liquid or gaseous form by pressure discharge from an electrically driven high pressure pump) containing 3.39 tonnes, or in a liquid hydrogen tanker containing 3.5 tonnes. The request for storage of 8.5 tonnes was to provide contingency for expansion in the future, which would not have been possible without further physical modifications to the site.

The instantaneous release scenario was taken as the catastrophic failure of the tanker containing 3.5 tonnes of liquefied hydrogen. The continuous release scenario was modelled as a 50 mm hole in the same tanker. It is not stated how the release rate for this scenario was calculated, but it is given as 14.3 kg/s for a duration of 245 seconds.

In the original assessment, GASP 4.0 was used to model the vaporisation of hydrogen, and the subsequent dispersion of the vapour was modelled in DRIFT 2.31. The DIN files have been recreated in GASP 4.2.12, the current version of GASP used by HSE. There are only minor differences observed in the output from the two versions of GASP. In the original assessment, “windy” weather was considered, as well as the standard F2 and D5 conditions. Four atmospheric scenarios were therefore run: F2, D5, D10 and D15. The D10 and D15 weather conditions were modelled as well as the normal D5 and F2 conditions, as buoyant lift off of a cloud is considered less likely at higher wind speeds. Modelling high wind speeds in the assessment ensures that scenarios that could harm a receiver at ground level are being considered.

DRIFT 2.31 predicts that the cloud becomes buoyant and lifts off the ground for all F2 and some D5 scenarios that were successfully run by the model. Only cases without buoyant lift off were included in the risk calculations in the original assessment. Buoyant lift off occurred for a catastrophic failure of the tanker for F2 and D5 weather conditions, for both the instantaneous and continuous releases when modelled by DRIFT 2.31. For D10 and D15 weather, lift off of the cloud occurred when modelling an instantaneous release, but not when modelling a continuous release. The continuous release outputs for these weather categories were therefore used for modelling catastrophic vessel failure releases in the original assessment. For the releases from 50 mm vessel holes, it was found that DRIFT 2.31 would not run as a continuous release when modelled in F2 weather.

The inputs for DRIFT 3.6.14 have been obtained by directly importing the GASP output file. The finite duration model has been used and the results compared to the steady continuous model in DRIFT 2.31. For most scenarios the cloud is buoyant and lifts off the ground. DRIFT 3.6.14 was run successfully for all the scenarios modelled for this assessment. Sensitivity studies have been performed looking at the effect of using the centreline height maximum cloud distance compared with using different receiver heights on the maximum downwind distance to the Lower Flammable Limit (LFL) output by DRIFT 3. This is to ascertain what options should be considered for buoyant releases.

When the cloud is buoyant, the downstream distances are reported as opposed to downwind distances. The downstream distances represent the path through the cloud, either along the centreline or up to a specified height. These distances are longer than the downwind distance, which is the horizontal distance that the cloud travels. When the cloud is not buoyant, the downwind and downstream distances are

approximately the same. In this section, the downstream distance has been shown on the graphs for all cases, both buoyant and non-buoyant, for consistency.

2.3.1 Lower Flammable Limit (LFL) isopleths in F2 weather conditions

Figure 3 shows the LFL isopleths obtained for a release from the catastrophic failure of a vessel storing liquefied hydrogen in F2 weather conditions. For this scenario, DRIFT 3.6.14 predicts that the cloud does not lift off the ground. Isopleths are only available for the DRIFT 3.6.14 results as DRIFT 2.31 was unable to run this scenario.

Further investigation has shown that the cloud should lift off in F2 weather conditions. This has been corrected in DRIFT 3.7, which will replace DRIFT 3.6.14 once it has undergone full testing. The changes to the calculated downstream distances are relatively small and so the impact of changing model versions would be minor.

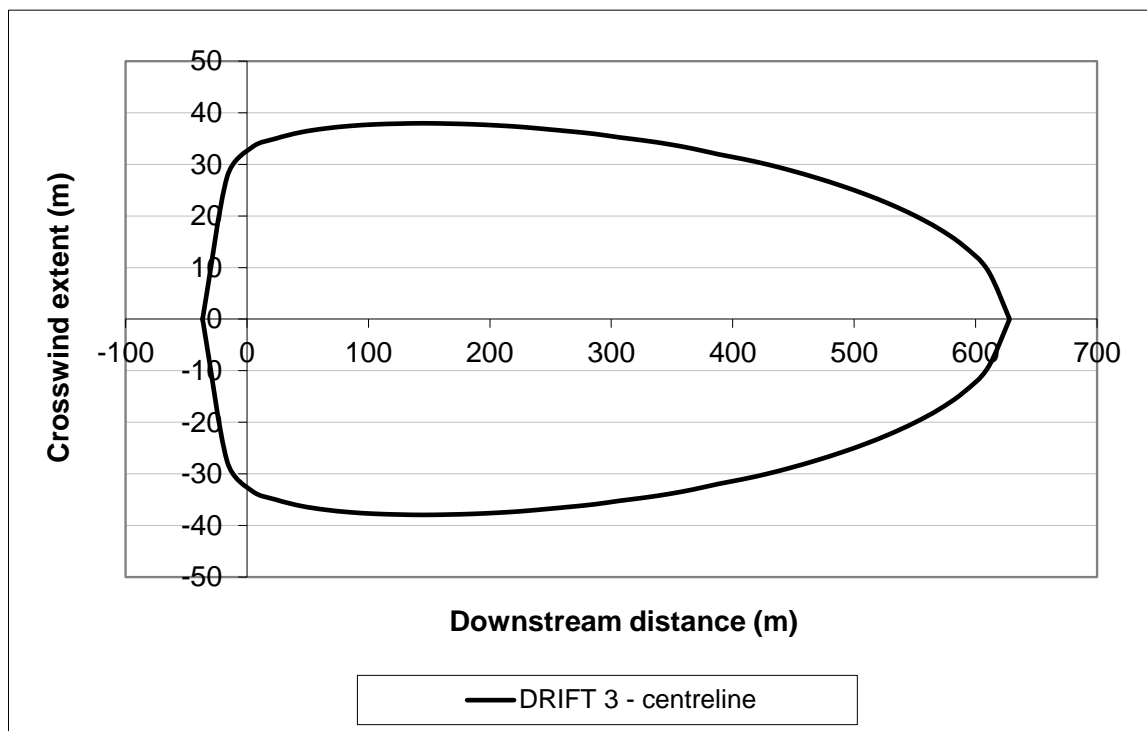


Figure 3 LFL isopleths obtained at the centreline height for a liquefied hydrogen release from a catastrophic vessel failure in F2 weather conditions

The LFL isopleths obtained for a release of liquefied hydrogen through a 50 mm vessel hole in F2 weather conditions are shown in Figure 4. DRIFT 2.31 was unable to run this scenario so only results from DRIFT 3.6.14 are presented. The cloud is buoyant and lifts off the ground. There is a possibility that only considering scenarios without buoyancy lift off, as assumed in the original assessment, may not be the most appropriate method for dealing with such releases. The effects of varying the receiver height have therefore been investigated to check the validity of this assumption. Figure 4 displays the isopleths using the centreline height of the cloud together with receiver heights of 0 m, 2 m, 5 m, 10 m and 20 m. A receiver height of 50 m was also investigated but the cloud outputs generated by DRIFT 3 did not reach this height.

Figure 4 shows that using a specific receiver height rather than the centreline distance reduces the maximum downstream extent of the LFL isopleth generated by the model. The maximum downstream extent (downstream distance on the graph) is approximately 70 m, if the centreline height in DRIFT 3 is used, compared to just under 40 m if a receiver height of 2 m is used to generate the output from DRIFT 3.

The exact values are given in Table 2 (where 'NR' indicates no result) and are 68 m for the centreline height and 39 m for a receiver height of 2 m.

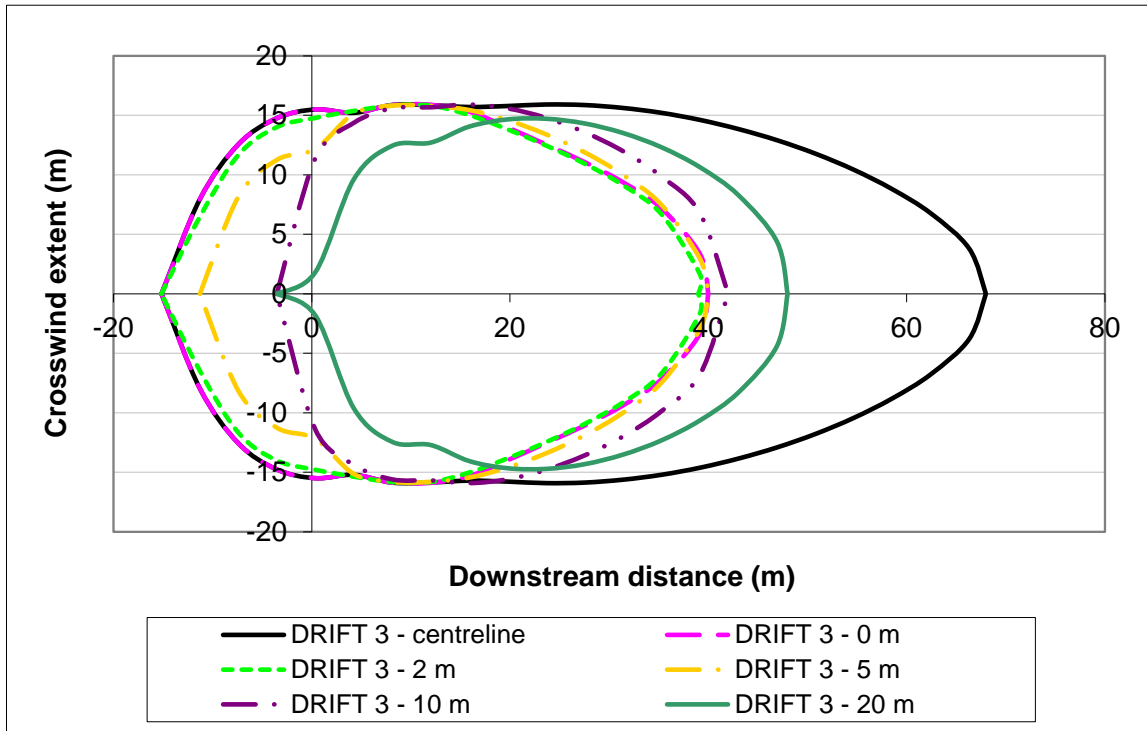


Figure 4 LFL isopleths obtained for a liquefied hydrogen release through a 50 mm vessel hole in F2 weather conditions for a range of receiver heights

Table 2 Maximum downstream distances to the LFL for a catastrophic failure of a liquefied hydrogen tanker and a release through a 50 mm vessel hole in F2 weather conditions

<i>Model – receiver height</i>	<i>Maximum downstream distance to the LFL (m)</i>	
	<i>Catastrophic</i>	<i>50 mm hole</i>
DRIFT 2 – Centreline	NR	NR
DRIFT 3 – Centreline	628	68
DRIFT 3 – 0 m	N/A	40
DRIFT 3 – 2 m	N/A	39
DRIFT 3 – 5 m	N/A	40
DRIFT 3 – 10 m	N/A	42
DRIFT 3 – 20 m	N/A	48
DRIFT 3 – 50 m	N/A	N/A

NR indicates no result obtained

N/A indicates that either the cloud did not lift off the ground or that it did not reach the specified height

2.3.2 Lower Flammable Limit (LFL) isopleths in D5 weather conditions

Figure 5 shows the extent of the LFL isopleth obtained for a catastrophic failure of a liquefied hydrogen tanker in D5 weather conditions. DRIFT 3 models the cloud as buoyant for this scenario, with lift off from the ground predicted by the model as illustrated in Figure 6. The effects of different receiver heights on the LFL extent are shown in Figure 5. Isopleths are only available for the DRIFT 3.6.14 results, as DRIFT 2.31 was unable to run this scenario.

Figure 5 shows that the maximum downstream distance to the LFL is larger if calculated at the centreline height than if calculated at the receiver heights modelled between 0 m and 50 m. This shows that the cloud centreline height rises higher than 50 m (it actually approaches 90 m as can be seen from Figure 6). The distances to the maximum downstream LFL extent are 221 m for the centreline height, down to 177 m at receiver heights of 0 m or 2 m.

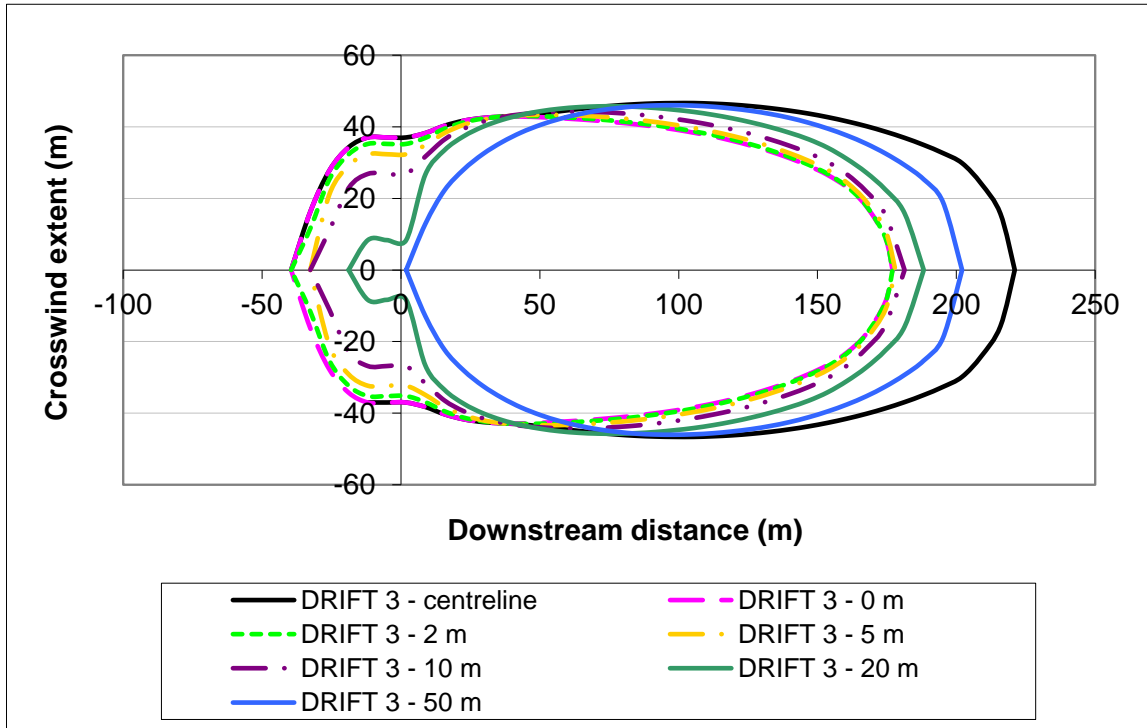


Figure 5 LFL isopleths obtained for a liquefied hydrogen release from a catastrophic vessel failure in D5 weather conditions for a range of receiver heights

It can be seen from Figure 6 that the cloud only extends to a distance of approximately 200 m downwind. As the cloud is buoyant, the centreline distance is longer than this distance (221 m), making it appear that the cloud extends further than it actually does (note that for non-buoyant clouds, the centreline distance and the downwind distance are approximately the same). In flash fire modelling, a person is assumed to receive harm if they are within the cloud envelope but are relatively unaffected outside of this distance. In this example, if the person is at a distance of 220 m from the release point, i.e. they are within the centreline distance, they are not actually within the cloud envelope and so are unlikely to suffer much harm. From a modelling point of view, however, if the centreline distance is used to define the cloud extent, then the person will be considered to be within the flash fire envelope and will be harmed. The use of the centreline distance for flash fire modelling of buoyant releases is therefore cautious.

One point to note from Figure 6 is that there appears to be a discontinuity around a downwind distance of 0 m i.e. close to the release point. Contouring can be problematic in integral models such as DRIFT with complex concentration profiles and cloud trajectories. The apparent discontinuity close to the release point is due to the superposition of the assumed initial cloud over the source at $t = 0$ s, and the subsequent steady plume that moves away from the source. It is caused by the model transition from the ground area source to the plume.

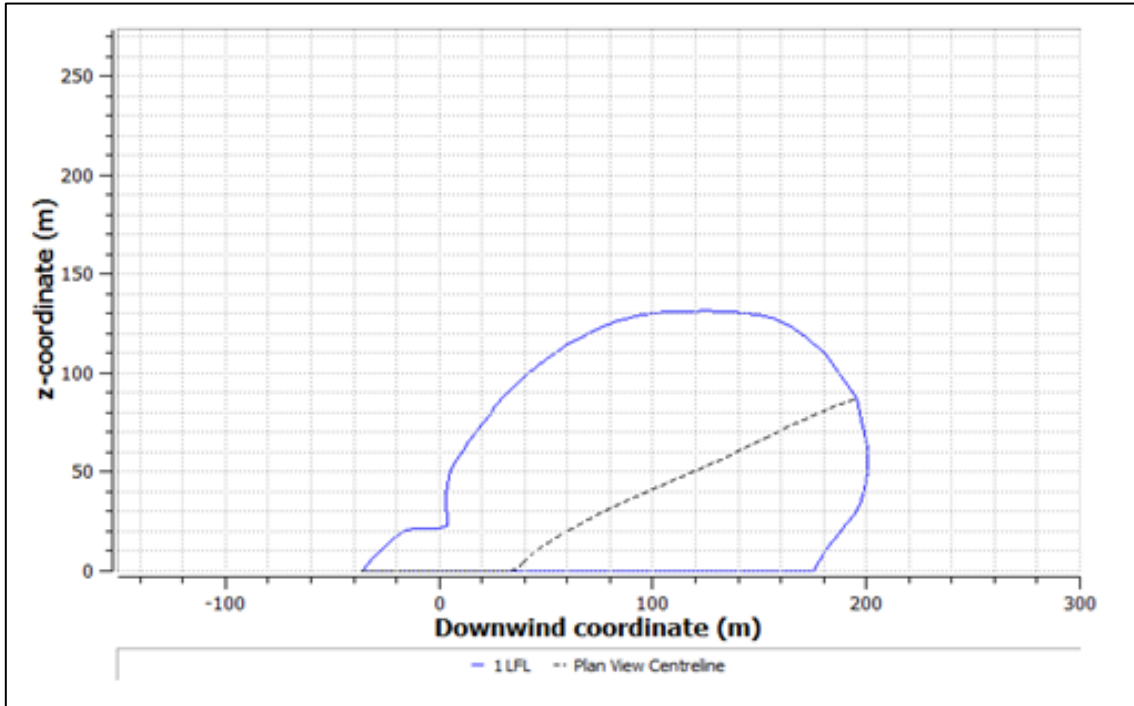


Figure 6 DRIFT 3.6.14 elevation plot for a liquefied hydrogen release from a catastrophic vessel failure in D5 weather conditions

The LFL isopleth obtained for a release of liquefied hydrogen modelled through a 50 mm vessel hole in D5 weather conditions is shown in Figure 7. As DRIFT 3 predicts the cloud will be buoyant, the effects of varying the receiver height have been investigated. Figure 7 displays the isopleths using the centreline height of the cloud together with receiver heights of 0 m, 2 m, 5 m, 10 m and 20 m. There is no isopleth at a receiver height of 50 m as the cloud does not extend to this height. Results are given for modelling a continuous release in DRIFT 2.31 for comparison.

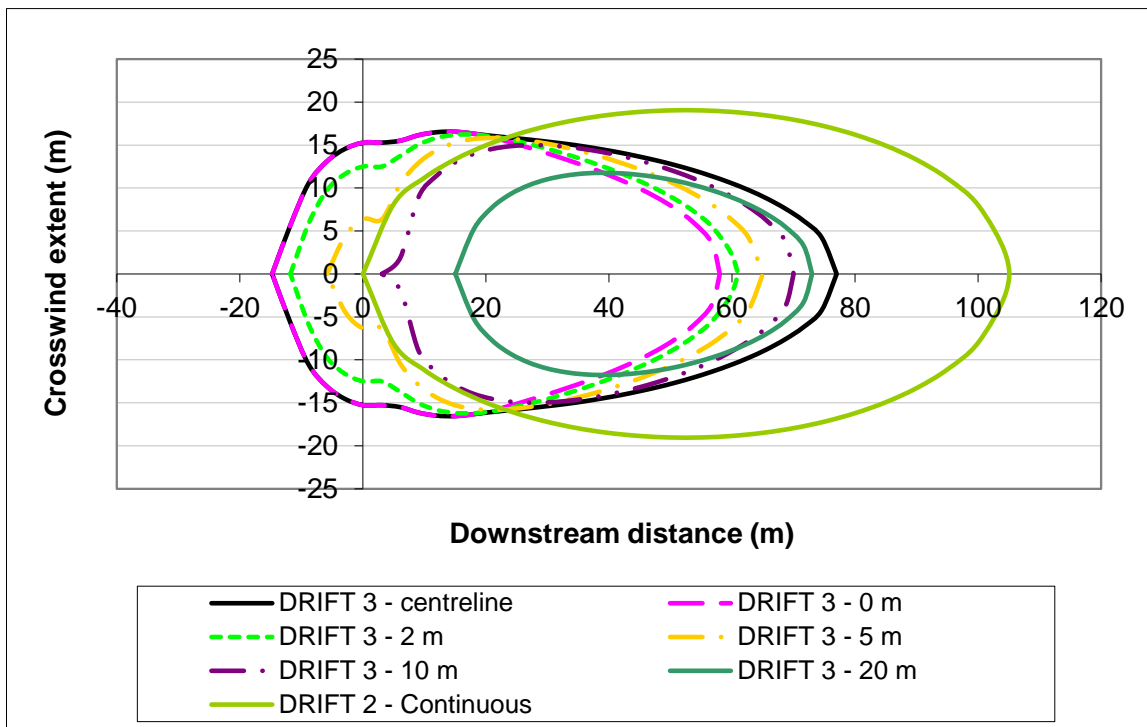


Figure 7 LFL isopleths obtained for a liquefied hydrogen release through a 50 mm vessel hole in D5 weather conditions for a range of receiver heights

DRIFT 3.6.14 predicts a significantly smaller maximum downstream LFL extent than DRIFT 2.31 for this scenario. The distances are given in Table 3. The longest maximum LFL distance generated using DRIFT 3.6.14 is 77 m using the centreline height and the shortest is 58 m using a receiver height of 0 m, whilst DRIFT 2.31 predicts a distance of 105 m. DRIFT 2.31 does not predict an upwind component to the release, unlike DRIFT 3.6.14, which is likely to explain part of the difference observed between the results from the two models.

Table 3 shows the maximum downstream distances to the LFL obtained for the different releases modelled.

Table 3 Maximum downstream distances to the LFL for a catastrophic failure of a liquefied hydrogen tanker and a release through a 50 mm vessel hole in D5 weather conditions

<i>Model – receiver height</i>	<i>Maximum downstream distance to the LFL (m)</i>	
	<i>Catastrophic</i>	<i>50 mm hole</i>
DRIFT 2 – Centreline	NR	105
DRIFT 3 – Centreline	221	77
DRIFT 3 – 0 m	177	58
DRIFT 3 – 2 m	177	61
DRIFT 3 – 5 m	178	65
DRIFT 3 – 10 m	181	70
DRIFT 3 – 20 m	188	73
DRIFT 3 – 50 m	202	N/A

NR indicates no result obtained

N/A indicates that either the cloud did not lift off the ground or that it did not reach the specified height

2.3.3 Lower Flammable Limit (LFL) isopleths in D10 weather conditions

Figure 8 shows the LFL isopleths obtained for a catastrophic failure of a liquefied hydrogen tanker in D10 weather conditions from both DRIFT 2.31 and DRIFT 3.6.14. DRIFT 2 did not model this scenario as buoyant; however, DRIFT 3.6.14 predicts a buoyant cloud that lifts off the ground. The effects of varying the receiver height on the downstream LFL extents are shown in the figure, with heights of 0 m, 2 m, 5 m, 10 m, 20 m and 50 m considered.

Figure 8 for the catastrophic failure of the tanker illustrates that the isopleths obtained using DRIFT 2.31 are considerably larger than those obtained using DRIFT 3.6.14 and that they do not extend upwind. The maximum downstream distance to the LFL increases as the receiver height increases. The actual distances are shown in Table 4, along with the equivalent distances from a 50 mm vessel hole. From the table it can be seen that, for the catastrophic release, DRIFT 2 produces a maximum downstream distance to the LFL that is 119 m larger than the maximum downstream distance predicted by DRIFT 3.6.14 at the centreline height. This in turn is 71 m longer than if a receiver height of 0 m is used.

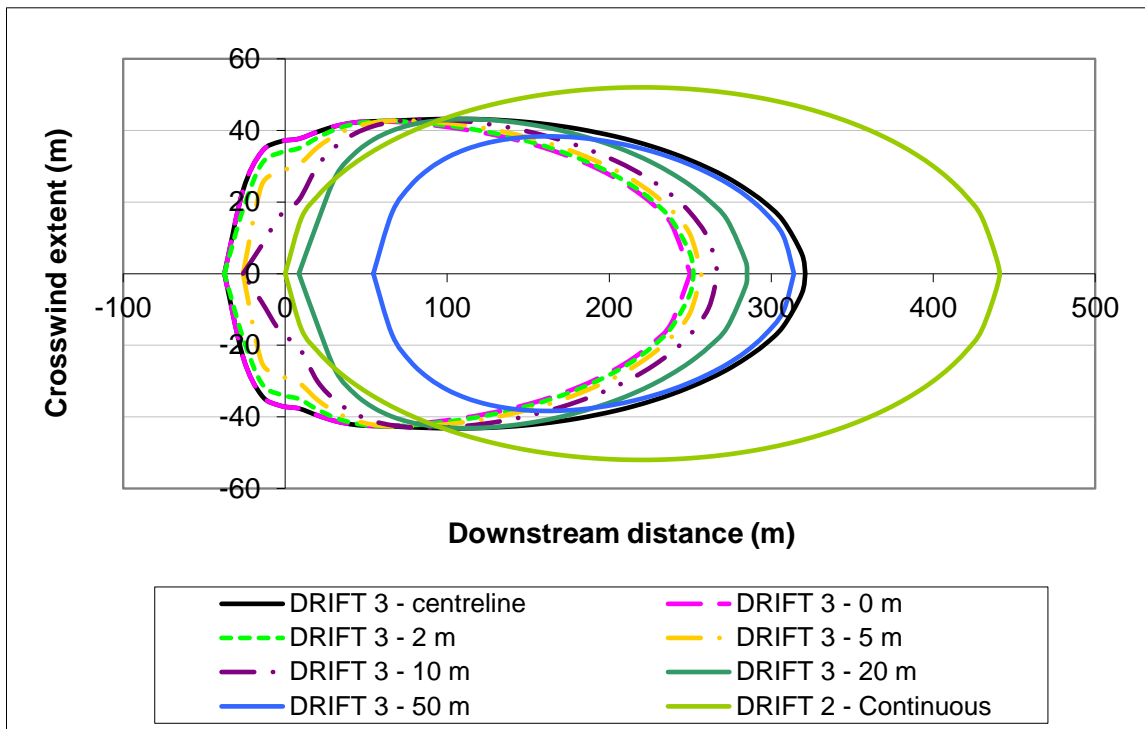


Figure 8 LFL isopleths obtained for a liquefied hydrogen release from a catastrophic vessel failure in D10 weather conditions for a range of receiver heights

The LFL isopleths obtained for a release of liquefied hydrogen through a 50 mm vessel hole in D10 weather conditions are shown in Figure 9. As DRIFT 3.6.14 predicts that the cloud will be buoyant, the effects of varying the receiver height have been investigated. Figure 9 displays the isopleths using the centreline height of the cloud together with receiver heights of 0 m, 2 m and 5 m. The cloud does not extend to a height of 10 m and hence further receiver heights have not been considered.

Figure 9 shows that for the 50 mm vessel hole, the DRIFT 2 contour is larger than any of the DRIFT 3 contours generated, and that the DRIFT 2 output does not extend upwind, whereas the DRIFT 3 isopleth does extend upwind. There is a negligible difference between the maximum downstream distance to the LFL using the centreline height in DRIFT 3 and the equivalent distance using differing receiver heights. This suggests that the cloud remains near the ground. The maximum downstream distances to the LFL obtained for the different releases modelled are given in Table 4.

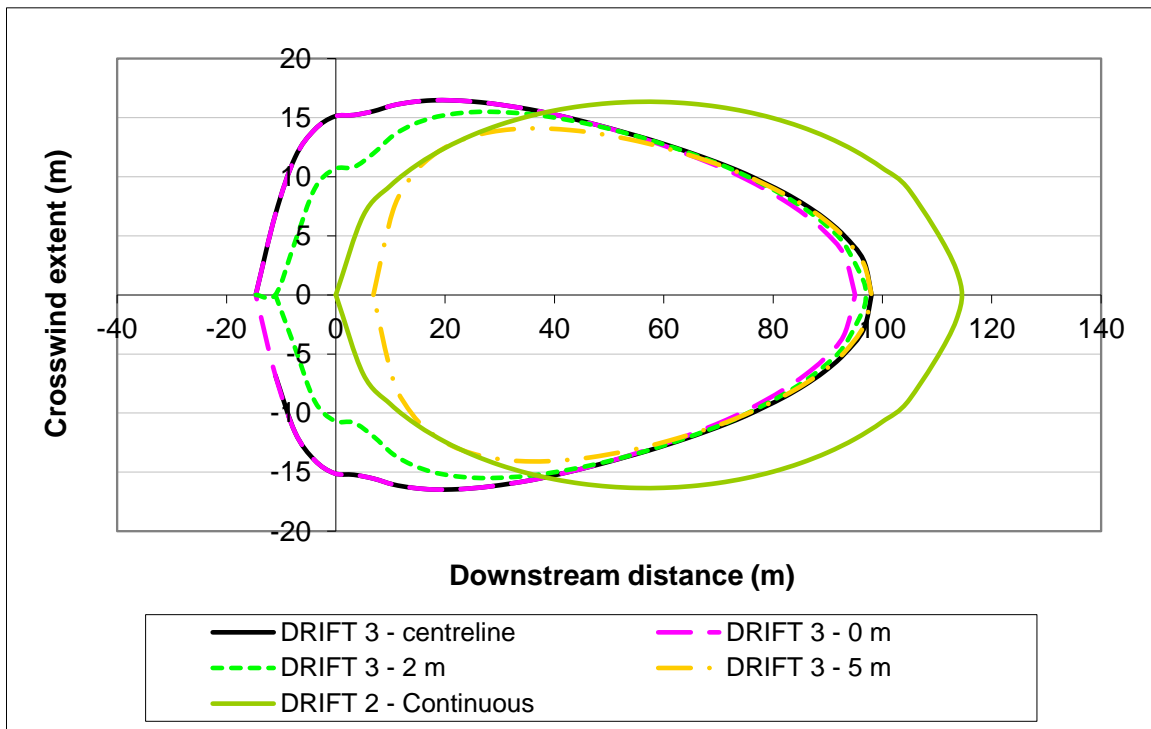


Figure 9 LFL isopleths obtained for a liquefied hydrogen release through a 50 mm vessel hole in D10 weather conditions for a range of receiver heights

Table 4 Maximum downstream distances to the LFL for a catastrophic failure of a liquefied hydrogen tanker and a release through a 50 mm vessel hole in D10 weather conditions

<i>Model – receiver height</i>	<i>Maximum downstream distance to the LFL (m)</i>	
	<i>Catastrophic</i>	<i>50 mm hole</i>
DRIFT 2 – Centreline	440	114
DRIFT 3 – Centreline	321	98
DRIFT 3 – 0 m	250	95
DRIFT 3 – 2 m	252	97
DRIFT 3 – 5 m	257	98
DRIFT 3 – 10 m	267	N/A
DRIFT 3 – 20 m	285	N/A
DRIFT 3 – 50 m	314	N/A

N/A indicates that either the cloud did not lift off the ground or that it did not reach the specified height

2.3.4 Lower Flammable Limit (LFL) isopleths in D15 weather conditions

Figure 10 shows the LFL isopleths obtained for a catastrophic failure of a liquefied hydrogen tanker in D15 weather conditions for both DRIFT 2.31 and DRIFT 3.614. DRIFT 2 did not model this scenario as buoyant; however, DRIFT 3.6.14 predicts a buoyant cloud that lifts off the ground. The effects of varying the receiver height on the maximum downstream distance to the LFL are shown in the figure.

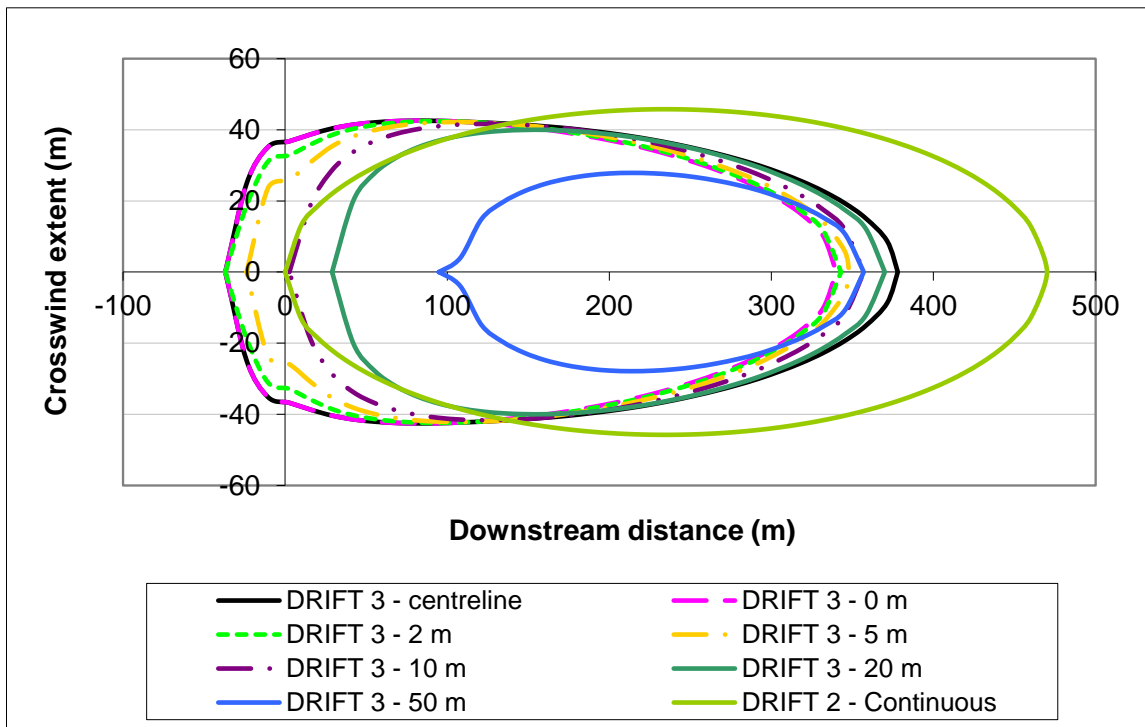


Figure 10 LFL isopleths obtained for a liquefied hydrogen release from a catastrophic vessel failure in D15 weather conditions for a range of receiver heights

The LFL isopleths obtained for a release of liquefied hydrogen through a 50 mm vessel hole in D15 weather conditions are shown in Figure 11. In this case, the cloud does not lift off and so isopleths are displayed for DRIFT 2.31 and the centreline height in DRIFT 3.6.14 only. This confirms the assumption in the original assessment that, as the wind speed increases, the effect of buoyancy decreases. This is due to the increased wind velocity in effect flattening the cloud as the cloud’s vertical velocity will be significantly lower than the horizontal wind speed.

As seen for the other wind speeds investigated, the results from DRIFT 2.31 indicate that the cloud is predicted to extend further downstream than when DRIFT 3.6.14 is used. DRIFT 2 does not model an upwind extent for the cloud, whereas DRIFT 3 does model an upwind extent to the LFL. This is true for both the catastrophic tanker failure and the release from a 50 mm vessel hole. For the release from the catastrophic tanker failure the DRIFT 3 results equate to a reduction of approximately 24% in the downstream LFL extent of the cloud when compared to the DRIFT 2 outputs. There is also a significant difference in the downstream distance to the LFL if a receiver height of 0 or 2 m is used in this case, rather than generating the outputs at the centreline height of the cloud. For the 50 mm vessel hole release, the reduction in the downstream LFL extent is over 30% when comparing the DRIFT 3 outputs to those obtained from DRIFT 2. The maximum downstream distances to the LFL output by the models are given in Table 5.

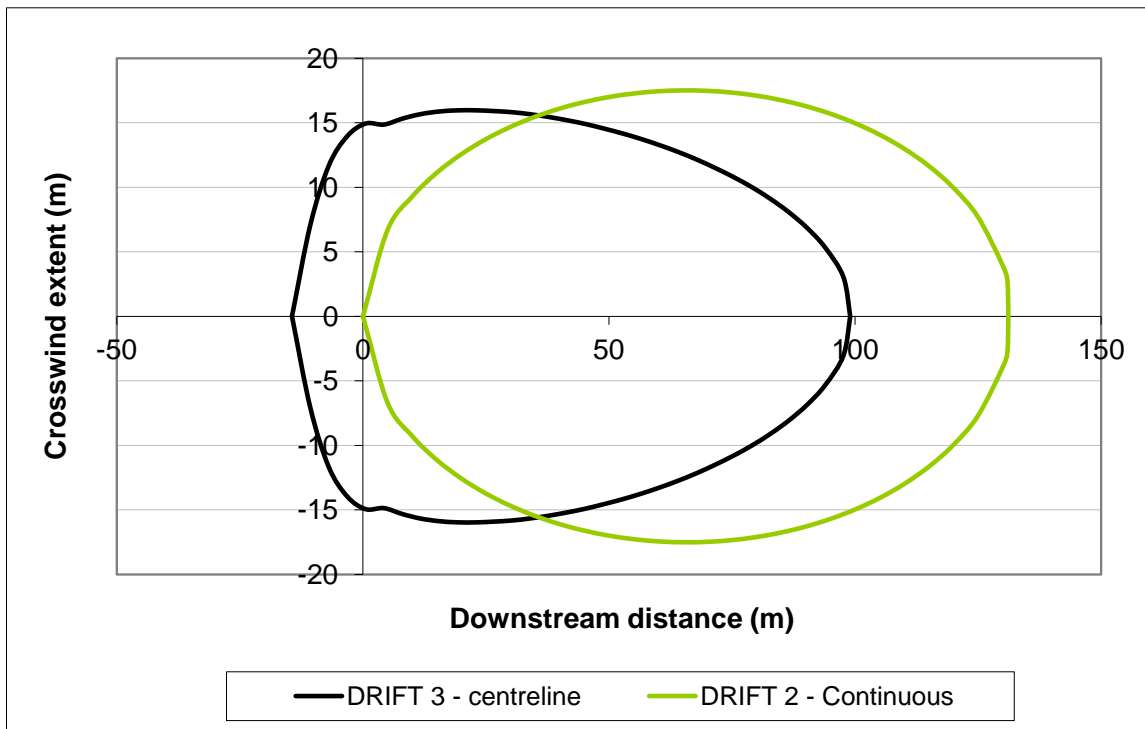


Figure 11 LFL isopleths obtained for a liquefied hydrogen release through a 50 mm vessel hole in D15 weather conditions

Table 5 Maximum downstream distances to the LFL for a catastrophic failure of a liquefied hydrogen tanker and a release through a 50 mm vessel hole in D15 weather conditions

<i>Model – receiver height</i>	<i>Maximum downstream distance to the LFL (m)</i>	
	<i>Catastrophic</i>	<i>50 mm hole</i>
DRIFT 2 – Centreline	470	132
DRIFT 3 – Centreline	378	99
DRIFT 3 – 0 m	340	N/A
DRIFT 3 – 2 m	343	N/A
DRIFT 3 – 5 m	348	N/A
DRIFT 3 – 10 m	357	N/A
DRIFT 3 – 20 m	370	N/A
DRIFT 3 – 50 m	357	N/A

N/A indicates that either the cloud did not lift off the ground or that it did not reach the specified height

The reduction in the maximum downstream distance to the LFL at a receiver height of 50 m, compared to a receiver height of 20 m, for the catastrophic tanker failure can be explained when the elevation plot is examined. Figure 12 shows that the cloud centreline height reaches a height of approximately 30 m, at which point the largest downstream LFL extent is calculated by the model. As the receiver height increases beyond this value, the downwind LFL extent of the cloud decreases.

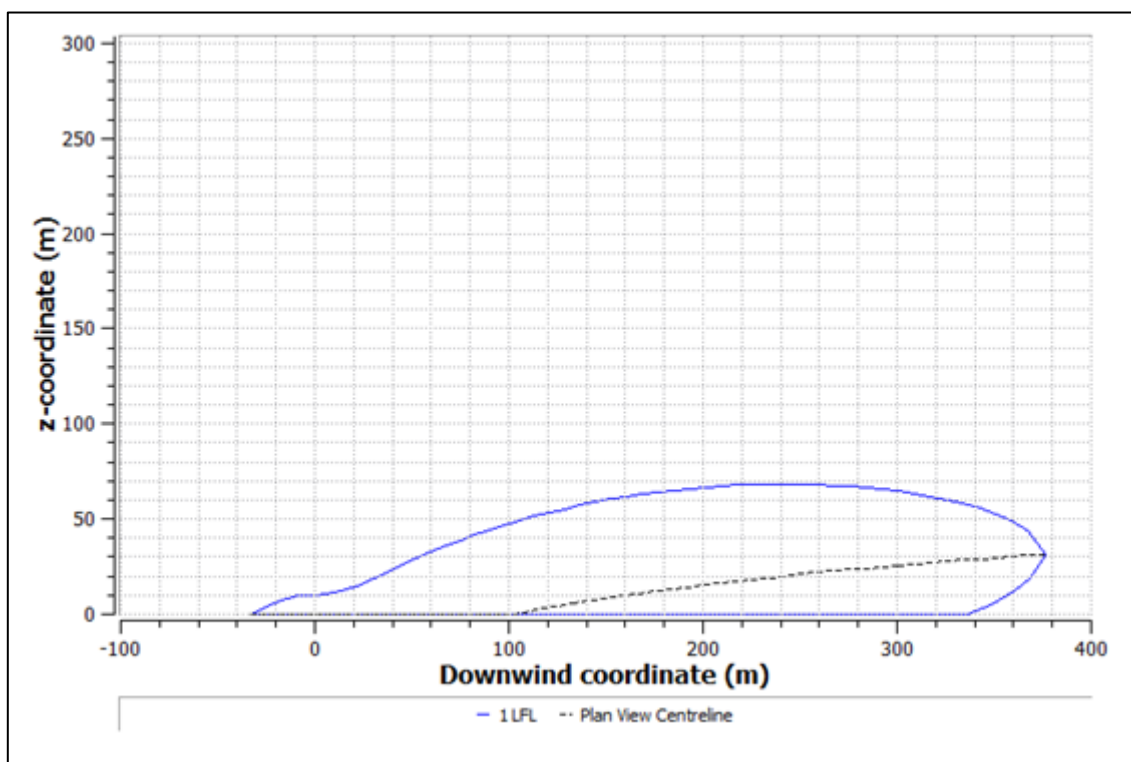


Figure 12 DRIFT 3.6.14 elevation plot for a liquefied hydrogen release from a catastrophic vessel failure in D15 weather conditions

2.4 SENSITIVITY ANALYSES FOR THE LIQUEFIED HYDROGEN ASSESSMENT

2.4.1 Steady continuous model

The scenarios were modelled as both instantaneous and continuous releases in DRIFT 2.31 for the original assessment, as explained in Section 2.2, although the results from the continuous release were used in the final assessment. The finite duration model was used in DRIFT 3.6.14 for the reassessment, and the results generated compared against those obtained using the DRIFT 2 steady continuous model in Section 2.3. DRIFT 3 also contains a version of the steady continuous model and this has been run for these scenarios to determine the impact on the results of moving from the steady continuous model to the finite duration model. It was found that there was no difference to the calculated maximum downstream distances to the LFL for the scenarios investigated.

2.4.2 Pool roughness length

In the original liquefied hydrogen assessment, the pool roughness length within GASP was set to 0 m, and the reassessment used the same value. The policy in HSE has changed since the original assessment and a pool roughness length of 0.00023 m is now used for Hazardous Substances Consent purposes [33]. This is considered a recommended standard value for outdoor pools. Both of the scenarios (catastrophic tanker failure and 50 mm vessel hole) have been run for each of the four wind speeds, using the recommended pool roughness length. The maximum downstream distances to the LFL from DRIFT 3.6.14 have been compared with the results using a pool roughness length of 0 m. The catastrophic tanker failure results in D5 weather are shown in Figure 13 (where the isopleth from a pool roughness length of 0.00023 m is labelled as 'DRIFT 3 – Corrected'). The largest difference is 2 m; no greater differences were seen for any of the other weather conditions in the catastrophic tanker failure case. No difference was seen for any of the 50 mm vessel hole cases.

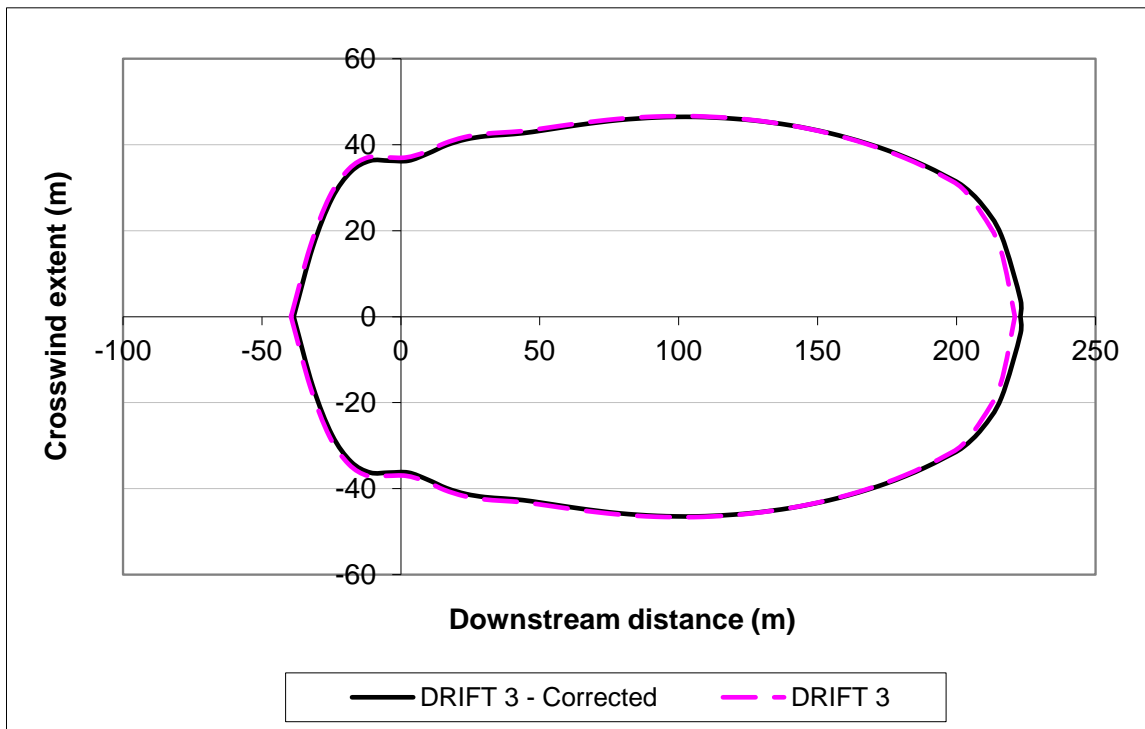


Figure 13 LFL isopleths obtained at the centreline height for a liquefied hydrogen release from a catastrophic vessel failure in D5 weather conditions, varying the pool roughness length

2.4.3 Relative humidity

In the original assessment of the liquefied hydrogen site, a relative humidity of 70% was assumed. Sensitivity tests have been performed using relative humidities of 50%, 60% and 80%, and these have been compared to the results generated when using a 70% relative humidity. For this set of sensitivity tests, a recommended pool roughness length of 0.00023 m has been assumed in all cases. LFL isopleths have been plotted for the catastrophic tanker failure case for each of the four weather conditions (F2, D5, D10 and D15) for the centreline height.

Figure 14 shows plots of the isopleths for the LFL from a release following a catastrophic tanker failure in F2 weather, using the centreline height. Changing the relative humidity makes little difference to the overall distance the cloud travels for this particular case. Figure 15 to Figure 17 show the plots of the isopleths for a release from a catastrophic tanker failure using the centreline height for D5, D10 and D15 weather. From the figures for the category D weather conditions it can be seen that, as the relative humidity decreases, the cloud extent increases. In addition, the effect of the relative humidity appears to increase as the wind speed increases, in that larger differences are seen in the downstream extent to the LFL for the higher wind speed scenarios when the relative humidity is changed. The percentage differences for the D10 and D15 weather cases are similar, with slightly larger differences seen for the scenario modelled in D10 weather. Table 6 lists the maximum downstream distances to the LFL for each scenario, for receiver heights of 2 m, 20 m and 50m and for each value of the relative humidity investigated. The values in the table show that greater differences are seen in the maximum downstream LFL extents for different relative humidities at the higher wind speeds modelled. The table and figures illustrate that the extent of the cloud increases with decreasing relative humidity in category D weather conditions.

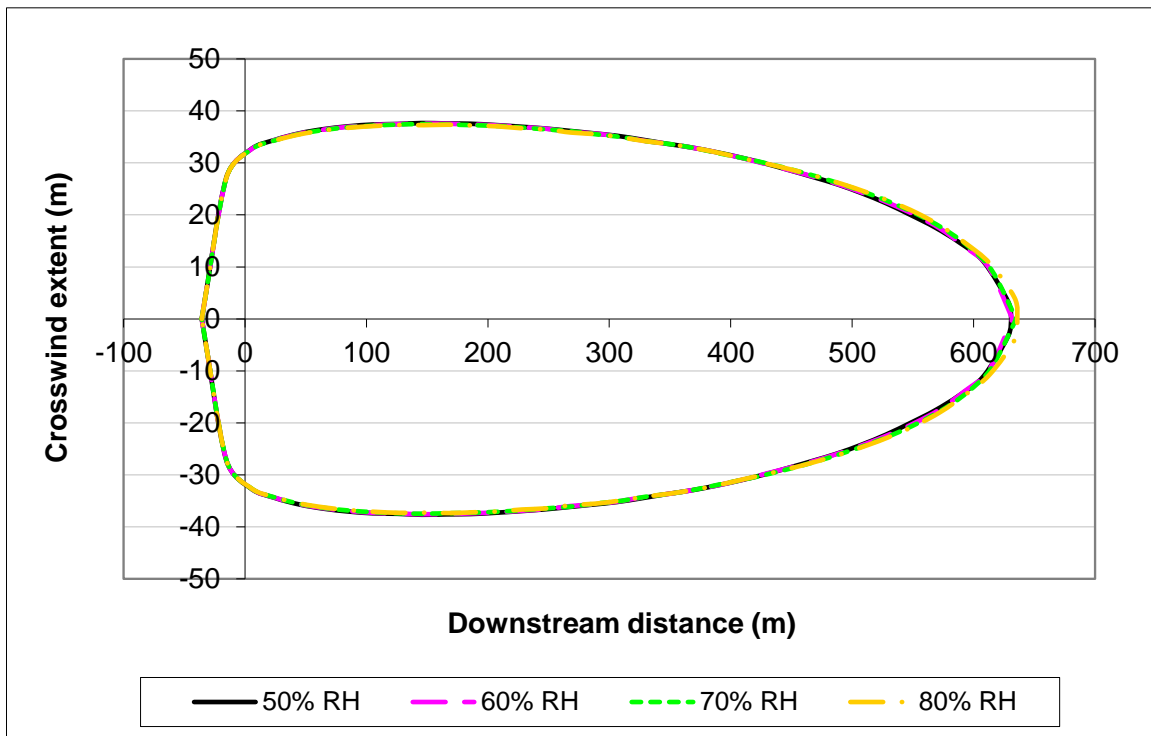


Figure 14 LFL isopleths obtained for a liquefied hydrogen release from a catastrophic vessel failure in F2 weather conditions, at the centreline height of the cloud, varying the relative humidity

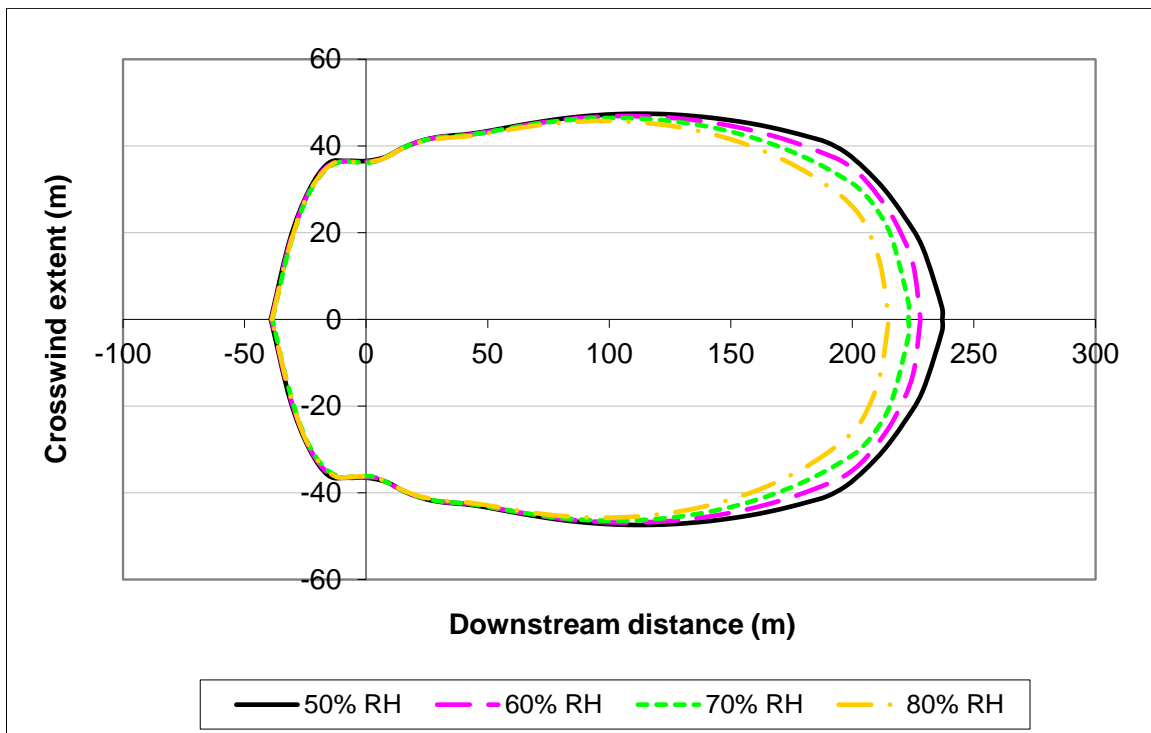


Figure 15 LFL isopleths obtained for a liquefied hydrogen release from a catastrophic vessel failure in D5 weather conditions, along the centreline height of the cloud, varying the humidity

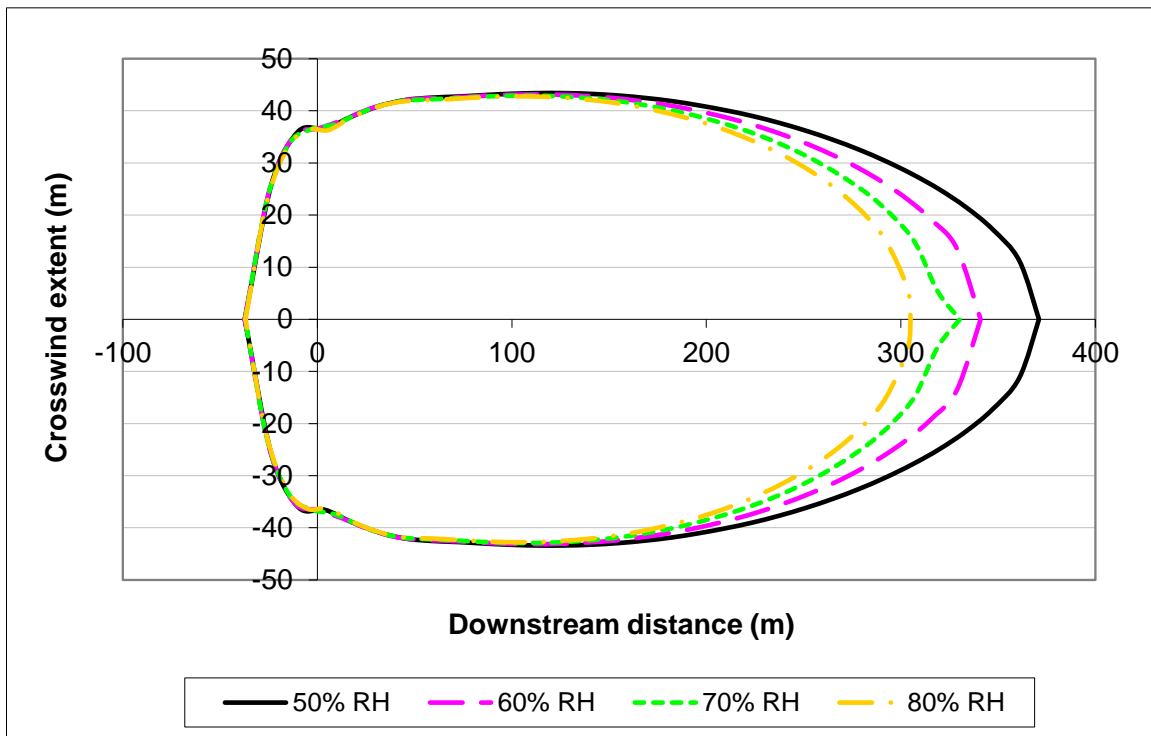


Figure 16 LFL isopleths obtained for a liquefied hydrogen release from a catastrophic vessel failure in D10 weather conditions, along the centreline height of the cloud, varying the relative humidity

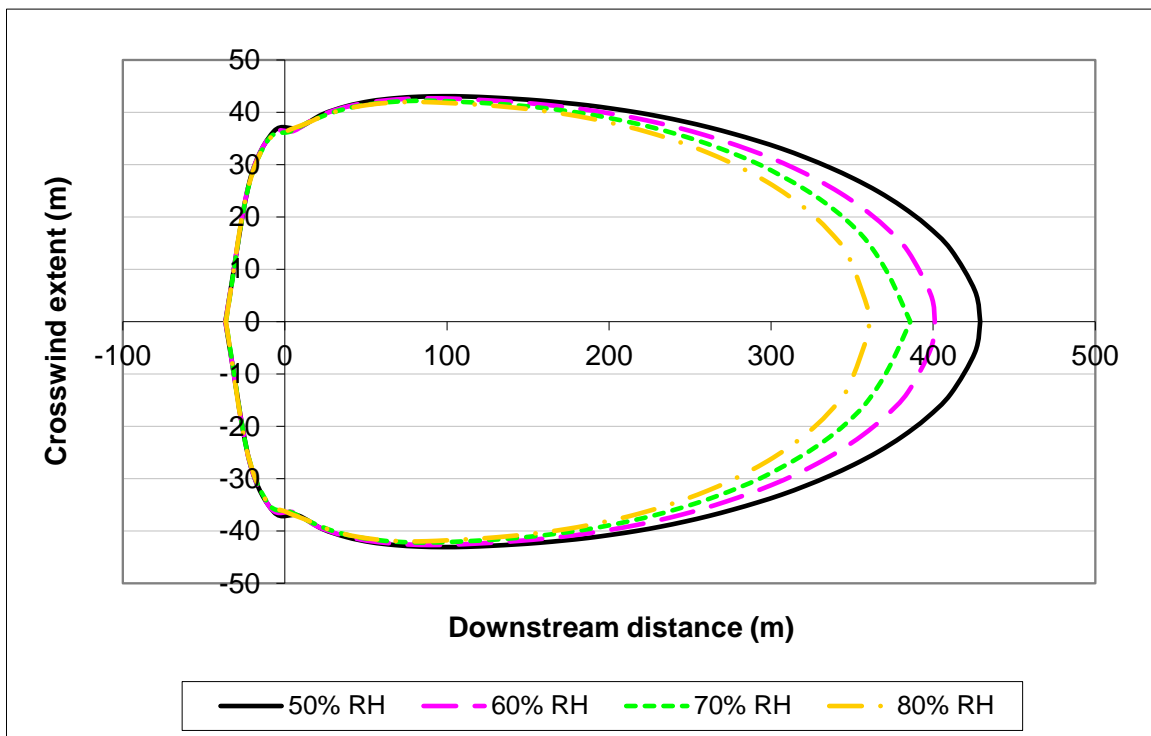


Figure 17 LFL isopleths obtained for a liquefied hydrogen release from a catastrophic vessel failure in D15 weather conditions, along the centreline height of the cloud, varying the relative humidity

Table 6 shows the maximum downstream distances to the LFL when the relative humidity is varied.

Table 6 Maximum downstream distances to the LFL for a liquefied hydrogen release from a catastrophic vessel failure, varying the relative humidity

<i>Model – receiver height</i>	<i>Maximum downstream distance to the LFL (m) at specified relative humidity</i>			
	<i>50%</i>	<i>60%</i>	<i>70%</i>	<i>80%</i>
F2 – Centreline	631	632	634	636
D5 – Centreline	237	228	223	215
D5 – 2 m	188	182	177	173
D5 – 20 m	202	195	188	182
D5 - 50 m	214	208	204	196
D10 – Centreline	371	341	321	305
D10 – 2 m	291	268	252	239
D10 – 20 m	330	304	285	270
D10 – 50 m	365	335	314	298
D15 – Centreline	429	401	379	360
D15 – 2 m	397	367	344	324
D15 – 20 m	424	395	372	351
D15 – 50 m	396	375	359	344

For the D15 scenario, the maximum downstream distance to the LFL at a receiver height of 50 m is lower than that predicted for a receiver height of 20 m. The reason for this has been explained previously in Section 2.3.4.

The maximum downstream extent of the LFL decreases with increasing relative humidity. As the water content in the atmosphere increases, more water condenses due to the low temperature of the liquefied hydrogen, which releases latent heat into the cloud. This decreases the cloud density, which leads to greater mixing and hence the cloud disperses more quickly.

Plots have been produced showing the effect of the relative humidity on the release from a 50 mm vessel hole. Figure 18 to Figure 21 illustrate the effects of the relative humidity in F2, D5, D10 and D15 weather respectively, along the centreline height of the cloud. The figures show that increasing the relative humidity decreases the maximum downstream distance to the LFL, as observed for the catastrophic vessel failure.

Table 7 lists the maximum distances to the LFL extent for each scenario, at different receiver heights. It confirms the conclusion that increasing the relative humidity decreases the maximum distance downstream that the cloud spreads, which is explained above. It also shows that, as the wind speed increases, the maximum downstream LFL extent increases due to the wind making the cloud less buoyant and, in effect, flattening it (see Section 2.3.4).

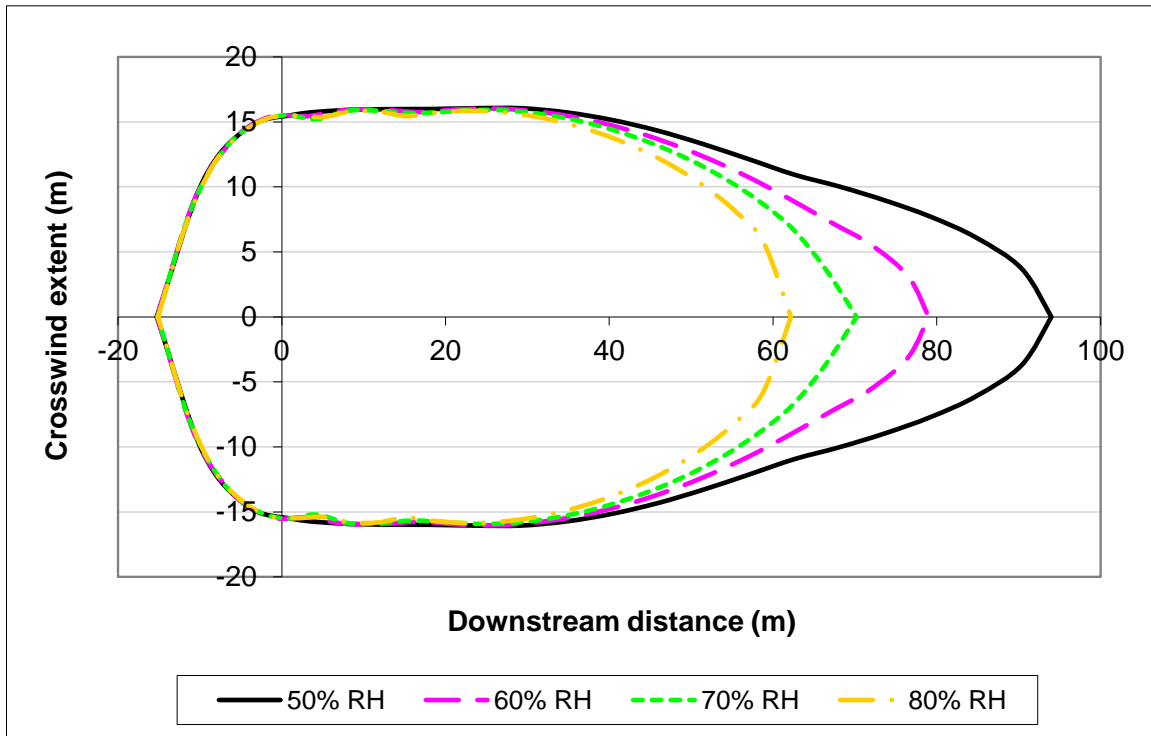


Figure 18 LFL isopleths obtained for a liquefied hydrogen release from a 50 mm vessel hole in F2 weather conditions, along the centreline height, varying the relative humidity

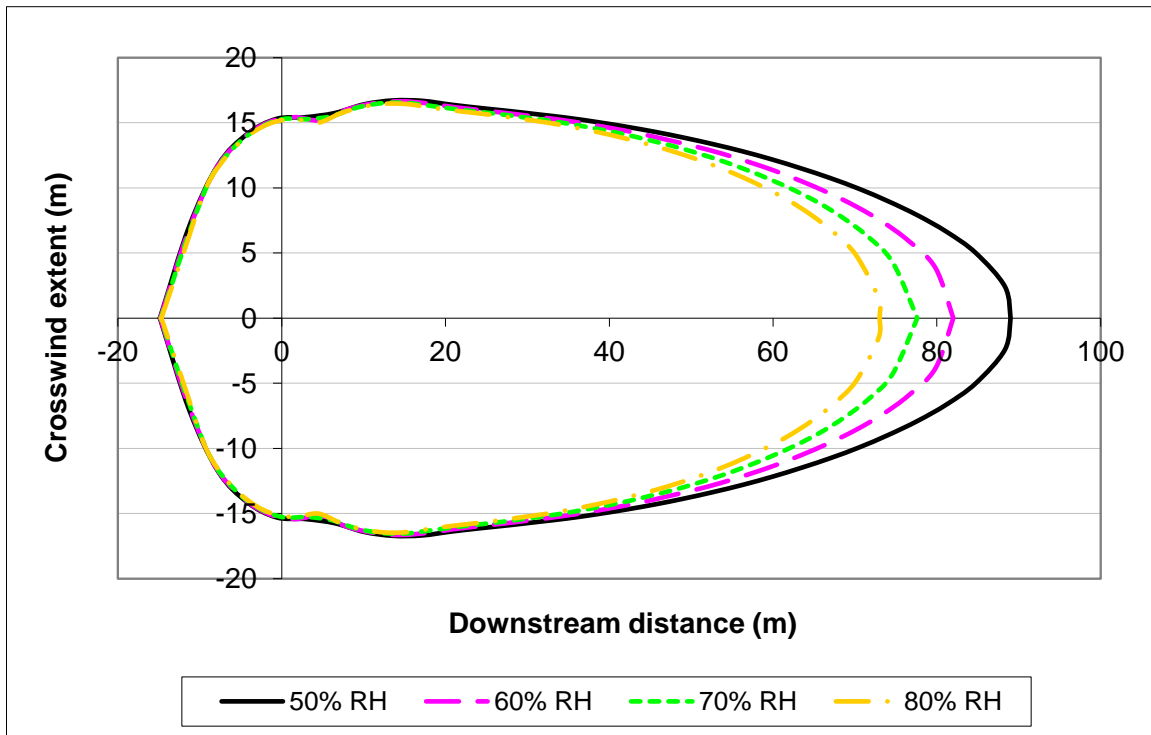


Figure 19 LFL isopleths obtained for a liquefied hydrogen release from a 50 mm vessel hole in D5 weather conditions, along the centreline height, varying the relative humidity

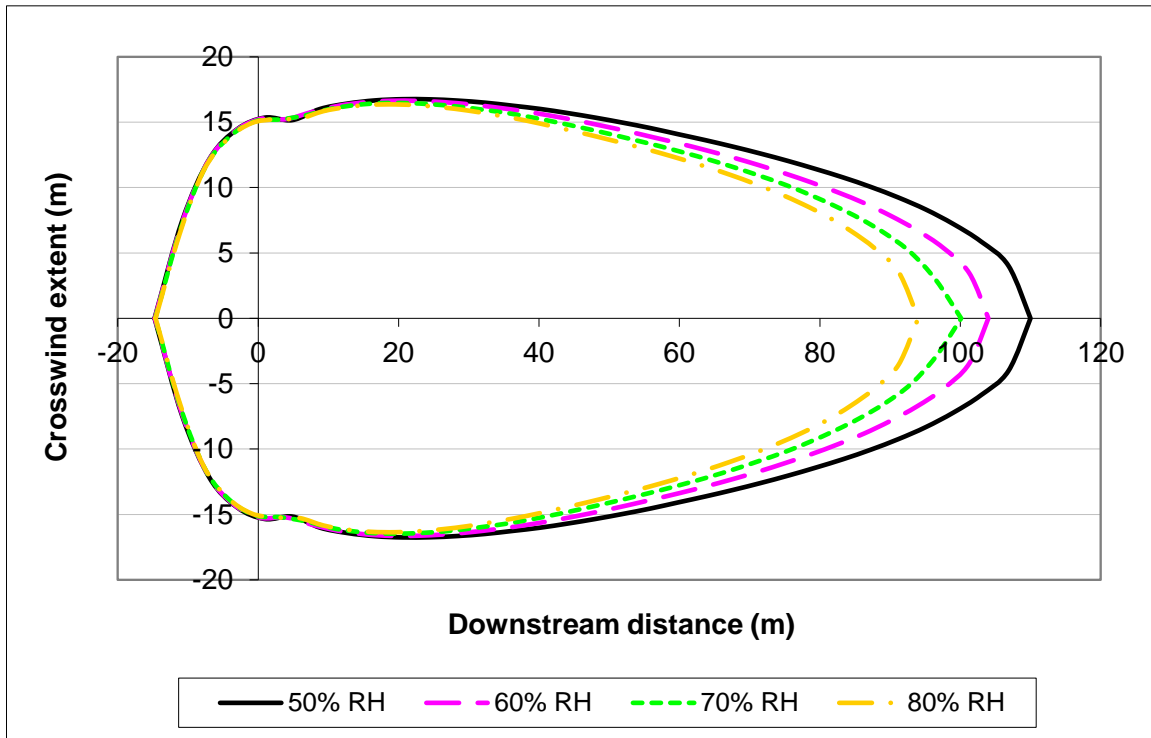


Figure 20 LFL isopleths obtained for a liquefied hydrogen release from a 50 mm vessel hole in D10 weather conditions, along the centreline height, varying the relative humidity

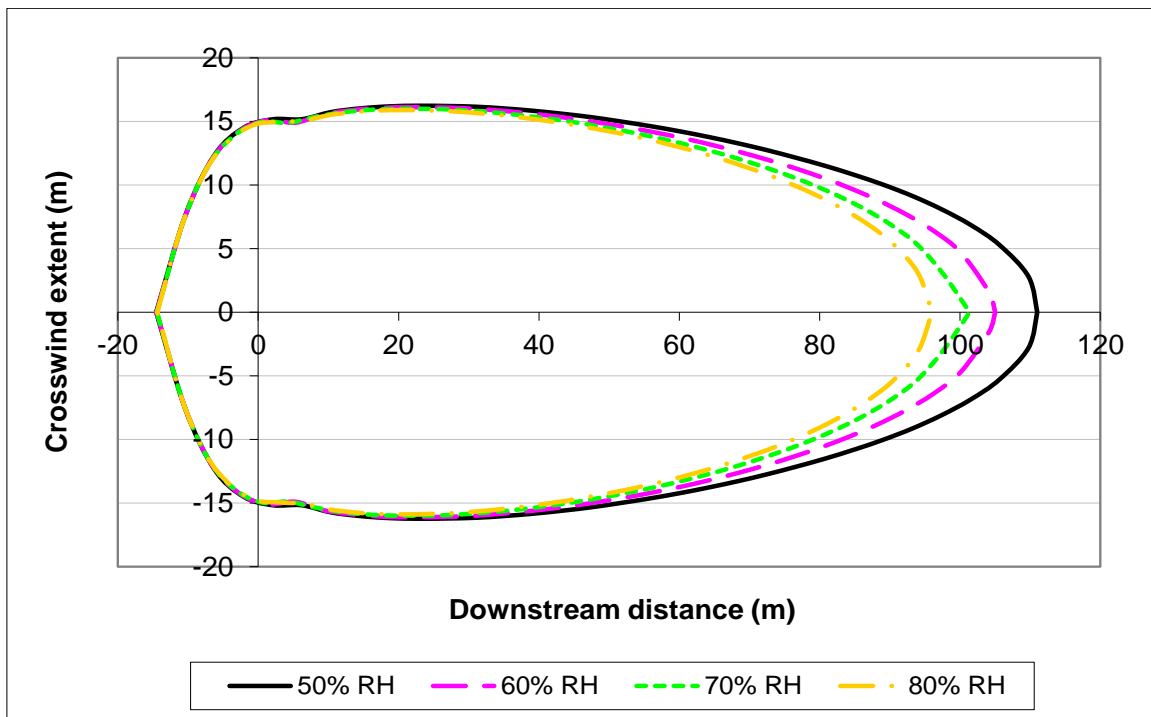


Figure 21 LFL isopleths obtained for a liquefied hydrogen release from a 50 mm vessel hole in D15 weather conditions, along the centreline height, varying the relative humidity

Table 7 shows the maximum downstream distances to the LFL for different values of the relative humidity.

Table 7 Downstream distances for a liquefied hydrogen release from a 50 mm vessel hole, varying the relative humidity

<i>Model – receiver height</i>	<i>Maximum downstream distance to the LFL (m) at specified relative humidity</i>			
	<i>50%</i>	<i>60%</i>	<i>70%</i>	<i>80%</i>
F2 – Centreline	94	79	68	62
F2 – 2 m	43	41	39	35
F2 – 20 m	56	50	48	44
F2 – 50 m	N/A	N/A	N/A	N/A
D5 – Centreline	89	82	77	73
D5 – 2 m	70	65	61	57
D5 – 20 m	86	78	73	69
D5 – 50 m	N/A	N/A	N/A	N/A
D10 – Centreline	110	104	98	94
D10 – 2 m	109	103	97	92
D10 – 20 m	N/A	N/A	N/A	N/A
D10 – 50 m	N/A	N/A	N/A	N/A
D15 – Centreline	111	105	99	96

N/A indicates that the cloud did not reach the specified height

2.5 LIQUEFIED NATURAL GAS (LNG) ASSESSMENT

The original assessment concerned a site containing one liquefied natural gas (LNG) storage tank, with a capacity of 21,000 tonnes, but with the capacity to install a further two tanks. The original consent claimed 42,000 tonnes. The existing tank has a double skin with insulation sandwiched in-between, although it is not clear if the outer wall would retain the LNG in the event of an inner tank failure. The tank is therefore treated as single-walled.

A number of scenarios were considered in the original assessment. These were:

- A. Catastrophic failure of the vessel and failure of the high wall bund;
- B. Major joint failure of the vessel and failure of the high wall bund;
- C. Minor joint failure of the vessel and failure of the high wall bund;
- D. Catastrophic failure of the tank only with the high wall bund remaining intact;
- E. Major joint failure of the tank only with the high wall bund remaining intact;
- F. Minor joint failure of the tank only with the high wall bund remaining intact;
- G. Vapour release;
- H. Failure of the LNG pipe-work during ‘export’ from the tank; and
- I. Failure of the LNG fill line during liquefaction.

Scenarios E, F and G do not contribute significantly to either pool fire or flash fire risks and were not considered further in original assessment. Scenario I was found to have potential release rates over an order of magnitude less than scenario H, and hence the risks were considered insignificant. To retain consistency, only scenarios A, B, C, D and H have been reassessed in DRIFT 3.6.14. These scenarios encompass a range of LNG releases that result in pool formation. This allows the performance of DRIFT 3 to be tested when modelling the dispersion of the flammable cloud that is created as evaporation of the liquefied gas occurs. HSE has often had to provide advice to Local Authorities on hazardous substance consents and land-use planning queries relating to LNG.

The original assessment considered results from both the instantaneous and steady continuous models in DRIFT 2.3.1. These results have been compared to the finite duration model in DRIFT 3.14.

In the original assessment both dry soil and wet soil conditions were considered in D5 and F2 weather conditions, although the dispersion modelling using DRIFT 2 was only performed for wet soil as this is considered cautious for flash fires (i.e. the pool size will be bigger on wet soil than on dry soil). All of these scenarios have been considered in the reassessment. The relative humidity was assumed to be 70%, which is above the now recommended value of 60%. The reassessment has used the 70% value for consistency with the previous results.

GASP 4.0.0 was used in the original assessment to model the spreading of the pool. GASP 4.2.12 has been used in the reassessment to derive the inputs to be used in DRIFT 3.6.14. The outputs have been checked against those from GASP 4.0.0 to ensure that the results are comparable. In some of the cases, the vaporisation rate satisfied the HSE 'peaky' criteria. In these cases, three sets of results were produced:

- using outputs directly generated by GASP and running the finite duration model in DRIFT (the 'non-peaky' methodology);
- adjusting GASP outputs according to the 'peaky' methodology as described in Section 2.2 and using the finite duration model in DRIFT; and
- importing the GASP file into DRIFT and running the time varying model within DRIFT.

The results of all three methodologies are shown in the graphs, where relevant. All the DRIFT results have been reported at a height fractionally above the pool height.

2.5.1 Scenario A – catastrophic failure of the vessel and the high wall bund

This scenario represents a release of 21,000 tonnes of LNG. The results seen for a release of this scale may show different trends to much smaller releases.

The results assuming dry soil for Scenario A are shown in Figure 22 for D5 weather and in Figure 23 for F2 weather for DRIFT 3.14 only. The equivalent plots assuming wet soil are shown in Figure 24 for D5 weather and Figure 25 for F2 weather. In the plots where wet soil has been assumed, results from DRIFT 2 are also shown. In the original assessment, this scenario was modelled as both a continuous release and an instantaneous release in DRIFT 2. DRIFT 2 results are available for both types of release for D5 weather, however, the continuous release did not run successfully in DRIFT 2 for F2 weather and so results are only available for the instantaneous release in this case.

The outputs generated by GASP satisfy the HSE 'peaky' criteria in all cases except when modelling the release in F2 weather assuming a spill on dry soil. For the cases meeting the 'peaky' criteria, the DRIFT 3 results have been obtained using the 'non-peaky' methodology, the 'peaky' methodology, and the time varying model option in DRIFT 3. Results from all three methodologies are shown in the figures where applicable.

In some of the plots, the contours appear to be approximately circles that have been stretched downstream (e.g. Figure 22). In these cases DRIFT 3 predicts an upwind element to the cloud that is approximately the radius of the pool. It appears that the pool evaporation generates a cloud above the pool, which moves downstream with the wind for a short distance before diluting below the LFL.

The 'peaky' methodology results for the dry and wet D5 scenarios generate maximum downwind distances to the LFL between those generated for the 'non-peaky' method and those obtained using the time varying model. In the F2 wet soil case, the 'peaky' methodology produces the shortest downwind LFL extents when compared to the 'non-peaky' and time varying methodologies.

DRIFT 2 instantaneous and continuous models produce LFL isopleths that have a larger maximum crosswind extent in D5 weather than those obtained using the finite duration model in DRIFT 3. The maximum downwind distance to the LFL for the instantaneous release in DRIFT 2 is also longer than any of the DRIFT 3 release results, which used the finite duration model. The maximum downwind distance to the LFL for the continuous release in DRIFT 2 is shorter than the distance produced by the time varying model in DRIFT 3. The maximum downwind LFL extent from DRIFT 3 is larger in F2 weather, for the 'non-peaky', 'peaky' and time varying DRIFT 3 methodologies investigated, when compared to the LFL extent generated for the instantaneous release obtained from DRIFT 2 for this scenario.

The observations made concerning the different DRIFT 3 methodologies are explained in Section 2.7.

The downwind distances produced by the finite duration and time varying models in DRIFT 3 are shown in Table 8.

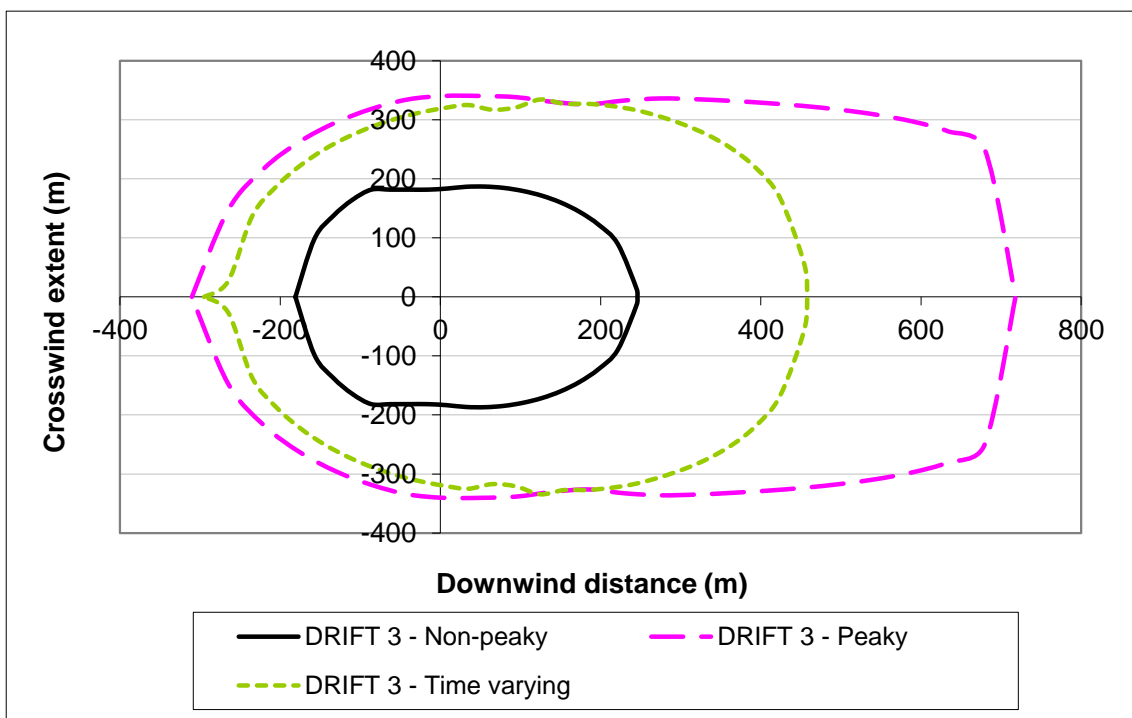


Figure 22 LFL isopleths for a release of LNG from a catastrophic vessel failure in D5 weather, assuming dry soil

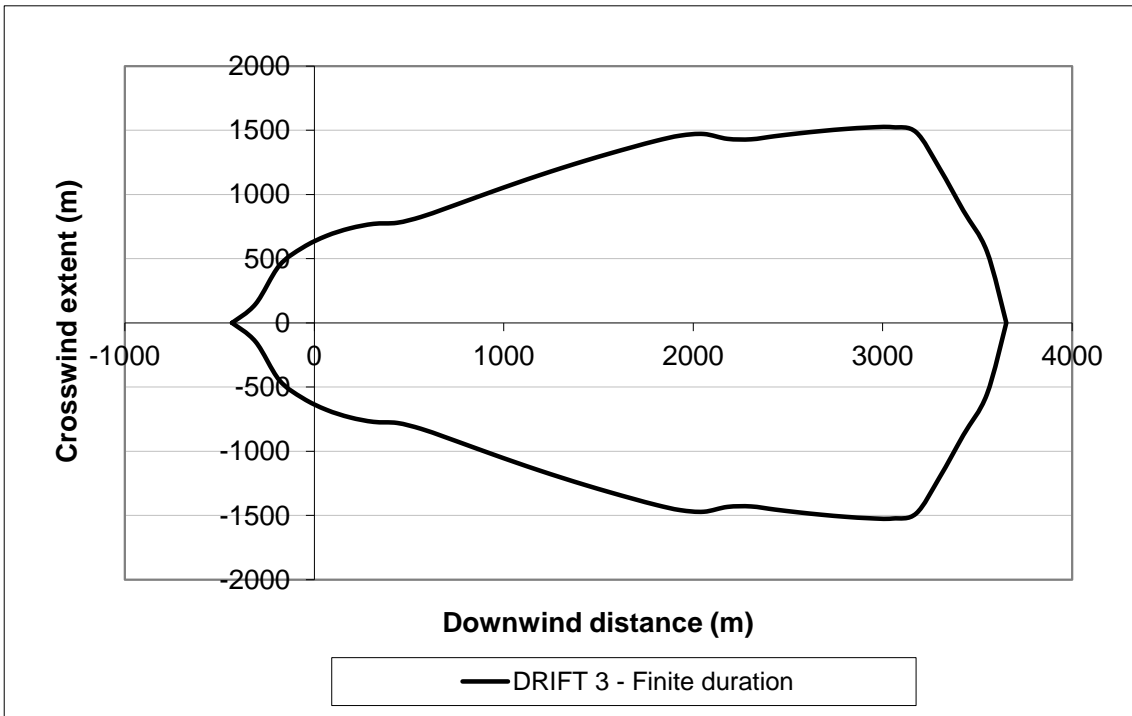


Figure 23 LFL isopleths for a release of LNG from a catastrophic vessel failure in F2 weather, assuming dry soil

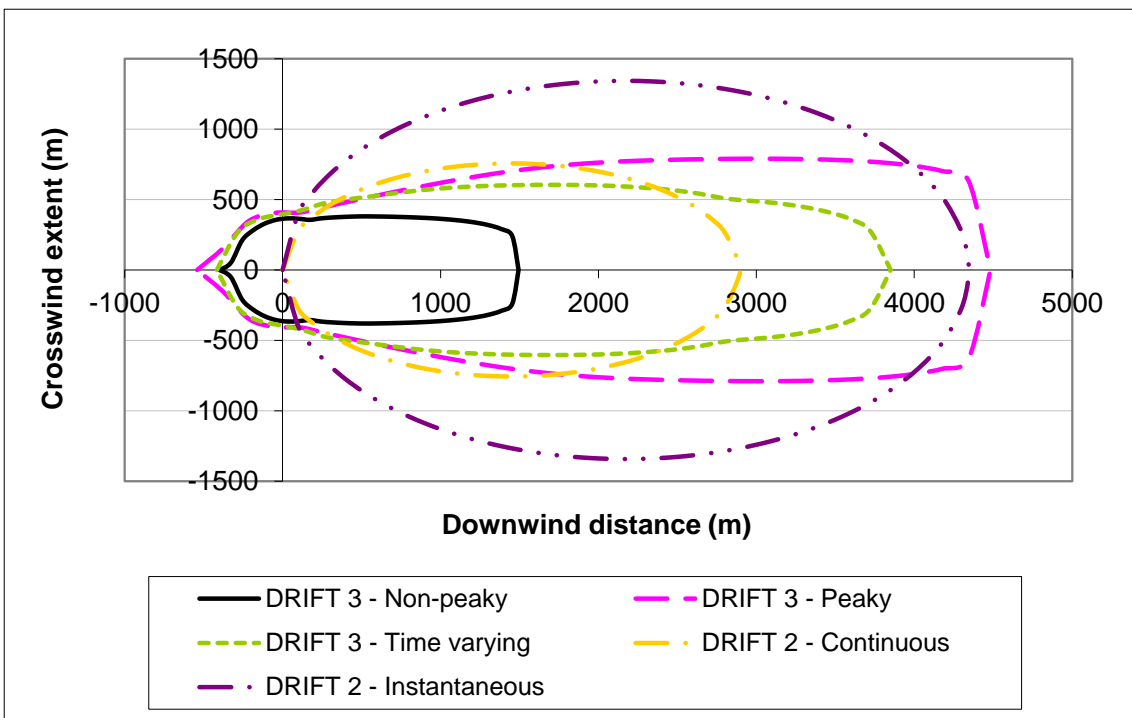


Figure 24 LFL isopleths for a release of LNG from a catastrophic vessel failure in D5 weather, assuming wet soil

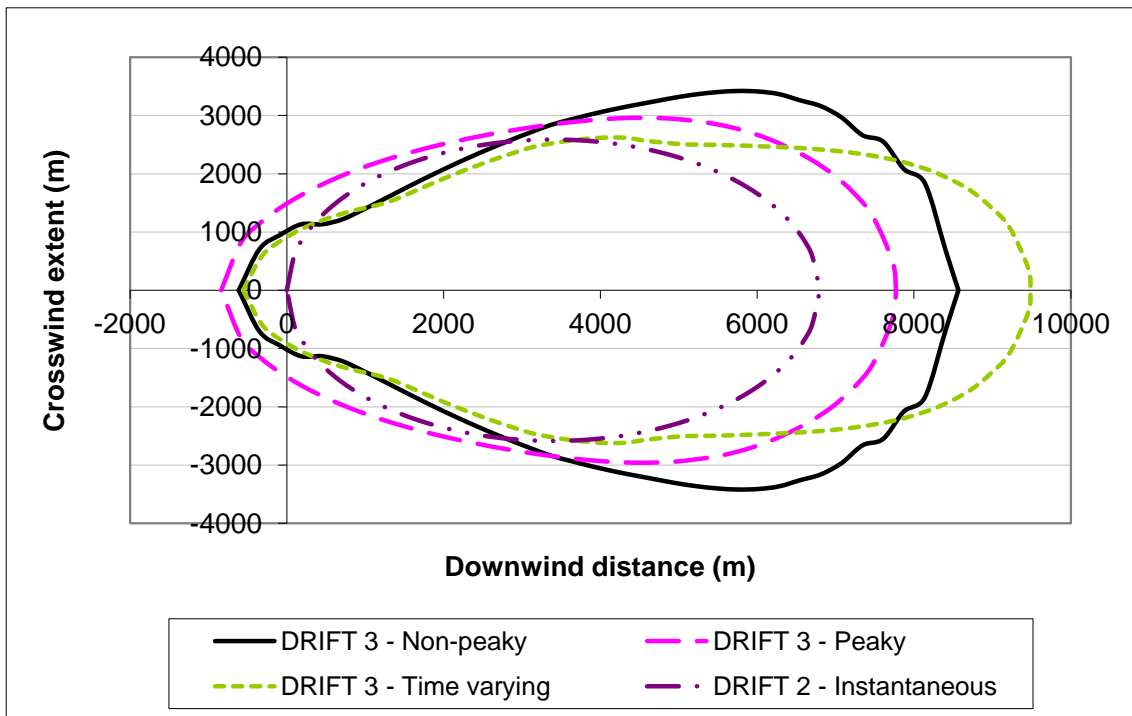


Figure 25 LFL isopleths for a release of LNG from a catastrophic vessel failure in F2 weather, assuming wet soil

Table 8 shows the maximum downwind distances to the LFL for Scenario A under different conditions. The large differences observed between the wet and dry soil scenarios are due to the change in the vaporisation rate that is calculated in GASP and used as a source term in DRIFT.

Table 8 Maximum downwind distances to the LFL for a release of LNG from a catastrophic vessel failure (Scenario A), varying the modelling methodology

<i>Scenario A conditions</i>	<i>Maximum downwind distance to the LFL (m) using specified methodology</i>				
	<i>DRIFT 3</i>			<i>DRIFT 2</i>	
	<i>'Non-peaky'</i>	<i>'Peaky'</i>	<i>Time varying</i>	<i>Continuous</i>	<i>Instantaneous</i>
D5 dry soil	246	718	458	NR	NR
F2 dry soil	3653	N/A	N/A	NR	NR
D5 wet soil	1494	4482	3850	2893	4344
F2 wet soil	8567	7770	9485	NR	6791

NR indicates no result obtained

N/A indicates that the release was not 'peaky' and only 'non-peaky' results are reported

2.5.2 Scenario B – major joint failure of the vessel and failure of the high wall bund

This scenario corresponds to a 1000 mm hole in the vessel and the failure of the high bund wall. The release rate is 3970 kg s^{-1} and the duration is 1800 s. The results from GASP do not satisfy the HSE 'peaky' criteria. Results have therefore only been obtained using the standard 'non-peaky' methodology.

The results assuming dry soil for Scenario B are shown in Figure 26 for D5 weather and in Figure 27 for F2 weather. The equivalent plots assuming wet soil are shown in Figure 28 for D5 weather and Figure 29 for F2 weather. In the plots where wet soil has been assumed, results obtained from DRIFT 2 are also shown. In the original assessment, this scenario was modelled as both a continuous release and an instantaneous release in DRIFT 2 (see Section 2.2 for an explanation). Results are available from DRIFT 2 for both types of release in D5 weather. The original assessment appears to have generated results for both types of release

in F2 weather, however, only the results for the instantaneous release could be obtained to plot the isopleths. The maximum downwind distances to the LFL are given in Table 9.

In some of the plots, the contours appear to be approximately circles that have been stretched downstream (e.g. Figure 26). In these cases DRIFT 3 predicts an upwind element to the cloud that is within the radius of the pool, or approximately the same size as the pool radius. It appears that the pool evaporation generates a cloud above the pool, which moves downstream with the wind for a short distance before diluting below the LFL.

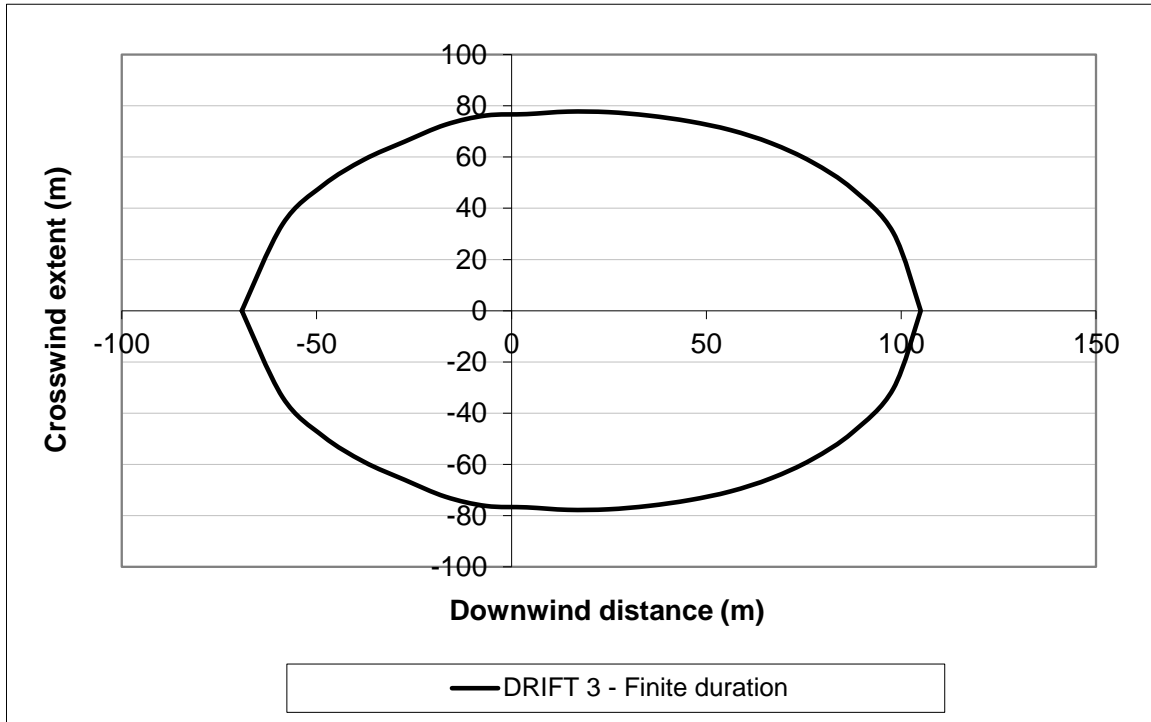


Figure 26 LFL isopleths for a release of LNG from a 1000 mm vessel hole in D5 weather, assuming dry soil

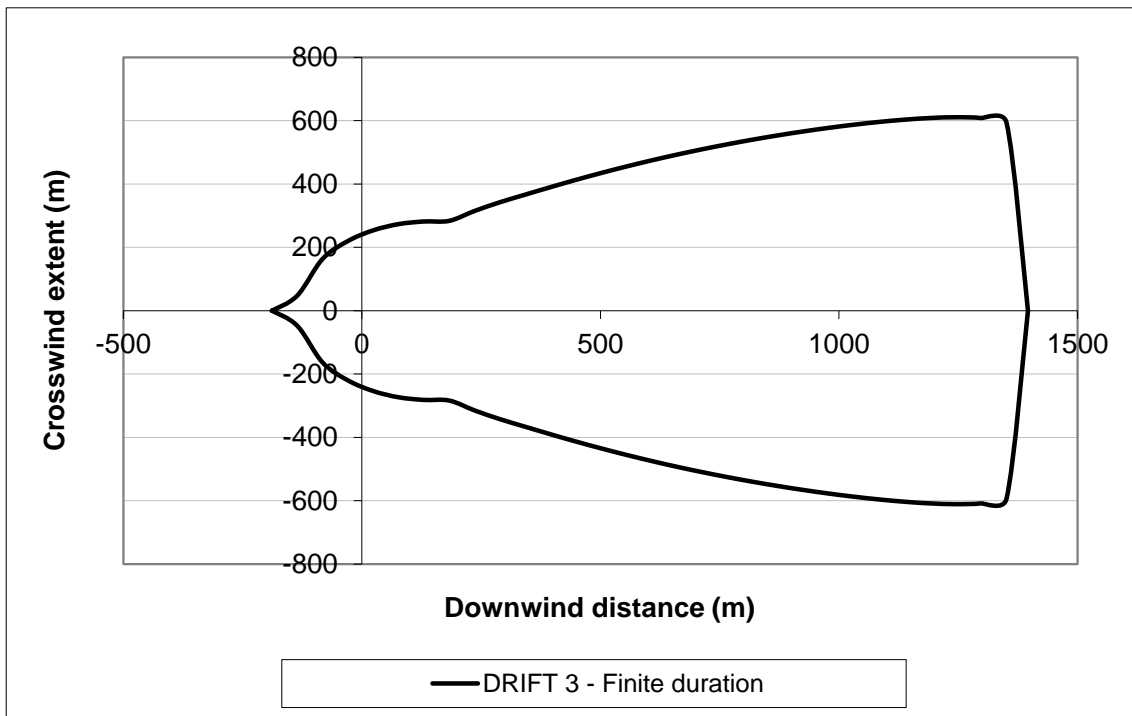


Figure 27 LFL isopleths for a release of LNG from a 1000 mm vessel hole in F2 weather, assuming dry soil

Figure 28 shows that the maximum downwind distance to the LFL produced in DRIFT 2 for the instantaneous release onto wet soil in D5 weather is significantly larger than the results obtained from DRIFT 3 using the finite duration model for this case. The DRIFT 2 maximum LFL extent using the instantaneous model is also significantly larger than that produced using the continuous model in DRIFT 2. Figure 29 shows that the isopleth produced using the instantaneous model in DRIFT 2 is smaller than that obtained using the finite duration model in DRIFT 3 for releases onto wet soil in F2 weather.

The results indicate that the cloud travels significantly further in F2 weather conditions than in D5. At the higher wind speed the edges of the cloud will be subject to greater turbulence and this will occur from the point of release onwards. This process will enable the dispersion to occur more rapidly, meaning that the width of the cloud is smaller than in F2 weather. The increased turbulence on a narrower cloud will lead to the cloud dispersing more quickly and not travelling as far downstream. This is particularly noticeable for a large release with a wide crosswind extent.

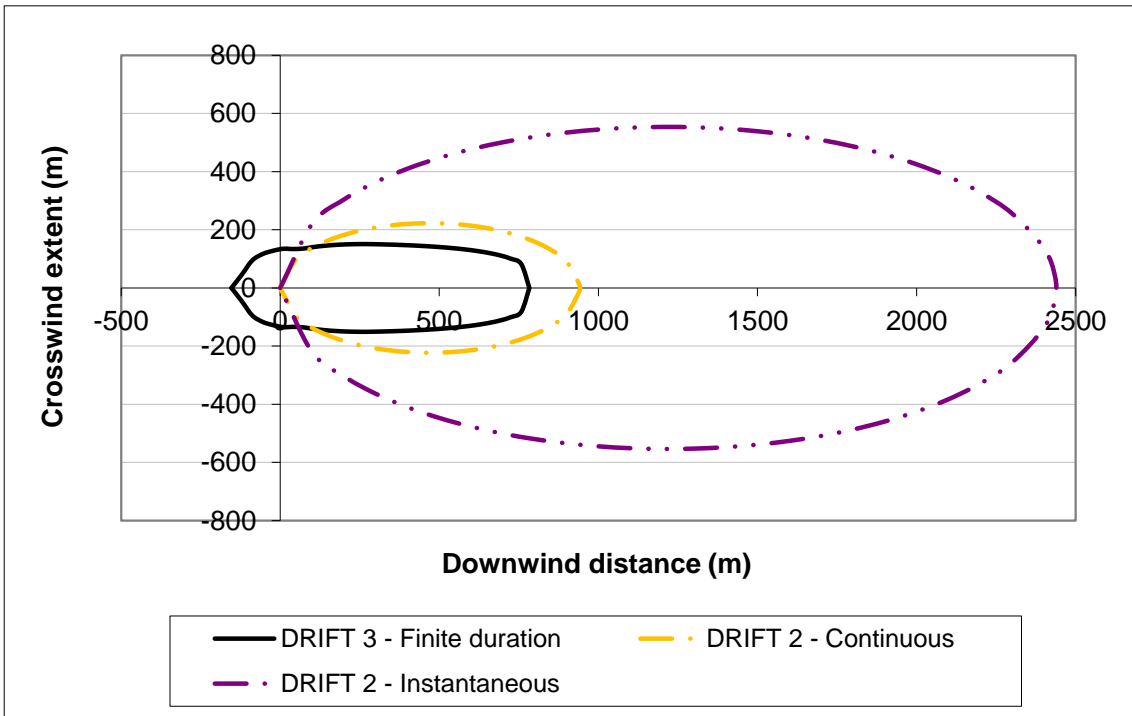


Figure 28 LFL isopleths for a release of LNG from a 1000 mm vessel hole in D5 weather, assuming wet soil

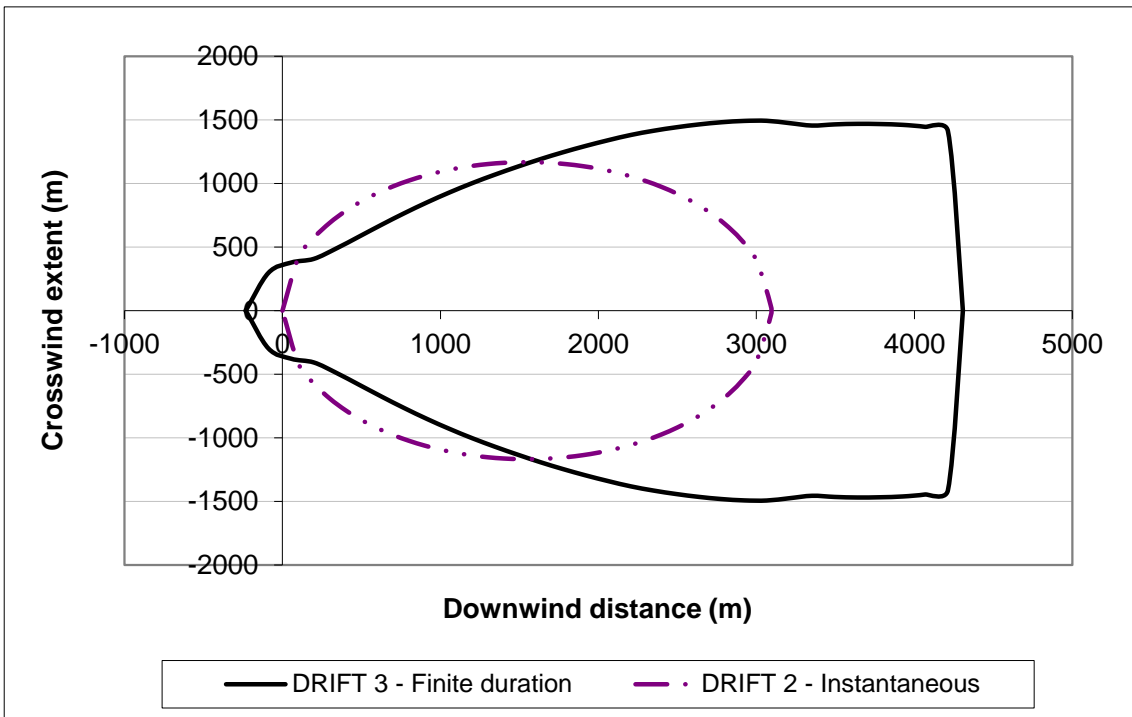


Figure 29 LFL isopleths for a release of LNG from a 1000 mm vessel hole in F2 weather, assuming wet soil

Table 9 shows the maximum downwind distances to the LFL for Scenario B under different release conditions. The large differences observed between the wet and dry soil scenarios are due to the change in the vaporisation rate that is calculated in GASP and used as a source term in DRIFT.

Table 9 Maximum downwind distances to the LFL for a release of LNG from a 1000 mm vessel hole (Scenario B), varying the modelling methodology

Scenario B conditions	Maximum downwind distance to the LFL (m) using specified methodology		
	DRIFT 3	DRIFT 2	
	Finite duration	Continuous	Instantaneous
D5 dry soil	105	NR	NR
F2 dry soil	1396	NR	NR
D5 wet soil	783	941	2438
F2 wet soil	4307	NR	3091

NR indicates no result obtained

2.5.3 Scenario C – minor joint failure and failure of the high wall bund

In this scenario, a release from a 300 mm vessel hole has been modelled using a release rate of 327 kg s^{-1} and duration of 1800 s. The results from GASP do not satisfy the HSE ‘peaky’ criteria and hence the ‘non-peaky’ methodology has been used to obtain the results. The finite duration model has been used in DRIFT 3.14.

The LFL isopleth for the release in D5 weather assuming dry soil is shown in Figure 30 and the results for the release in F2 weather assuming dry soil are shown in Figure 31. The results assuming wet soil are shown in Figure 32 and Figure 33 for D5 and F2 weather respectively. For the wet soil scenarios, results are available from DRIFT 2 and these are also plotted in the figures. DRIFT 2 results are available for both the instantaneous and continuous models in the D5 case. DRIFT 2 results are only available for the instantaneous release for the wet soil F2 case. The downwind distances are reported in Table 10.

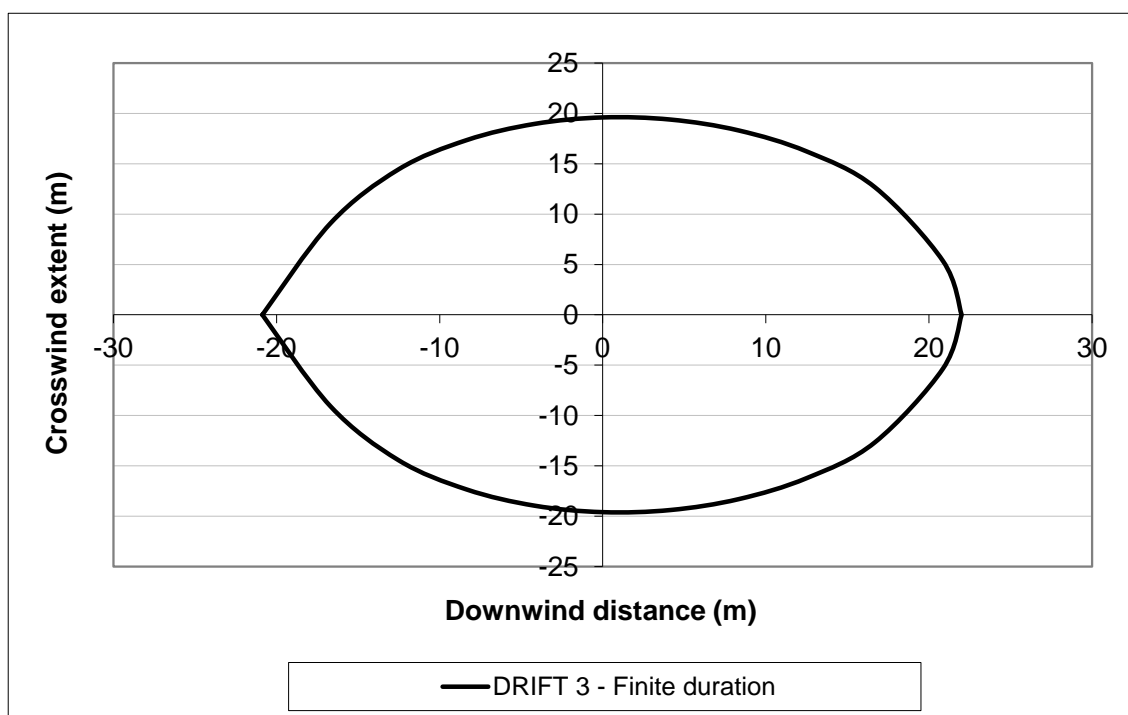


Figure 30 LFL isopleth for a release of LNG from a 300 mm vessel hole in D5 weather, assuming dry soil

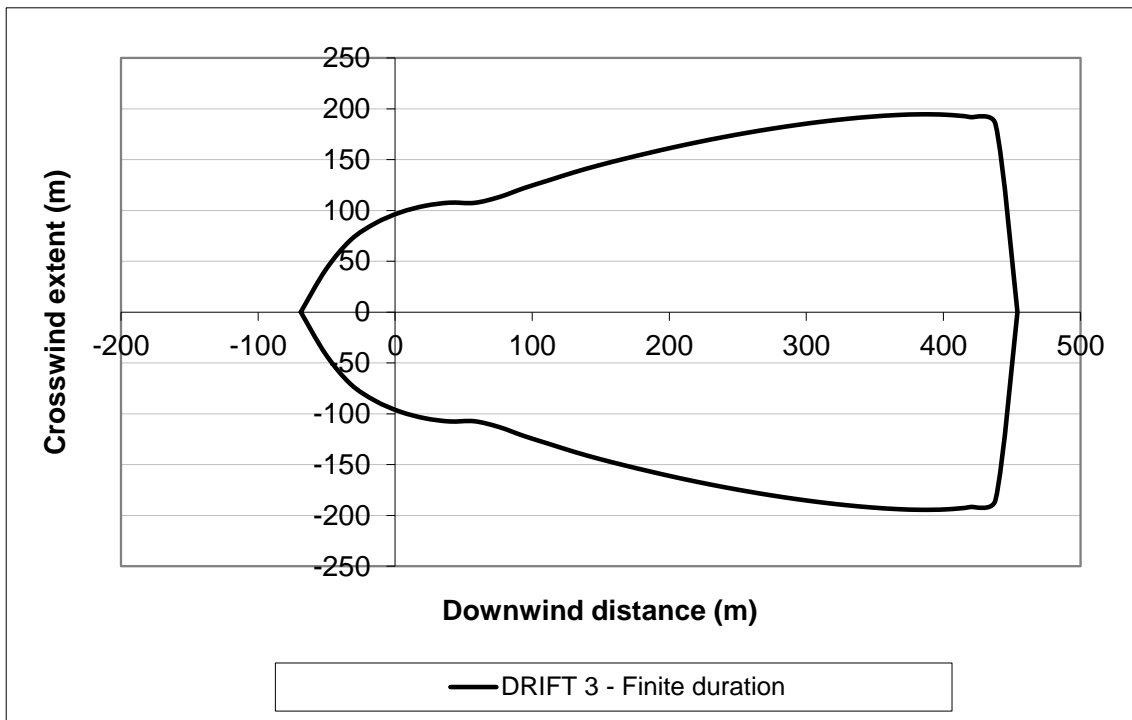


Figure 31 LFL isopleth for a release of LNG from a 300 mm vessel hole in F2 weather, assuming dry soil

Figure 32 shows that DRIFT 2 outputs longer downwind LFL extents than DRIFT 3 in the D5 wet soil case, when modelling the scenario as either a continuous or instantaneous release. For this case, the instantaneous model in DRIFT 2 predicts significantly larger LFL isopleths than the continuous model in DRIFT 2. The reasons for these differences are discussed in the following paragraph.

Approximating the release as instantaneous is only appropriate when the cloud travel time exceeds the release duration. Over the period of the release duration of 1800 s, in a 5 m/s wind, the cloud will travel significantly further than the 1100 m dispersion range shown in Figure 32. Therefore the release is better approximated as being continuous over this distance range. For a continuous release, the concentration in the cloud scales with release rate rather than the total mass released. Treating the release as being instantaneous within this continuous region will, in general, be very pessimistic, since diluting the entire cloud containing the total release mass to the same level requires a much greater quantity of air to be entrained compared with diluting the continuous plume which only contains a fraction of this mass over the distance range. Hence the LFL contour from the instantaneous cloud extends much further than the LFL contour from the continuous cloud output by either DRIFT 2 or DRIFT 3¹.

The LFL contour from the DRIFT 2 continuous release is predicted to extend further downwind than for DRIFT 3 because DRIFT 2 does not include the effect of cloud spreading and dilution over the source which is present in DRIFT 3.

Figure 33 shows that the DRIFT 2 instantaneous cloud produces isopleths for the F2 wet soil scenario that have similar downwind and crosswind extents to the DRIFT 3 finite duration cloud. The travel distance for the release duration is shorter in 2 m/s wind speed than 5 m/s wind speed, and accounting for the lower height of the dense cloud in low wind, it is possible that the distance range is close to that where the travel time equals the release duration. This might explain the similarity between the DRIFT 2 and DRIFT 3

¹ Sometimes, particularly for a large cloud in low wind conditions, an instantaneous dense release can give a shorter range than a continuous release. This is due to the effect of gravity driven radial spreading and increased entrainment of air arising from this. In such cases the cloud usually spreads further upwind and crosswind than the continuous release.

contour extents, although the flat end to the DRIFT 3 contour suggests that the LFL contour still lies within the continuous region.

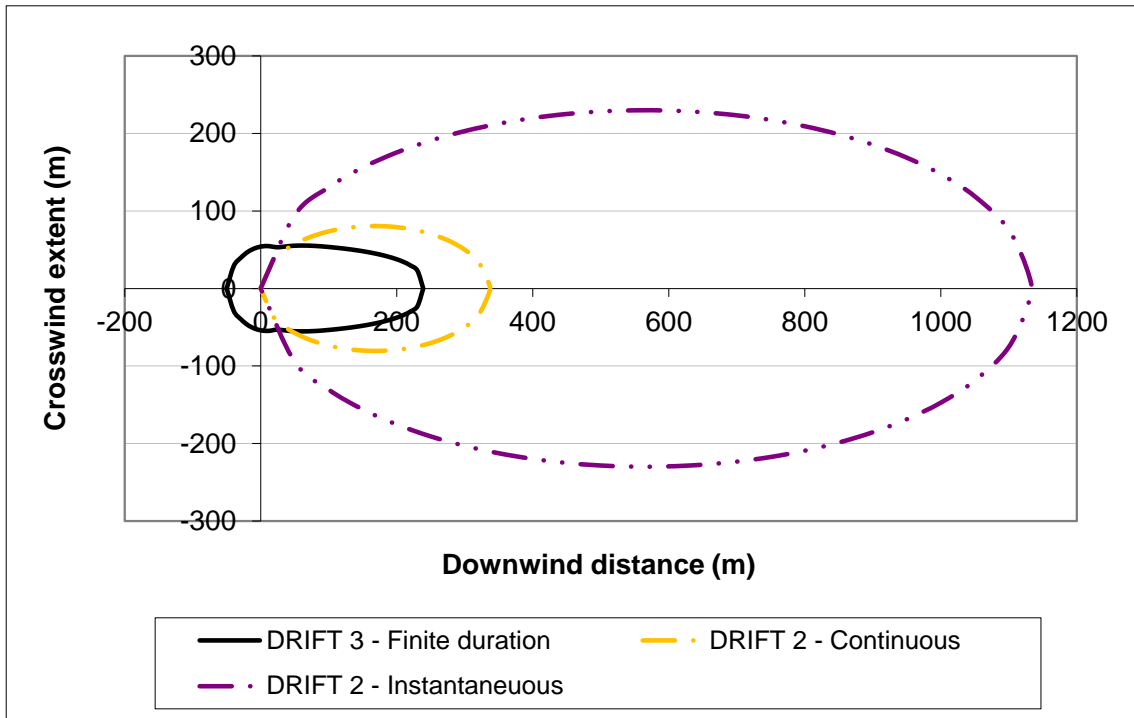


Figure 32 LFL isopleths for a release of LNG from a 300 mm vessel hole in D5 weather, assuming wet soil

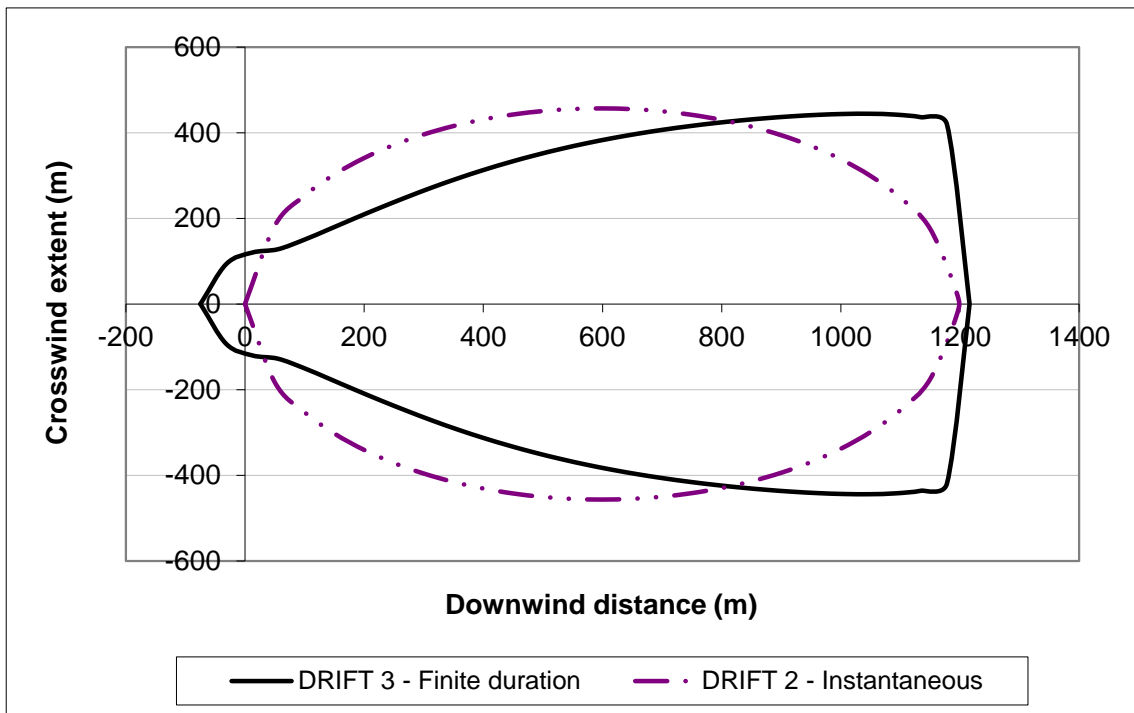


Figure 33 LFL isopleths for a release of LNG from a 300 mm vessel hole in F2 weather, assuming wet soil

The LFL distances output by the models are given in Table 10.

Table 10 Maximum downwind distances to the LFL for a release of LNG from a 300 mm vessel hole (Scenario C), varying the modelling methodology

<i>Scenario C conditions</i>	<i>Maximum downwind distance to the LFL (m) using specified methodology</i>		
	<i>DRIFT 3</i>	<i>DRIFT 2</i>	
	<i>Finite duration</i>	<i>Continuous</i>	<i>Instantaneous</i>
D5 dry soil	22	NR	NR
F2 dry soil	454	NR	NR
D5 wet soil	239	336	1131
F2 wet soil	1216	NR	1196

NR indicates no result obtained

2.5.4 Scenario D – catastrophic failure of the tank with the bund remaining intact

In this scenario, the LNG storage vessel fails catastrophically but the high walled bund remains intact, leading to a release of 1888 tonnes of LNG. The results from GASP satisfy the HSE ‘peaky’ criteria in all cases except for modelling D5 weather assuming dry soil. It should be noted that the D5 dry soil scenario falls just below the ‘peaky’ criteria having a ratio of the maximum vaporisation rate to the mean of 1.93. The ‘non-peaky’, ‘peaky’ and time varying methodologies have been considered for the relevant scenarios. The finite duration model has been used in DRIFT 3 for the ‘non-peaky’ and ‘peaky’ scenarios.

The LFL isopleths obtained for this scenario when assuming dry soil in D5 weather are shown in Figure 34 and those assuming dry soil in F2 weather are shown in Figure 35. The equivalent plots assuming wet soil are shown in Figure 36 and Figure 37. Note that the ‘peaky’ isopleth in Figure 37 appears to be less smooth than the other isopleths. The plots have been generated using the default parameters in DRIFT 3. Smoother plots can be obtained by adjusting the “Finite Duration Model Time Series Precision” parameter and increasing the “Finite Duration Time Series Extent” parameter in the model. This can lead to a small, approximately 5%, increase in the predicted LFL extent. In the interests of cleaner sensitivity comparisons between all runs, these parameters have not been adjusted.

DRIFT 2 was run using the instantaneous and continuous models for the D5 scenario on wet soil. Only results from the instantaneous model were available for the F2 scenario on wet soil.

In some of the plots, the contours appear to be approximately circles that have been stretched downstream (e.g. Figure 34). In these cases DRIFT 3 predicts an upwind element to the cloud that is within the radius of the pool, or approximately the same size as the pool radius. It appears that the pool evaporation generates a cloud above the pool, which moves downstream with the wind for a short distance before diluting below the LFL.

Figure 35 shows that the ‘peaky’ methodology produces the largest downwind LFL extent. This is also true of the DRIFT 3 results displayed in Figure 36, which also contains the results obtained from DRIFT 2 modelling this scenario as both a continuous release and an instantaneous release. This figure shows that the ‘non-peaky’ methodology in DRIFT 3 produces the smallest overall distances to the LFL for the D5 wet soil scenario, with the instantaneous release modelled in DRIFT 2 producing the largest distances to the LFL.

The time varying model in DRIFT 3 did not run for the F2 wet soil scenario. Again DRIFT 2 results are only available for the instantaneous release in F2 weather conditions. Figure 37 shows that the ‘peaky’ and ‘non-peaky’ methodologies in DRIFT 3 produce similar downwind LFL extents, which are larger than the downwind LFL extents predicted by the instantaneous model in DRIFT 2.

All of the results are reported in Table 11.

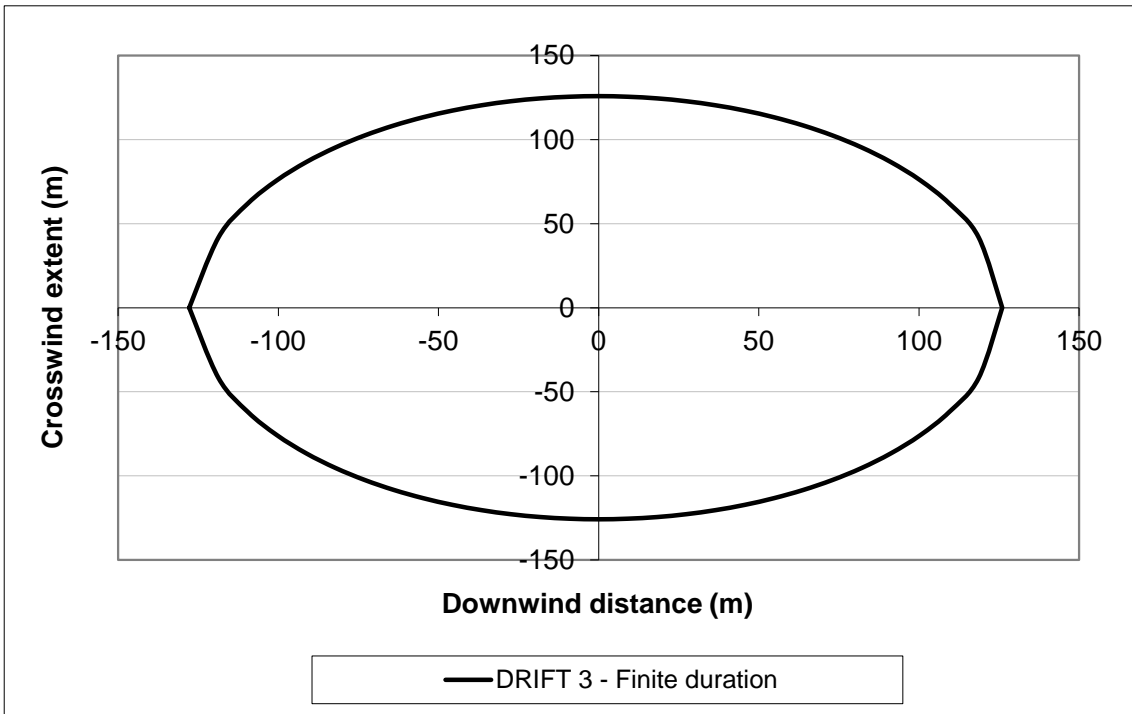


Figure 34 LFL isopleth for a release of LNG from a catastrophic vessel failure with the bund remaining intact in D5 weather, assuming dry soil

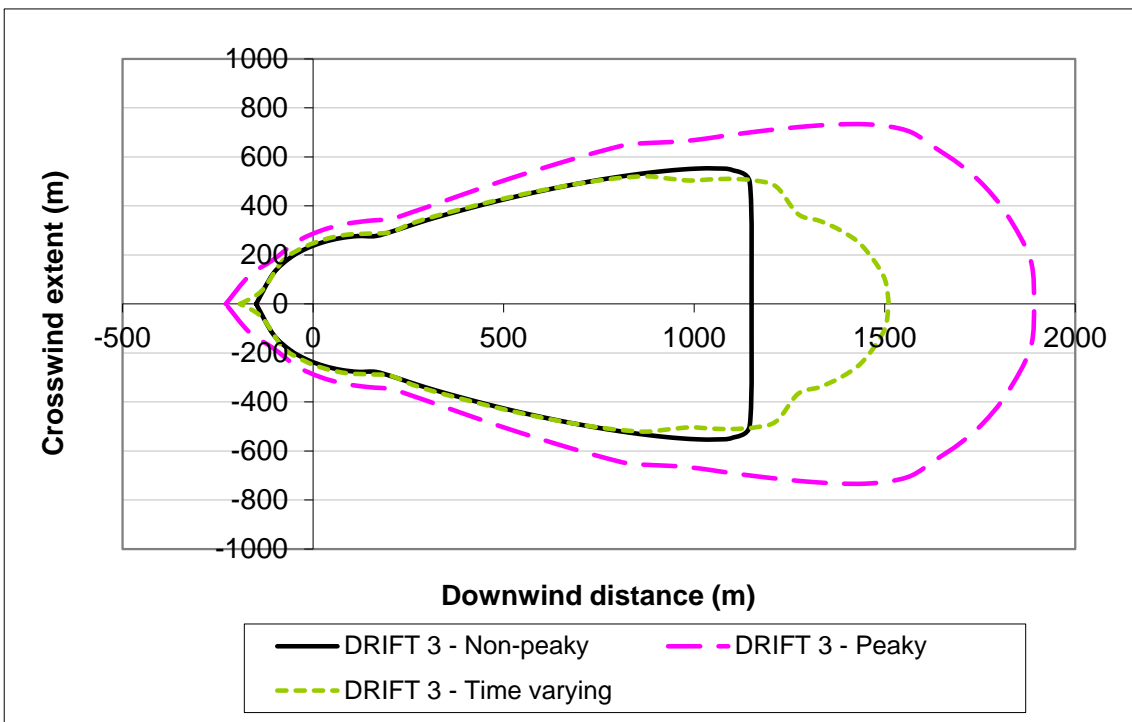


Figure 35 LFL isopleths for a release of LNG from a catastrophic vessel failure with the bund remaining intact in F2 weather, assuming dry soil

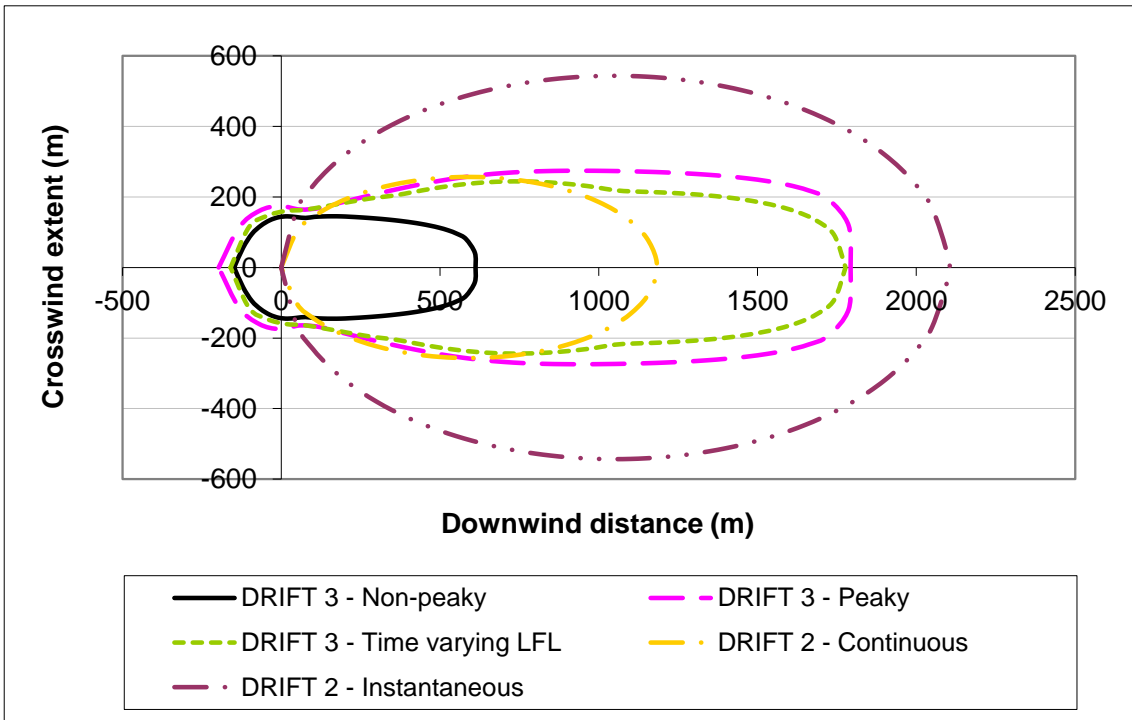


Figure 36 LFL isopleths for a release of LNG from a catastrophic vessel failure with the bund remaining intact in D5 weather, assuming wet soil

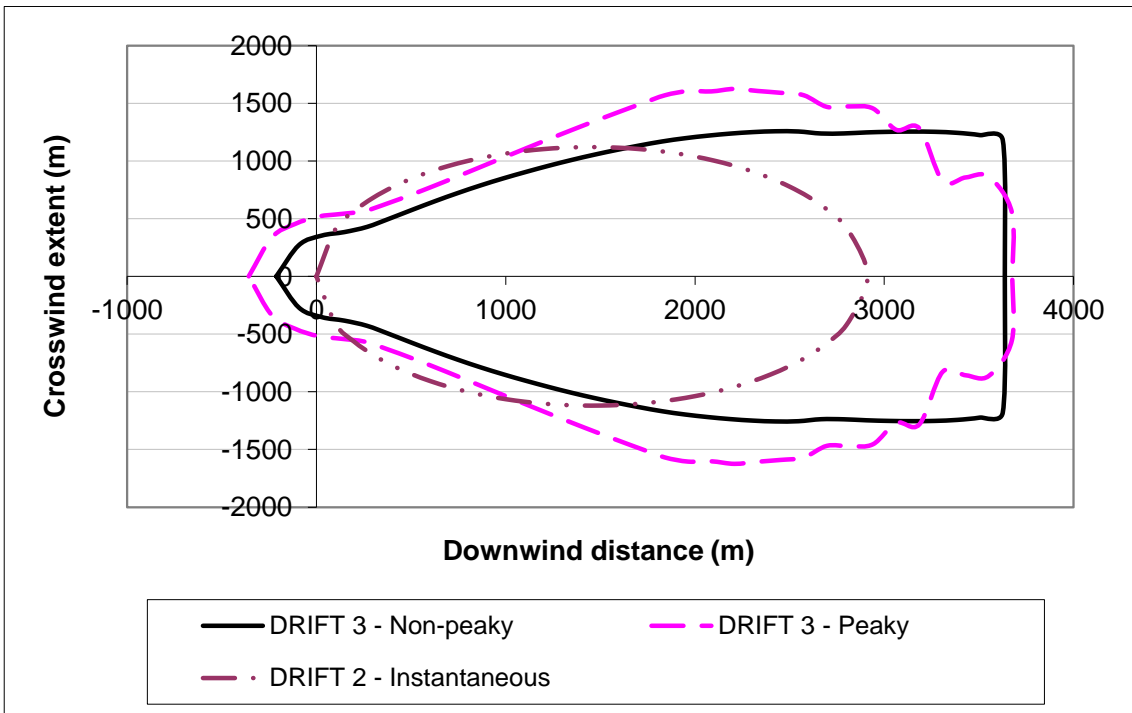


Figure 37 LFL isopleths for a release of LNG from a catastrophic vessel failure with the bund remaining intact in F2 weather, assuming wet soil

The maximum downwind distances to the LFL for Scenario D under different release conditions and using different release methodologies are shown in Table 11.

Table 11 Maximum downwind distances to the LFL for a release of LNG from a catastrophic vessel failure with the bund remaining intact (Scenario D), varying the modelling methodology

<i>Scenario D conditions</i>	<i>Maximum downwind distance to the LFL (m) using specified methodology</i>				
	<i>DRIFT 3</i>			<i>DRIFT 2</i>	
	<i>'Non-peaky'</i>	<i>'Peaky'</i>	<i>Time varying</i>	<i>Continuous</i>	<i>Instantaneous</i>
D5 dry soil	126	N/A	N/A	NR	NR
F2 dry soil	1151	1893	1511	NR	NR
D5 wet soil	612	1793	1777	1183	2102
F2 wet soil	3637	3676	NR	NR	2907

NR indicates no result obtained

N/A indicates that the release was not 'peaky' and only 'non-peaky' results are reported

2.5.5 Scenario H – failure of the liquefied natural gas (LNG) pipework

In this scenario, the pipework that 'exports' the LNG from the tank suffers a guillotine failure. The pipework is assumed to be 200 mm in diameter and 60 m long, leading to a continuous release rate of 61 kg/s upon failure. It is assumed that the isolation time is 30 minutes leading to a total mass released of 110 tonnes. The results from GASP do not satisfy the HSE 'peaky' criteria and hence only the 'non-peaky' methodology has been considered for each wind speed and soil type.

The LFL isopleths generated for the scenario assuming dry soil in D5 weather are shown in Figure 38 and those assuming dry soil in F2 weather are shown in Figure 39. The equivalent plots assuming wet soil are shown in Figure 40 and Figure 41. Figure 40 and Figure 41 contain results from DRIFT 2 from both the continuous and instantaneous models. The maximum downwind distances to the LFL are reported in Table 12.

The instantaneous release modelled in DRIFT 2 produces downwind LFL extents that are larger than those obtained for the continuous release, which are, in turn, larger than the results generated modelling a finite duration release in DRIFT 3. The reason for this has been explained in more detail in Section 2.5.3.

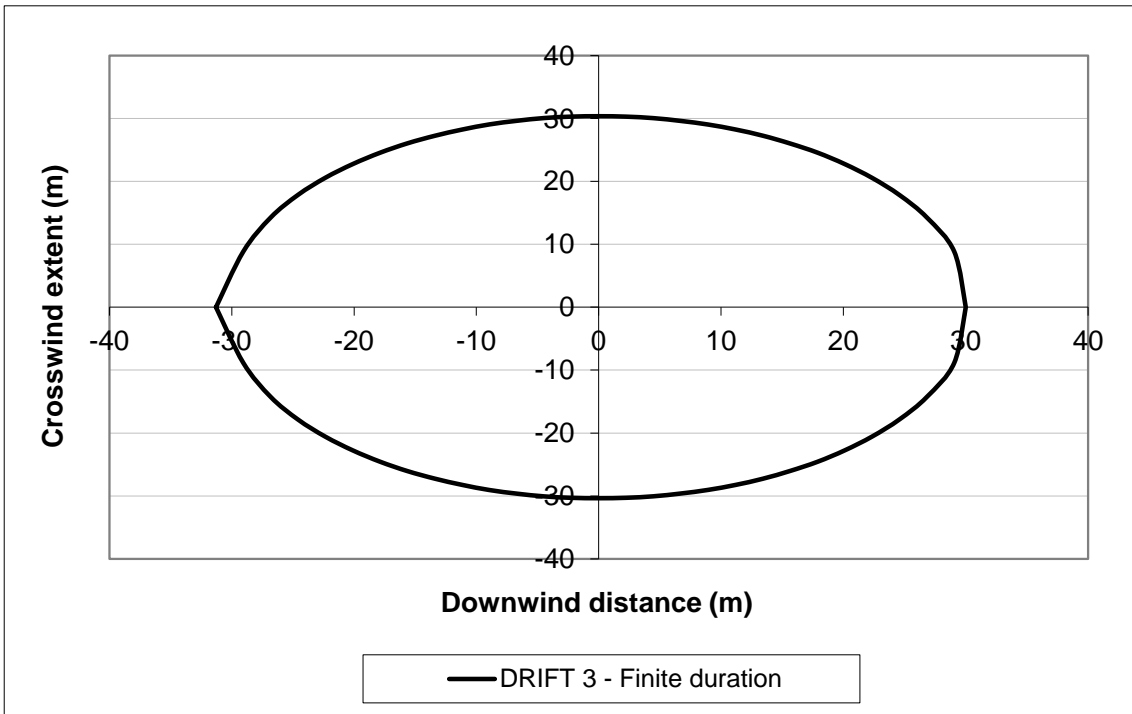


Figure 38 LFL isopleth for a guillotine release of LNG from pipework in D5 weather, assuming dry soil

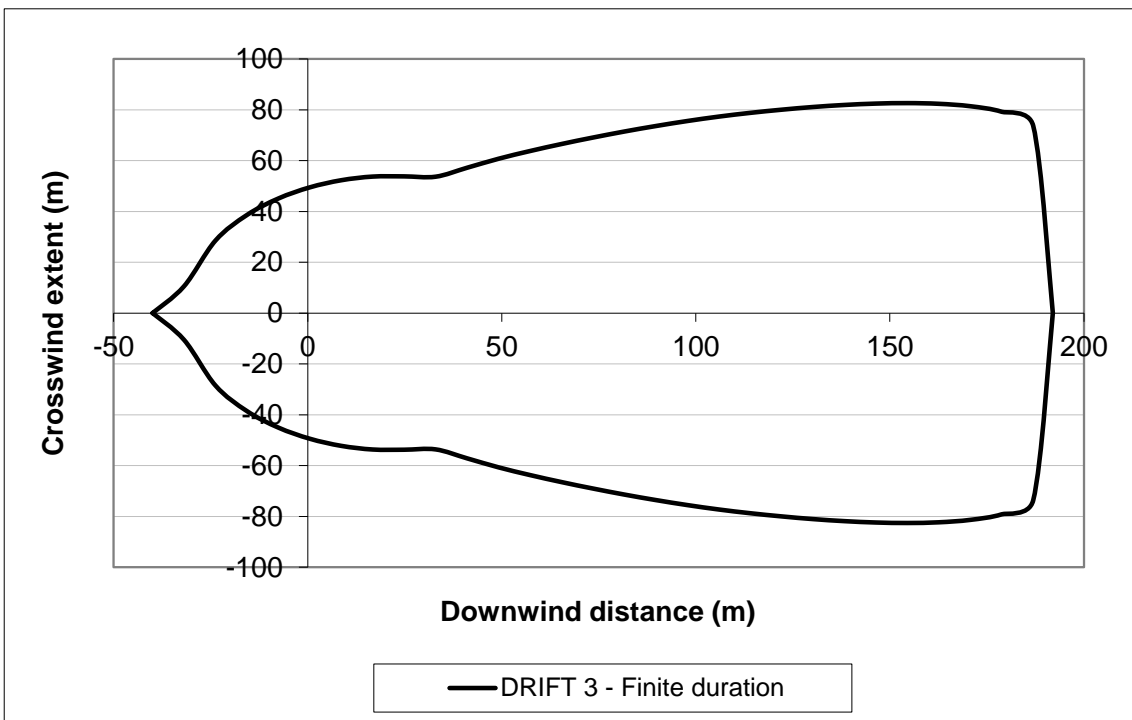


Figure 39 LFL isopleth for a guillotine release of LNG from pipework in F2 weather, assuming dry soil

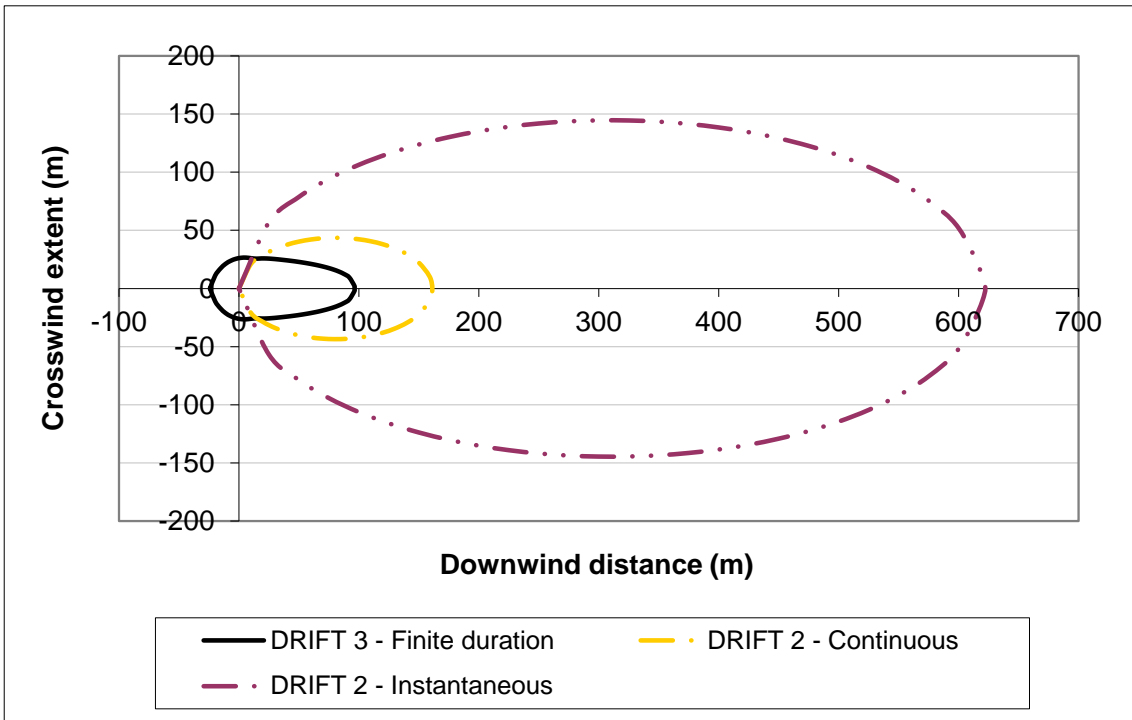


Figure 40 LFL isopleths for a guillotine release of LNG from pipework in D5 weather, assuming wet soil

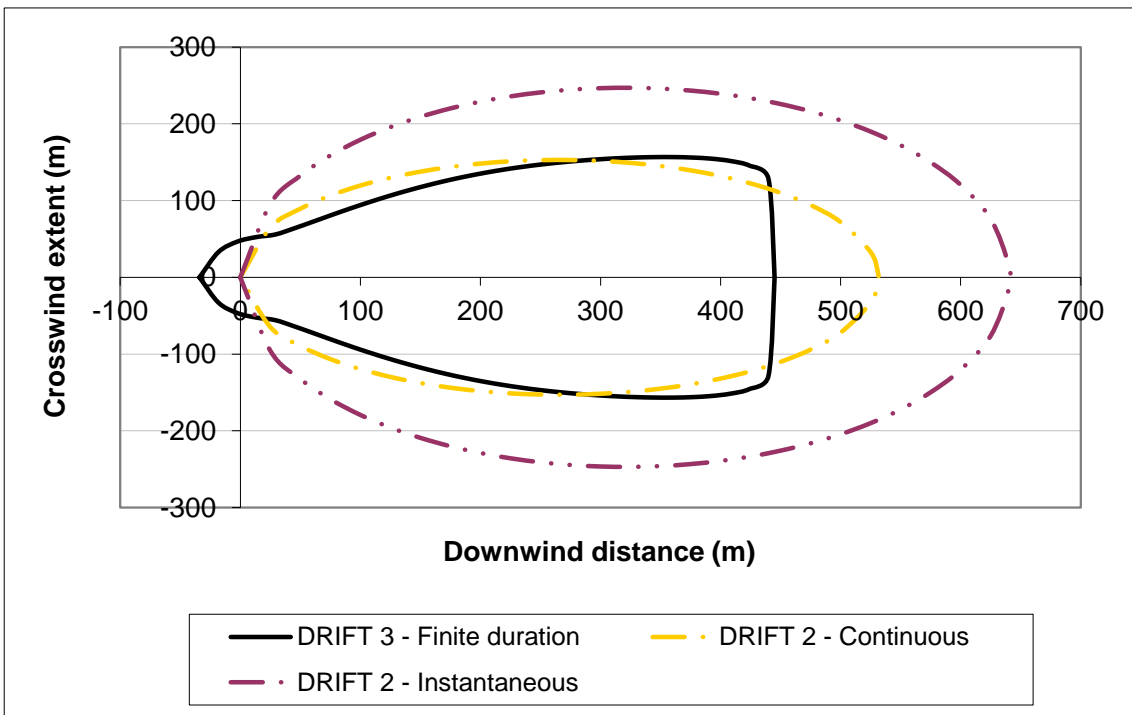


Figure 41 LFL isopleths for a guillotine release of LNG from pipework in F2 weather, assuming wet soil

The maximum downwind distances to the LFL for Scenario H under different release conditions are shown in Table 12.

Table 12 Maximum downwind distances to the LFL for a guillotine release of LNG from pipework (Scenario H), varying the modelling methodology

<i>Scenario H conditions</i>	<i>Maximum downwind distance to the LFL (m) using specified methodology</i>		
	<i>DRIFT 3</i>	<i>DRIFT 2</i>	
	<i>Finite duration</i>	<i>Continuous</i>	<i>Instantaneous</i>
D5 dry soil	30	NR	NR
F2 dry soil	192	NR	NR
D5 wet soil	96	161	621
F2 wet soil	445	531	641

NR indicates no result obtained

2.6 SENSITIVITY ANALYSES FOR THE LIQUEFIED NATURAL GAS (LNG) ASSESSMENT

2.6.1 Pool roughness length

In the original assessment, a pool roughness length of 0 m was used as an input in GASP. The standard HSE assumption regarding pool roughness length has changed since the original assessment was carried out and HSE now assumes a recommended pool roughness length of 0.00023 m. Sensitivity tests have been undertaken using this ‘corrected’ pool roughness length and the results (labelled “Corrected” in the figures) are shown in Figure 42 to Figure 45 for Scenario A (the catastrophic vessel failure and failure of the high wall bund event). Figure 42 and Figure 43 show the outputs assuming dry soil, for D5 and F2 weather scenarios respectively, and Figure 44 and Figure 45 show the equivalent results assuming wet soil. Comparisons are made using the ‘non-peaky’, ‘peaky’ and time varying methodologies to model the scenario. When a pool surface roughness length of 0 m is used, the F2 dry soil scenario does not satisfy the HSE ‘peaky’ criteria; when the pool surface roughness length is corrected to 0.00023 m, all scenarios modelled satisfy the HSE ‘peaky’ criteria.

In some of the plots, some of the contours appear to be approximately circles that have been stretched downstream (e.g. Figure 46). In these cases DRIFT 3 predicts an upwind element to the cloud that is within the radius of the pool, or approximately the same size as the pool radius. It appears that the pool evaporation generates a cloud above the pool, which moves downstream with the wind for a short distance before diluting below the LFL.

The time varying isopleth for the surface roughness length of 0.00023 m in Figure 43 appears to be less smooth than the other isopleths. The plots have been generated using the default parameters in DRIFT 3. Smoother plots can be obtained by adjusting the “Finite Duration Model Time Series Precision” parameter and increasing the “Finite Duration Time Series Extent” parameter in the model. This can lead to a small, approximately 5%, increase in the predicted LFL extent. In the interests of cleaner sensitivity comparisons between all runs, these parameters have not been adjusted.

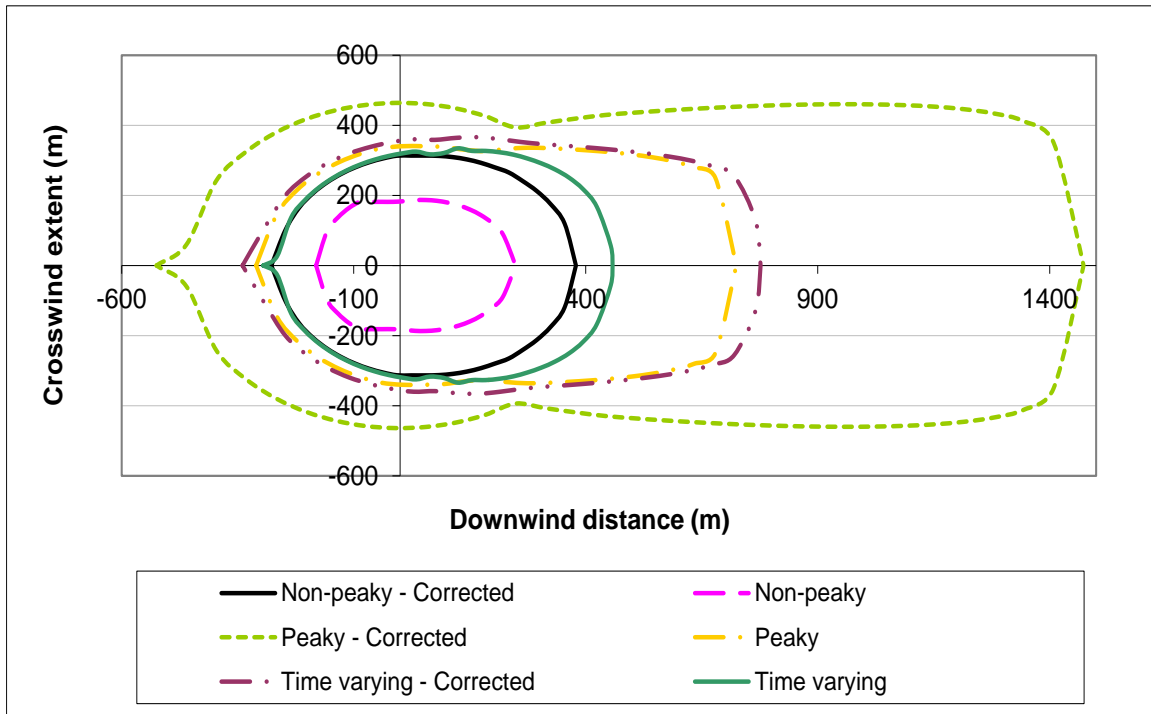


Figure 42 Effect of correcting the pool surface roughness length on the LFL isopleths generated by DRIFT 3 for a release of LNG from a catastrophic vessel failure in D5 weather, assuming dry soil

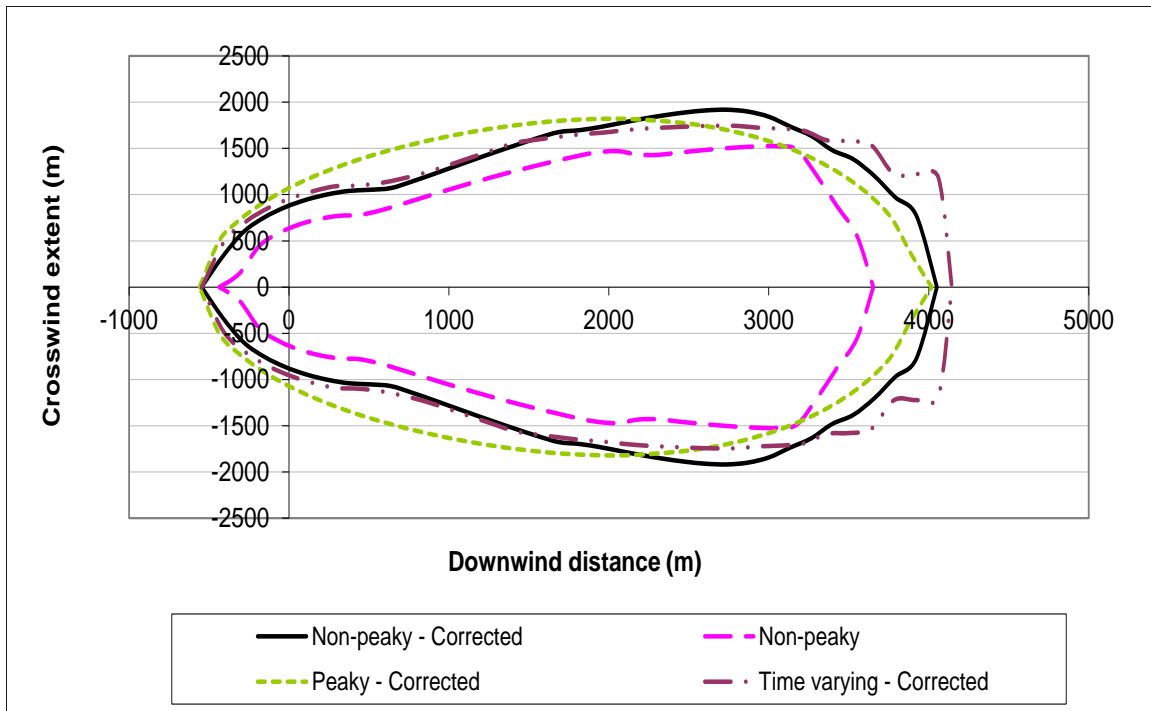


Figure 43 Effect of correcting the pool surface roughness length on the LFL isopleths generated by DRIFT 3 for a release of LNG from a catastrophic vessel failure in F2 weather, assuming dry soil

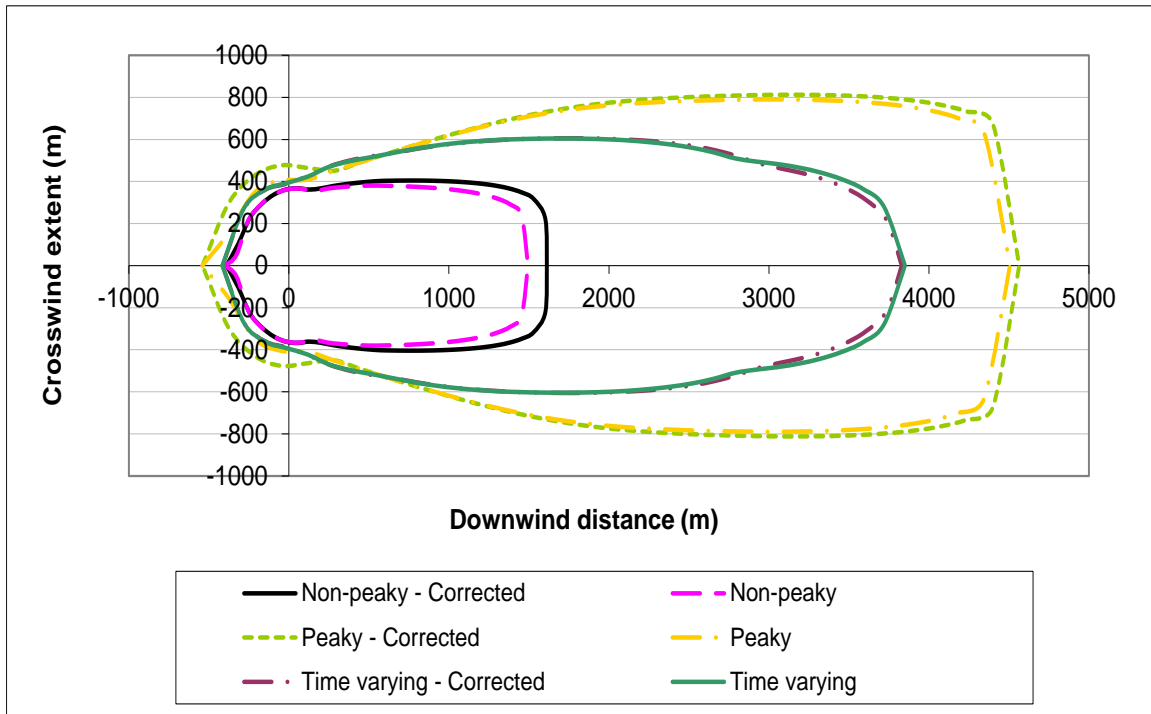


Figure 44 Effect of correcting the pool surface roughness length on the LFL isopleths generated by DRIFT 3 for a release of LNG from a catastrophic vessel failure in D5 weather, assuming wet soil

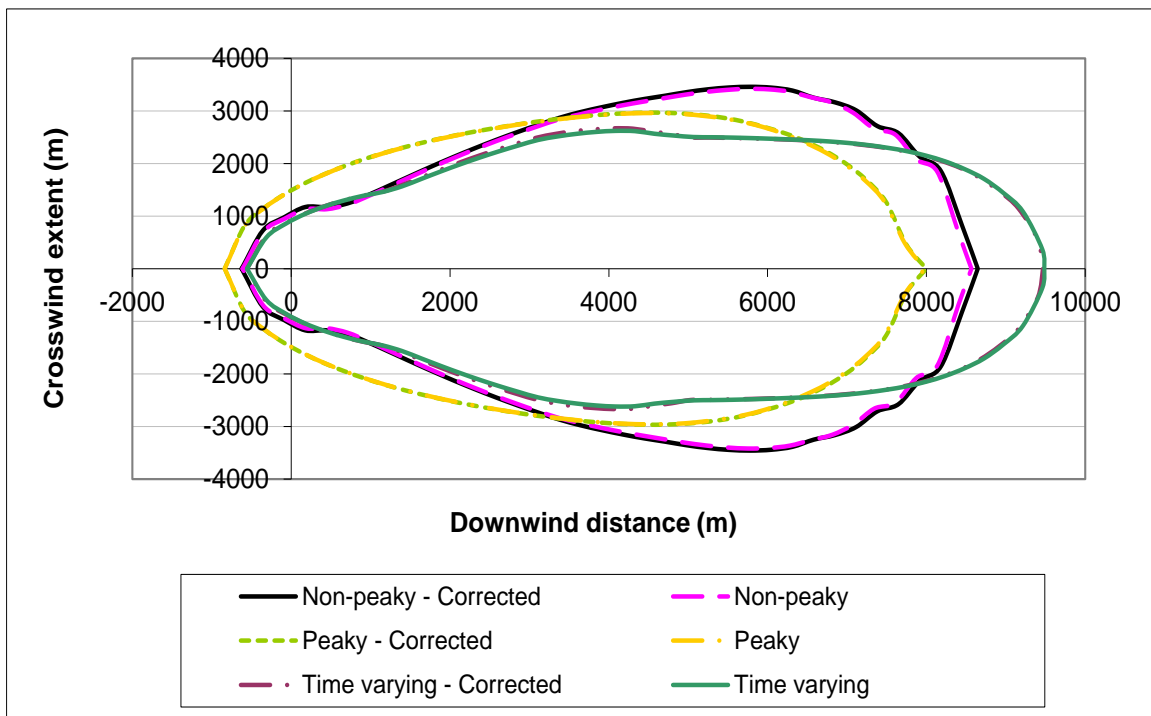


Figure 45 Effect of correcting the pool surface roughness length on the LFL isopleths generated by DRIFT 3 for a release of LNG from a catastrophic vessel failure in F2 weather, assuming wet soil

Similar results have been obtained for Scenario B (the 1000 mm vessel hole with failure of the high wall bund scenario). These results are shown in Figure 46 and Figure 47 assuming dry soil and in Figure 48 and Figure 49 assuming wet soil. In all cases the results using a pool surface roughness length of 0 m (labelled “Original” on the figures) are compared to using a value of 0.00023 m (labelled “Corrected” on the figures).

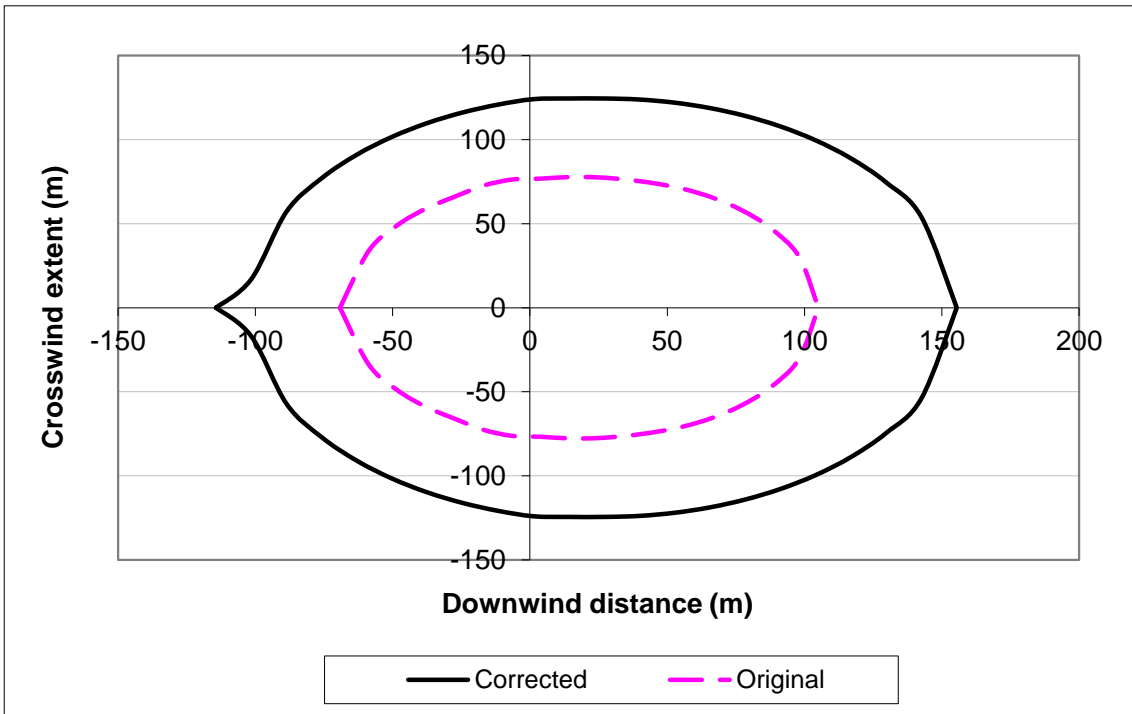


Figure 46 Effect of correcting the pool surface roughness length on the LFL isopleths generated by DRIFT 3 for a release of LNG from a 1000 mm vessel hole in D5 weather, assuming dry soil

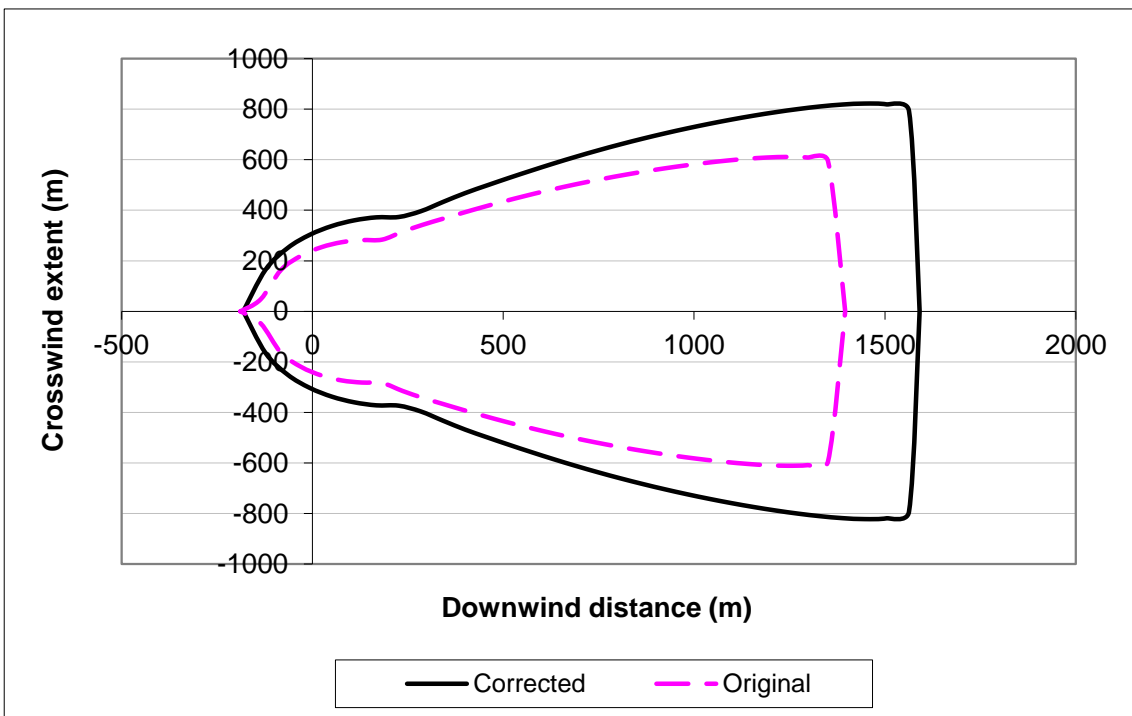


Figure 47 Effect of correcting the pool surface roughness length on the LFL isopleths generated by DRIFT 3 for a release of LNG from a 1000 mm vessel hole in F2 weather, assuming dry soil

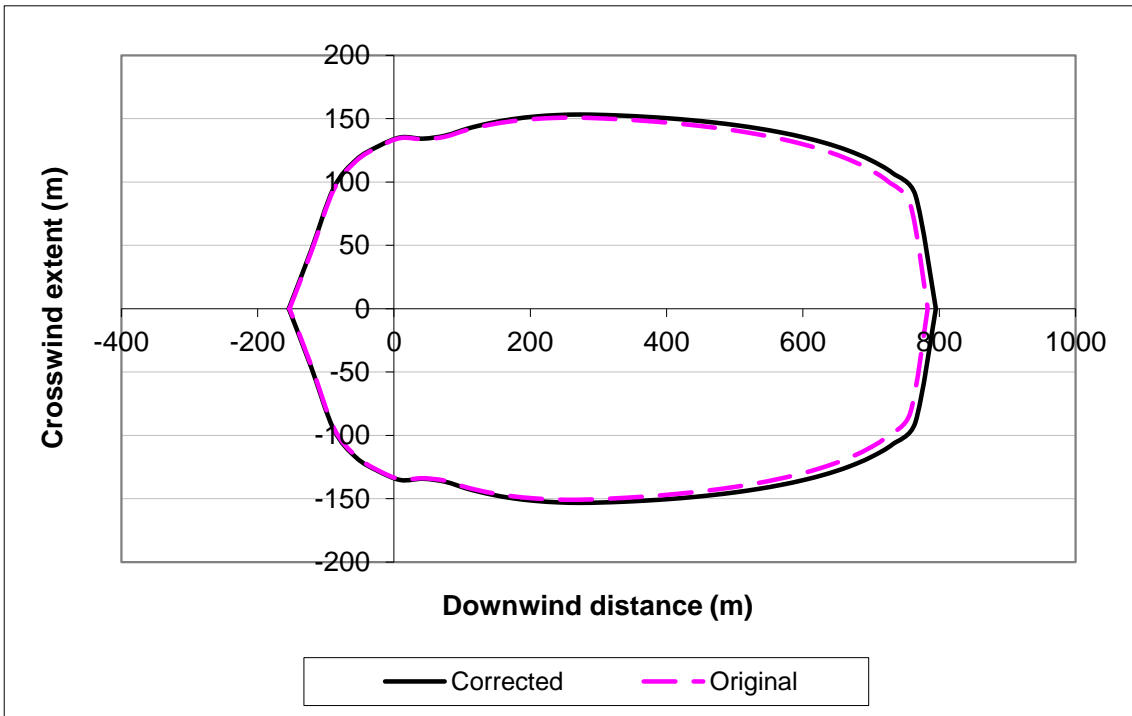


Figure 48 Effect of correcting the pool surface roughness length on the LFL isopleths generated by DRIFT 3 for a release of LNG from a 1000 mm vessel hole in D5 weather, assuming wet soil

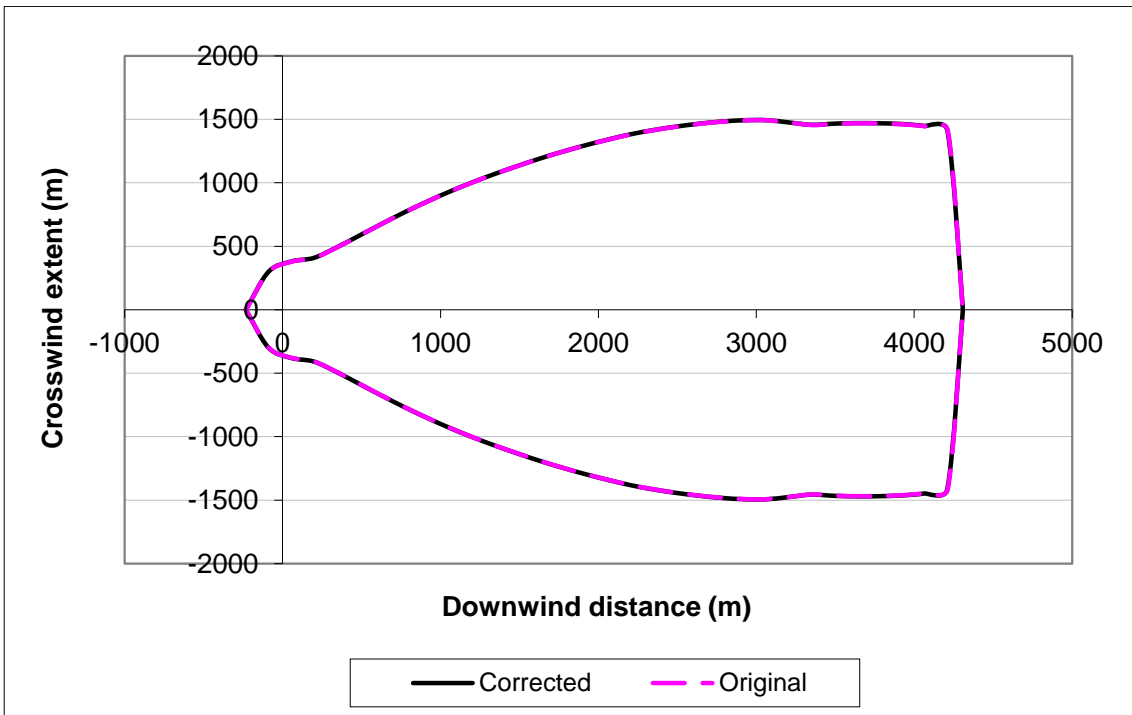


Figure 49 Effect of correcting the pool surface roughness length on the LFL isopleths generated by DRIFT 3 for a release of LNG from a 1000 mm vessel hole in F2 weather, assuming wet soil

Figure 42 shows that increasing the pool roughness length to 0.00023 m has a significant effect on the LFL isopleths predicted for a catastrophic failure of the vessel and failure of the high wall bund (Scenario A) for dry soil in D5 weather conditions. For all the methodologies used, the maximum downwind distances to the LFL are larger for the larger value of pool surface roughness length modelled. In this scenario, the majority

of the vaporisation is due to wind driven evaporation and only a small part is due to heat transfer. The modification from a smooth to a rough pool has a significant effect on the amount of wind driven evaporation that can occur, leading to large differences in the maximum calculated downwind distances.

Figure 43 shows that in F2 weather conditions for dry soil, the maximum downwind distance to the LFL increases when the pool surface roughness length is increased from 0 m to 0.00023 m. When the larger (i.e. the corrected) value of the pool surface roughness is used, the time varying model predicts a larger distance to the LFL than the 'peaky' and 'non-peaky' methodologies.

If wet soil is assumed, varying the pool surface roughness length has a negligible impact on the maximum downwind distances to the LFL. This is true for both Scenario A (catastrophic vessel failure) and Scenario B (1000 mm vessel hole). In Scenario B, the pool surface roughness length has an impact for both D5 and F2 weather when assuming dry soil, with longer downwind distances observed for the larger surface roughness length modelled.

Table 13 reports the maximum downwind distances to the LFL for Scenario A using the three different methodologies for the pool surface roughness lengths of 0 m and 0.00023 m. The greatest effect on the outputs is seen when assuming dry soil, particularly for D5 weather conditions.

Table 13 Maximum downwind distances to the LFL for a release of LNG from a catastrophic vessel failure, using the different release methodologies and modelling two pool surface roughness lengths

<i>Scenario A conditions</i>	<i>Maximum downwind distance to the LFL (m) using specified methodology and surface roughness length</i>					
	<i>'Non-peaky'</i>		<i>'Peaky'</i>		<i>Time varying</i>	
	<i>0 m</i>	<i>0.00023 m</i>	<i>0 m</i>	<i>0.00023 m</i>	<i>0 m</i>	<i>0.00023 m</i>
D5 dry soil	246	379	718	1426	458	777
F2 dry soil	3653	4051	N/A	3927	N/A	4144
D5 wet soil	1494	1612	4482	4561	3850	3829
F2 wet soil	8567	8647	7770	7785	9485	9467

N/A indicates that the release was not 'peaky' and only the 'non-peaky' results are displayed

Table 14 reports the results for Scenario B illustrating that the greatest impacts are seen when assuming a spill on dry soil.

Table 14 Maximum downwind distances to the LFL for a release of LNG from a 1000 mm vessel hole, modelling two pool surface roughness lengths

<i>Scenario B conditions</i>	<i>Maximum downwind distance to the LFL (m) using specified surface roughness length</i>	
	<i>Pool surface roughness length = 0 m</i>	<i>Pool surface roughness length = 0.00023 m</i>
D5 dry soil	105	155
F2 dry soil	1396	1591
D5 wet soil	783	795
F2 wet soil	4307	4308

Changing the pool surface roughness length in GASP when modelling spills onto wet soil gives no discernible difference in the outputs generated by the model. Changing the pool surface roughness length when modelling spills onto dry soil does lead to differences in the outputs generated by GASP. These changes in the GASP outputs subsequently lead to differences in the isopleths generated by DRIFT when modelling spills onto dry soil for the two pool surface roughness lengths modelled. When modelling dry

soil, the vaporisation rate calculated by GASP for a pool surface roughness of 0.00023 m is approximately 50% higher than that calculated for a pool surface roughness of 0 m. When assuming a spill onto wet soil, the vaporisation rate does not significantly change for the two pool surface roughness lengths modelled.

For wet soil, the higher ground thermal conductivity and diffusivity gives a higher heat flux to the cold pool. The result is boiling of the pool, in which case, the vaporisation rate is mainly determined by the heat flux from the ground rather than by air flow over the pool. For dry soil, the heat flux from the ground is much less and the pool is further below the boiling temperature, so the vaporisation rate is determined mainly by turbulent (diffusive) transport of vapour from the pool surface due to air flow over the pool. The pool surface roughness enhances the diffusive transport of vapour from the pool surface, which leads to the greater observed differences in the results between smooth and rough pools when modelling spills onto dry soil.

2.6.2 Relative humidity

A relative humidity of 70% was assumed in the original assessment. Sensitivity tests have been performed using relative humidities of 80% and 60%. A pool roughness length of 0.00023 m has been assumed in all cases, in line with the current HSE policy. LFL isopleths have been plotted for each of the two weather conditions and for modelling spills onto dry soil and wet soil. The results for Scenario A (catastrophic failure of the vessel and the high wall bund) are shown in Figure 50 to Figure 53, where the three different methodologies are reported i.e. 'peaky', 'non-peaky' and time varying.

In some of the plots, the contours appear to be approximately circles that have been stretched downstream (e.g. Figure 50). In these cases DRIFT 3 predicts an upwind element to the cloud that is within the radius of the pool, or approximately the same size as the pool radius. It appears that the pool evaporation generates a cloud above the pool, which moves downstream with the wind for a short distance before diluting below the LFL.

The figures show that in D5 weather conditions, the maximum downwind distance to the LFL is generally lower when a relative humidity of 80% is used than when a relative humidity of 60% is used. As the water content in the atmosphere increases, more water condenses due to the low temperature of the liquefied natural gas, which releases latent heat into the cloud. This decreases the cloud density, which leads to greater mixing and hence the cloud disperses more quickly. The process occurs for both wet and dry soil types. There is little difference in the downwind LFL extents calculated for the different relative humidities when modelling F2 weather assuming dry soil. When modelling a spill onto wet soil in F2 weather, changing the humidity has the most significant effect on the results when the time varying model is used. In percentage terms the difference is under 5% and is less than the differences seen in D5 weather. This is reflected in Table 15 which reports the maximum downwind distances to the LFL using 60%, 70% and 80% relative humidity.

The results in Table 15 show that the maximum downwind distances to the LFL obtained using 70% relative humidity lie between the 60% and 80% relative humidity results, except when using the 'non-peaky' method to model a spill onto dry soil in F2 weather conditions. For this particular set of conditions, the results generated using the three relative humidities vary by less than 0.5%.

The time varying isopleths in Figure 51 appear to be less smooth than the other isopleths. The plots have been generated using the default parameters in DRIFT 3. Smoother plots can be obtained by adjusting the "Finite Duration Model Time Series Precision" parameter and increasing the "Finite Duration Time Series Extent" parameter in the model. This can lead to a small, approximately 5%, increase in the predicted LFL extent. In the interests of cleaner sensitivity comparisons between all runs, these parameters have not been adjusted.

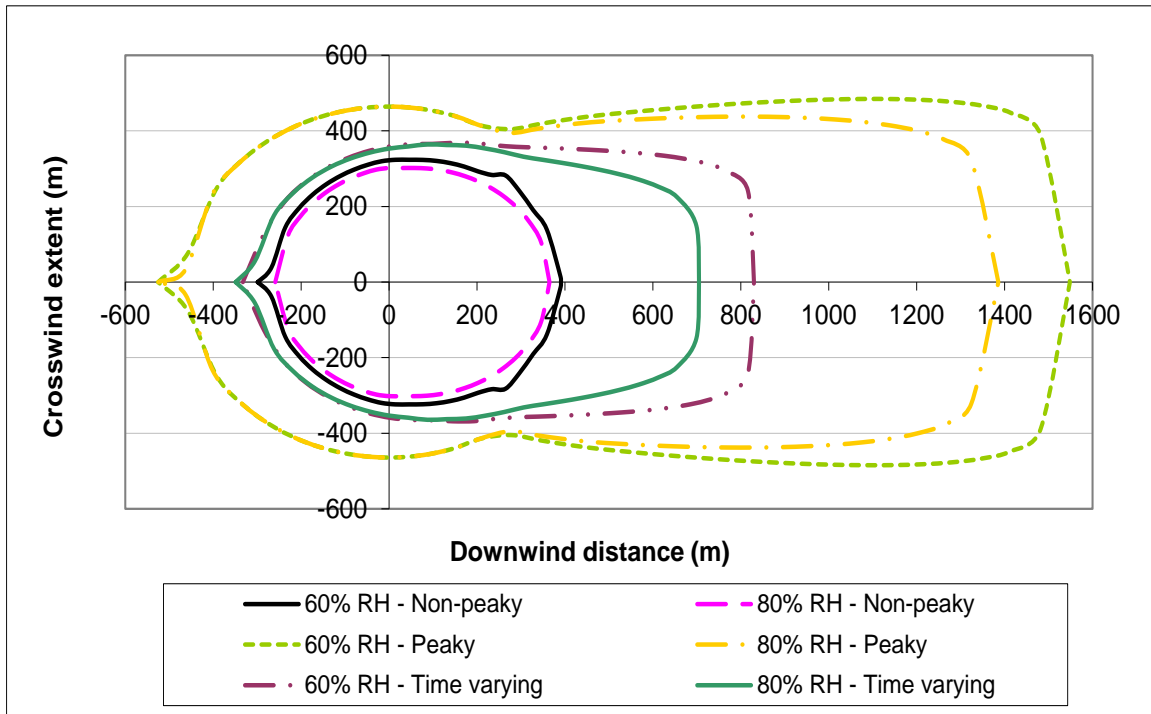


Figure 50 Effect of varying the relative humidity on the LFL isopleths for a release of LNG from a catastrophic vessel failure in D5 weather, assuming dry soil

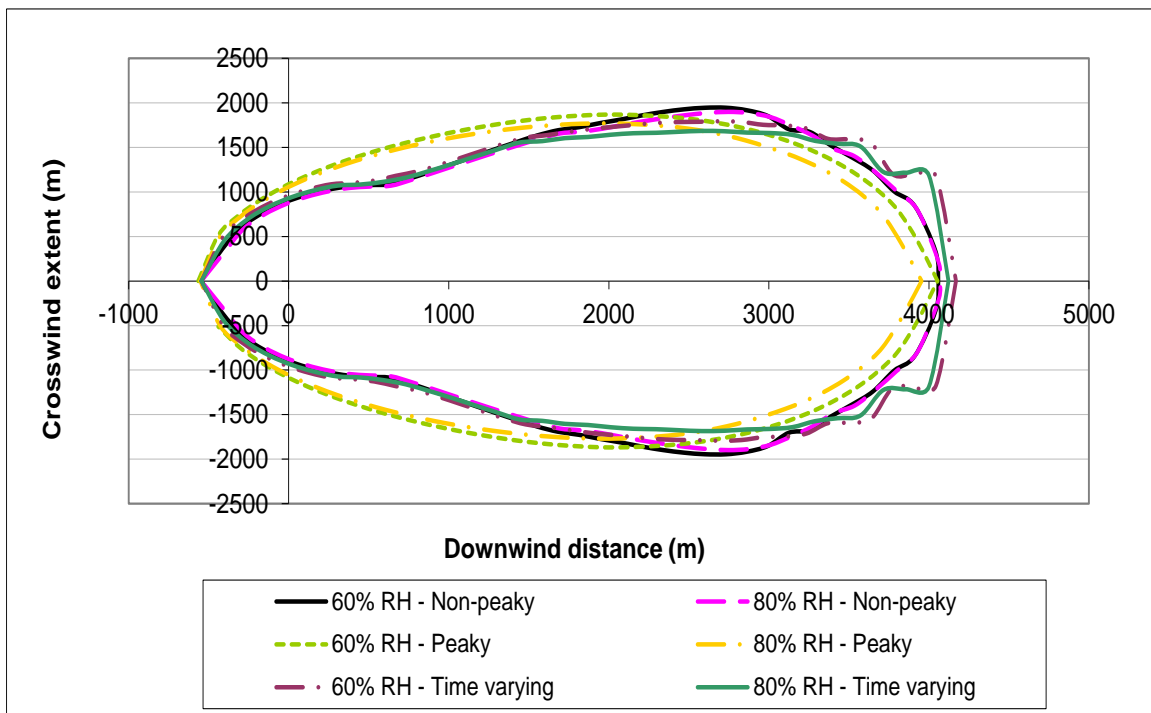


Figure 51 Effect of varying the relative humidity on the LFL isopleths for a release of LNG from a catastrophic vessel failure in F2 weather, assuming dry soil

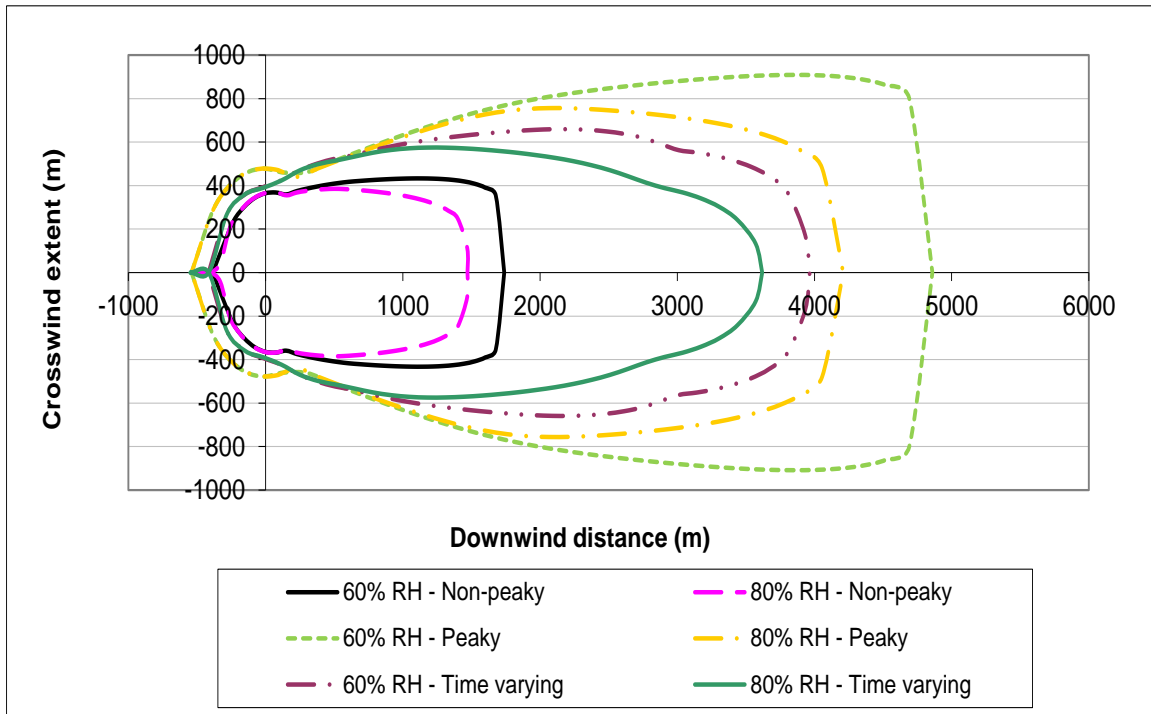


Figure 52 Effect of varying the relative humidity on the LFL isopleths for a release of LNG from a catastrophic vessel failure in D5 weather, assuming wet soil

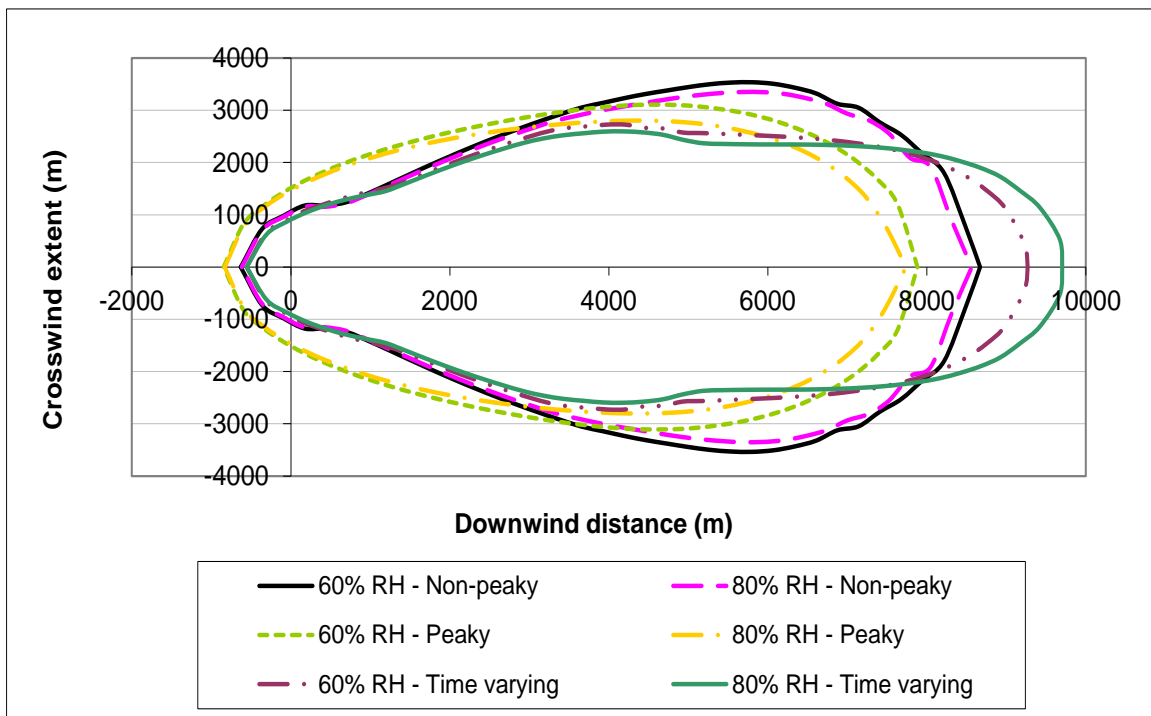


Figure 53 Effect of varying the relative humidity on the LFL isopleths for a release of LNG from a catastrophic vessel failure in F2 weather, assuming wet soil

Table 15 shows the maximum downwind distances to the LFL for Scenario A using three different values for the relative humidity.

Table 15 Maximum downwind distances to the LFL for a catastrophic release of LNG, using the ‘non-peaky’, ‘peaky’ and time varying methodologies, and varying the relative humidity

Scenario A conditions	Maximum downwind distance to the LFL (m) using specified methodology and relative humidity								
	‘Non-peaky’			‘Peaky’			Time varying		
	60%	70%	80%	60%	70%	80%	60%	70%	80%
D5 dry soil	391	379	365	1500	1426	1350	830	777	705
F2 dry soil	4059	4051	4069	3984	3927	3881	4169	4144	4122
D5 wet soil	1739	1612	1471	4831	4561	4180	3965	3829	3619
F2 wet soil	8670	8647	8566	7875	7785	7602	9268	9467	9703

2.6.3 Steady continuous model in DRIFT

DRIFT 2 contains the options to model either a continuous release or an instantaneous release (see Section 2.2). In DRIFT 3, there are also the options to model a finite duration release and a time varying release. Based on the work undertaken for assessing how to model toxic releases, HSE models the dispersion of vapour from pools in DRIFT 3 by importing the source term results generated by GASP and using the DRIFT 3 finite duration model option. To test the sensitivity to the model chosen, the scenarios were also modelled using the steady continuous option in DRIFT 3. The scenarios modelled for these sensitivity tests used a pool surface roughness length of 0 m, as was used in the original assessment.

Scenarios A and B were chosen for the sensitivity tests. These are both large releases, but Scenario A is an instantaneous release and Scenario B is continuous.

Scenario A (catastrophic vessel failure and failure of the high wall bund) has been rerun using the steady continuous option and the results compared with the results obtained using the finite duration option, assuming the ‘non-peaky’ methodology. Figure 54 illustrates the results in D5 weather assuming dry soil, whilst Figure 55 plots the results in F2 weather assuming dry soil. The equivalent plots for spills onto wet soil are shown in Figure 56 and Figure 57. The maximum downwind distances to the LFL are reported in Table 16.

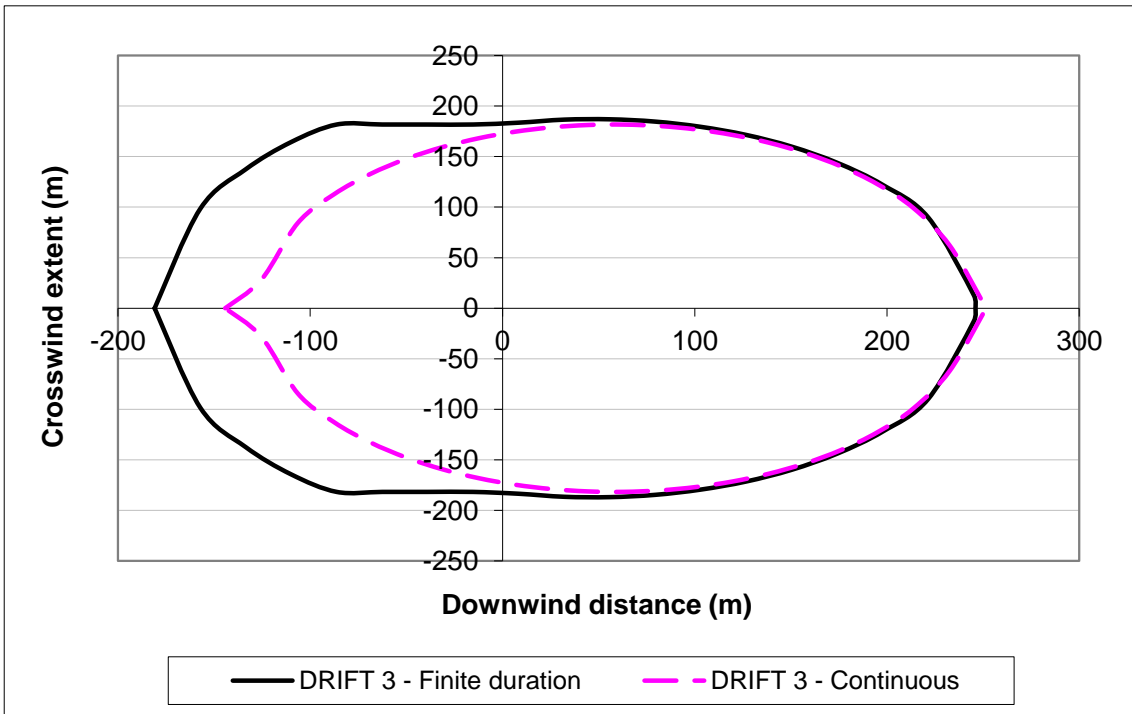


Figure 54 Effect of using the steady continuous model in DRIFT 3 on the LFL isopleths for a release of LNG from a catastrophic vessel failure in D5 weather, assuming dry soil

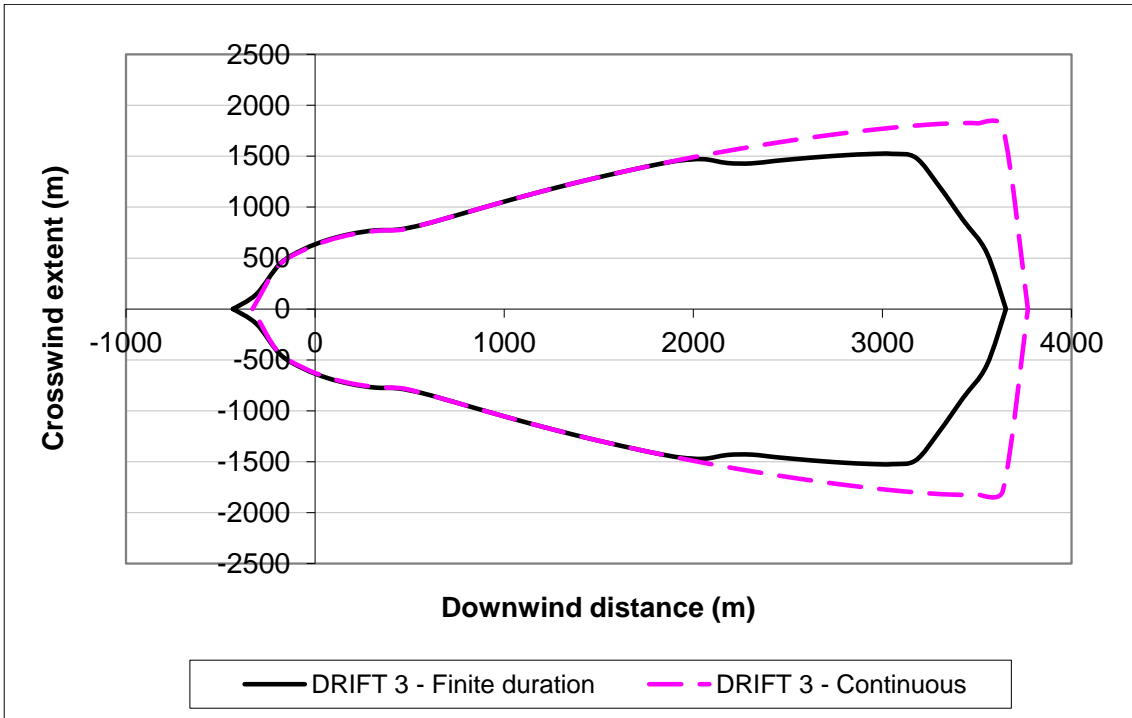


Figure 55 Effect of using the steady continuous model in DRIFT 3 on the LFL isopleths for a release of LNG from a catastrophic vessel failure in F2 weather, assuming dry soil

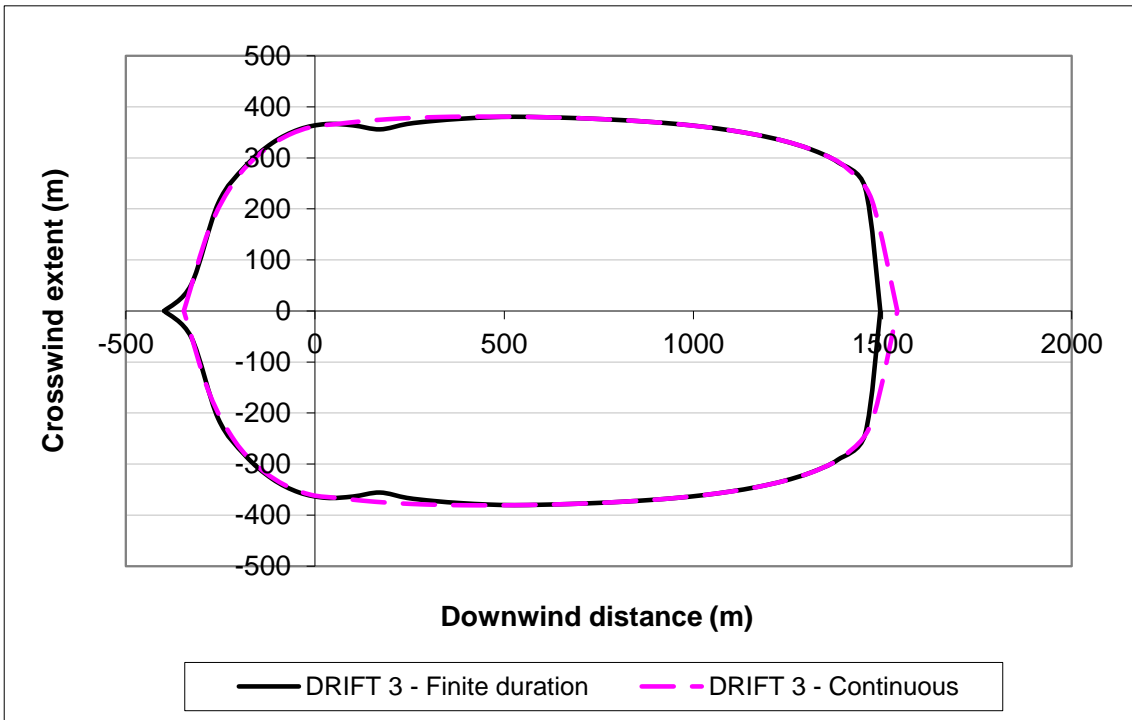


Figure 56 Effect of using the steady continuous model in DRIFT 3 on the LFL isopleths for a release of LNG from a catastrophic vessel failure in D5 weather on wet soil

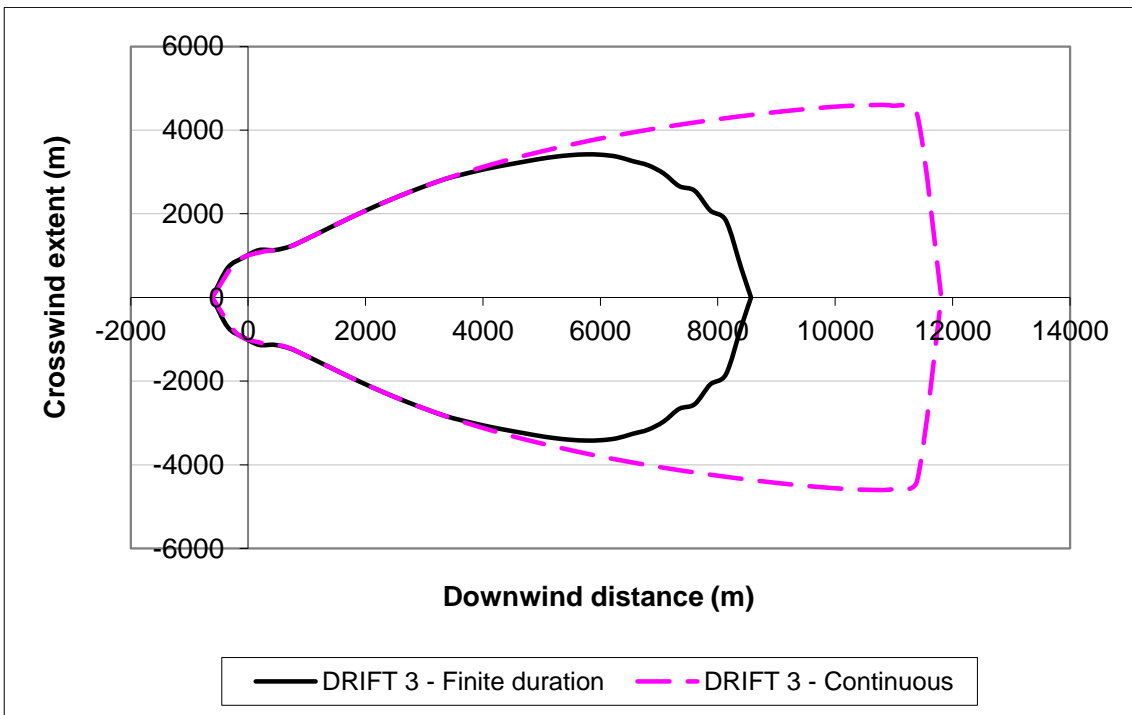


Figure 57 Effect of using the steady continuous model in DRIFT 3 on the LFL isopleths for a release of LNG from a catastrophic vessel failure in F2 weather on wet soil

Table 16 shows the maximum downwind distances to the LFL predicted by DRIFT 3.6.14 for Scenario A under different release conditions, using the finite duration and steady continuous models.

Table 16 Maximum downwind distances to the LFL predicted by DRIFT 3.6.14 for a release of LNG from a catastrophic vessel failure, using the finite duration and steady continuous models

<i>Scenario A conditions</i>	<i>Maximum downwind distance to the LFL (m)</i>	
	<i>Finite duration</i>	<i>Steady continuous</i>
D5 dry soil	246	244
F2 dry soil	3653	3705
D5 wet soil	1494	1494
F2 wet soil	8567	11490

The figures and the table show that there appears to be a difference in behaviour for the D5 and F2 weather scenarios. In D5 weather, the downwind LFL distances are unchanged when the steady continuous model is used instead of the finite duration model. In F2 weather, the distances are increased by moving to the steady continuous model.

The steady continuous model in DRIFT 3 considers a constant release rate over an extended period, where the release time is of a duration that is much longer than the time for dispersion. DRIFT 3 neglects along-wind diffusion when modelling a steady continuous release. This means that the decay of the downwind concentration profile on the centreline height along-wind axis is independent of the duration of the release and the overall quantity released.

The finite duration model is a modification of the steady continuous model which accounts for longitudinal mixing and spreading at the front and back along-wind edges of the cloud. The finite duration model can be thought of as gradually eroding a steady continuous 'core'. The effect of this is that, in the far field (i.e. some distance from the source) the concentrations predicted by the finite duration model will decay more rapidly than those predicted by the steady continuous model. This, in turn, leads to shorter predicted dispersion distances in some scenarios, particularly those with large release rates and where the cloud is still above criterion concentrations at long downwind distances. The finite duration model is expected to give a better representation of the physical processes that would occur during an actual release than the steady continuous model.

Scenario B (1000 mm vessel hole and failure of the high wall bund) was rerun using the steady continuous model in DRIFT 3. These sensitivity tests used the pool surface roughness length assumed in the original assessments (i.e. 0 m). The results are shown in Figure 58 and Figure 59 assuming a spill onto dry soil in D5 and F2 weather conditions respectively, and in Figure 60 and Figure 61 for the equivalent wet soil scenarios. The maximum downwind distances to the LFL are reported in Table 17.

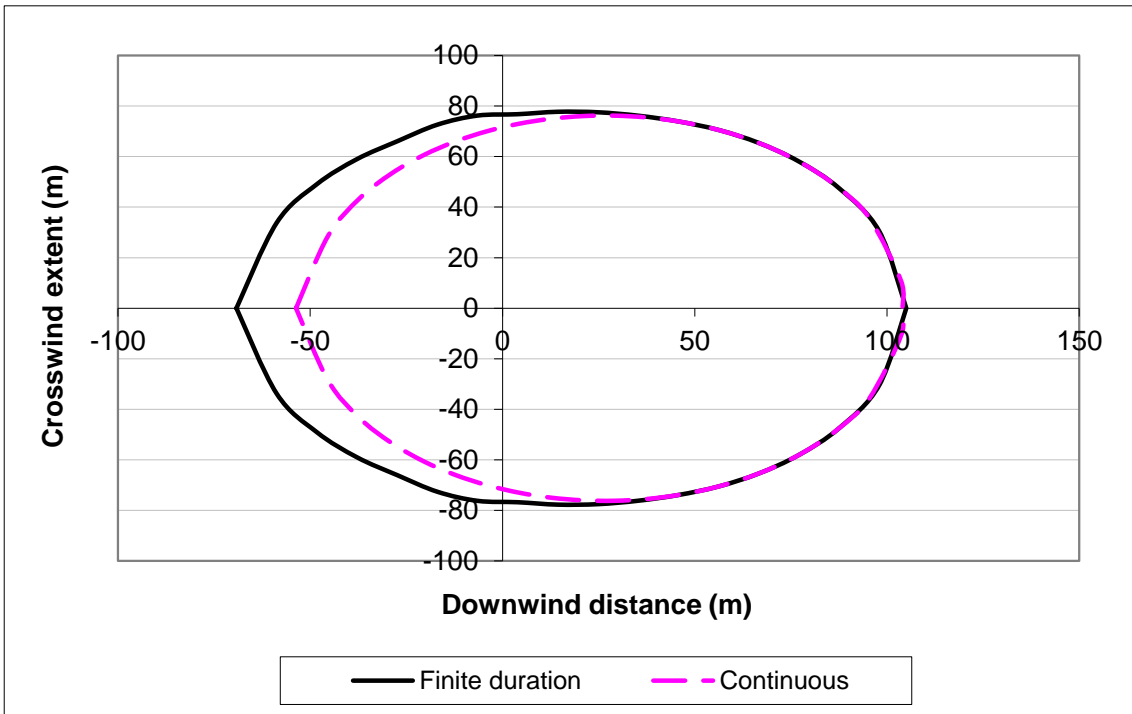


Figure 58 Effect of using the steady continuous model in DRIFT 3 on the LFL isopleths for a release of LNG from a 1000 mm vessel hole in D5 weather on dry soil

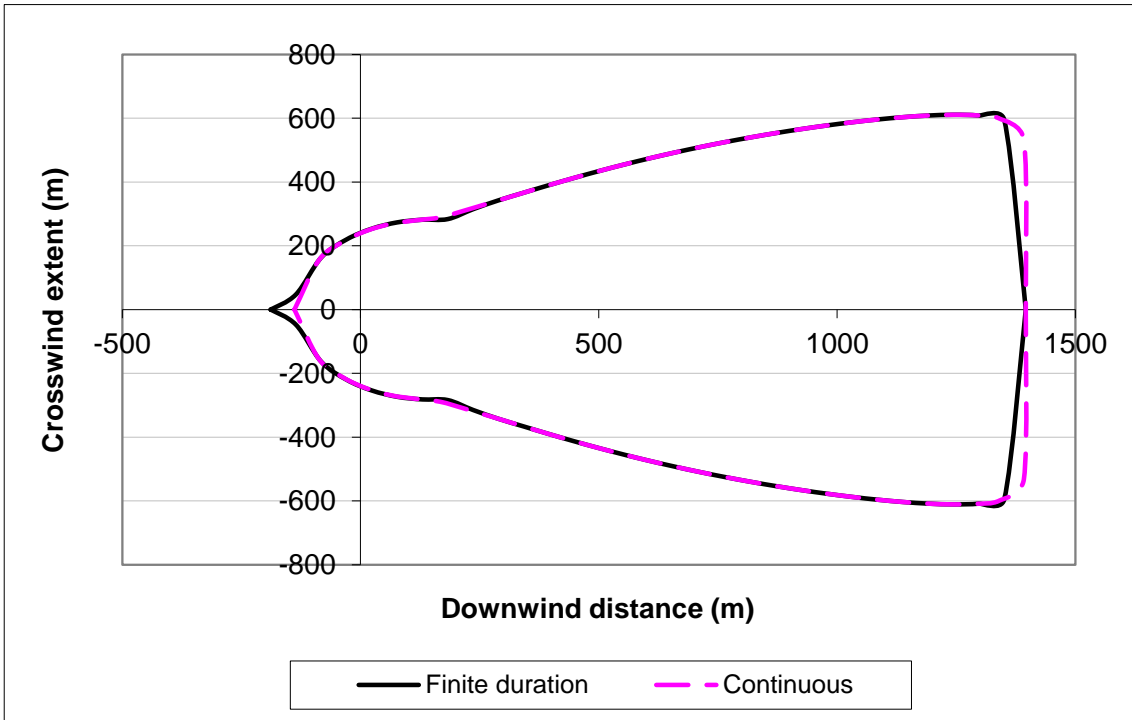


Figure 59 Effect of using the steady continuous model in DRIFT 3 on the LFL isopleths for a release of LNG from a 1000 mm vessel hole in F2 weather on dry soil

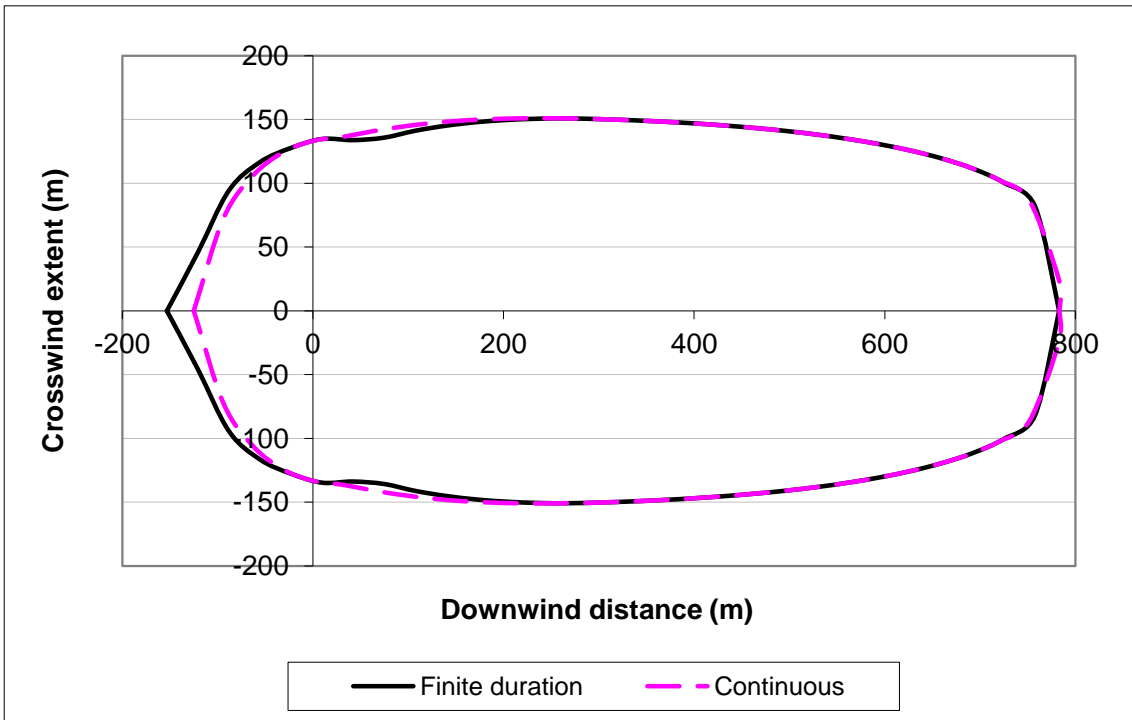


Figure 60 Effect of using the steady continuous model in DRIFT 3 on the LFL isopleths for a release of LNG from a 1000 mm vessel hole in D5 weather on wet soil

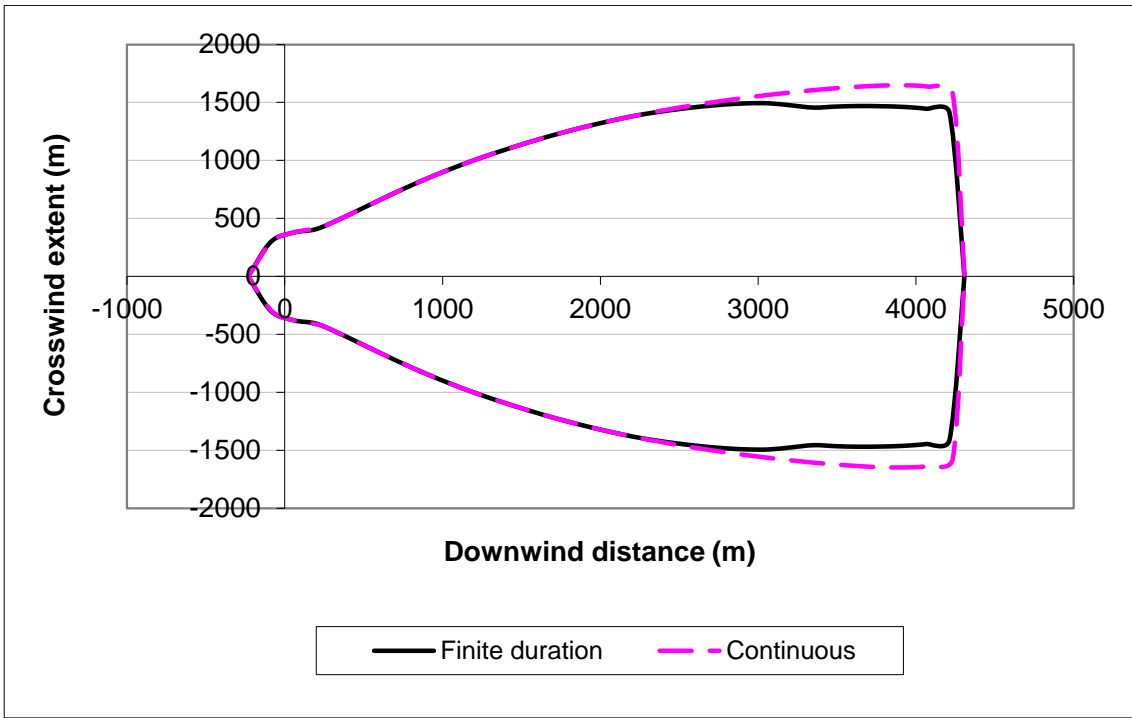


Figure 61 Effect of using the steady continuous model in DRIFT 3 on the LFL isopleths for a release of LNG from a 1000 mm vessel hole in F2 weather on wet soil

The maximum distances to the LFL predicted by DRIFT 3.6.14 for Scenario B under different release conditions, using the finite duration and steady continuous models, are shown in Table 17.

Table 17 Maximum downwind distances to the LFL predicted by DRIFT 3.6.14 for a release of LNG from a 1000 mm vessel hole, using the finite duration and steady continuous models

<i>Scenario B conditions</i>	<i>Maximum downwind distance to the LFL (m) using specified methodology</i>	
	<i>Finite duration</i>	<i>Steady continuous</i>
D5 dry soil	105	104
F2 dry soil	1396	1396
D5 wet soil	783	783
F2 wet soil	4307	4307

The figures and table show that there is no significant difference in the downwind LFL distances when comparing the results for the finite duration model to those obtained from the continuous model for the scenarios modelled.

2.7 DISCUSSION AND CONCLUSIONS FOR EVAPORATING POOLS

For both the consent assessments considered here, the LFL isopleths predicted by DRIFT 3.6.14 are, in general, shorter and narrower than those predicted by DRIFT 2.31. In the LNG case, this may be partly due to the change from using the continuous model in DRIFT 2, to using the finite duration model in DRIFT 3. When the results from the steady continuous model in DRIFT 3 are compared to those from the finite duration model, it can be seen that the maximum downwind distances to the LFL predicted by the finite duration model are shorter than, or the same as, those predicted by the steady continuous model. This is in line with the results seen when moving from DRIFT 2 continuous model to the finite duration model in DRIFT 3. Although the same basic equations are used in both the finite duration and the continuous models, the cloud is treated differently in post-processing. The finite duration model includes dilution of the leading and trailing edges of the plume, which means that the cloud spreads longitudinally. The larger the travel time, the greater the effect of this dilution.

Some of the differences between the LFL isopleths predicted by the instantaneous and continuous models in DRIFT 2.31, and the finite duration model in DRIFT 3.14 may be caused by the fact that DRIFT 2.31 is unable to model area sources. DRIFT 2.31 treats the GASP output as a line source along the crosswind axis, of length equal to the mean pool diameter predicted by GASP. The area source modelled by DRIFT 3.6.14 is necessarily more dilute than the line source modelled in DRIFT 2.31. Furthermore, when an area source is modelled, some of the flammable material will start to disperse from positions upwind of the origin and may spread further upwind and dilute due to gravity spreading. These factors may help to explain why DRIFT 3.6.14 predicts smaller downwind dispersion distances than those obtained in DRIFT 2.31 and also explains why an upwind component to the dispersion has been observed in DRIFT 3.6.14 but cannot be calculated in DRIFT 2.31.

For buoyant releases, consideration needs to be given to whether or not the centreline height should be used to calculate the downwind LFL extents. The maximum downwind distance to the LFL can vary considerably with the height chosen. In most cases the centreline height should be used as a person underneath the buoyant part of the cloud could suffer adverse effects if the cloud ignites. The exception could be if the cloud is highly buoyant and the distance to a person underneath it is large enough that they would be unaffected should the cloud ignite. This type of scenario would need to be considered on a case by case basis.

The pool surface roughness length can have a significant impact in some scenarios. The standard default value of 0.00023 m should be used unless there are specific reasons for using a different value.

Relative humidity can affect the predicted LFL isopleths for some substances. In general, the lower the relative humidity then the greater the distance that the flammable cloud extends. This is due to the increased latent heat released into the cloud as the water content increases (i.e. as relative humidity increases), which leads to enhanced mixing. The standard assumption is to use a value of 60%, unless there are specific reasons to use another value. This appears to be a relatively cautious choice, and is consistent with the value assumed in other HSE models.

Further consideration needs to be given to releases that satisfy the 'peaky' criteria (these are releases for which the maximum vaporisation rate output from GASP is at least twice the mean vaporisation rate calculated over the release duration). The time varying model has been investigated, together with the 'peaky' and 'non-peaky' methodologies. In most cases, the 'non-peaky' methodology produced the shortest downwind LFL extents and the 'peaky' model produced the longest, although there are a few scenarios where this is not the case. The time varying model generally produces downwind LFL extents that lie between the results obtained from the two other methods. The time varying model can be considered to be the most "realistic" approximation in that it endeavours to model the peak in the vaporisation rate from a release, as well as the steady vaporisation rate of the release after the peak. The time varying model in DRIFT 3.6.14 has not undergone thorough evaluation, however, and did not run successfully for all of the scenarios modelled during this testing. It is therefore not currently recommended for use in Hazardous Substances Consent assessments.

The 'non-peaky' methodology is likely to underestimate the effect of the peak in the release rate and can therefore lead to distances that are shorter than would be observed in the event of an incident. In comparison to the time varying model, the 'peaky' methodology may overestimate the dispersion distance in some scenarios. The 'peaky' methodology is the method recommended for use by HSE when the results from GASP meet the HSE 'peaky' criteria for a spill of a flammable liquid. This is consistent with advice issued previously for toxic releases.

The test scenarios modelled indicate that it is not always correct to assume that releasing a quantity of contaminant over a short period of time (i.e. equivalent to the 'peaky' methodology) is going to give a larger downwind hazard range than releasing the same quantity over a long time period (i.e. 'non-peaky'). A release over a shorter duration is affected more by initial gravity-driven radial spreading, which could shorten the downwind LFL extent, usually with greater upwind and crosswind spread. Reducing the release rate reduces the initial gravitational spread at the expense of a greater downwind distance to the LFL as the undiluted cloud is transported downwind. This also explains why longer hazard ranges are sometimes observed in D5 conditions than in F2 conditions as the radial gravity spreading (in the F2 case) exceeds downwind advection for longer extents. In some circumstances, this effect (which includes 'edge' entrainment driven by the gravity spreading front) dominates over the reduced 'top' entrainment rate in F2 conditions.

3 MODELLING CONTINUOUS FLASHING RELEASES OF FLAMMABLE SUBSTANCES FROM VESSEL, PIPEWORK, OR PIPELINE HOLES

3.1 INTRODUCTION

HSE previously assessed the hazards posed by the escape of a flammable liquid or gas from a vessel or pipework hole at a major hazards installation by using in-house models such as STREAM or PFAF (Pipeline Flowrate And Fireball Model) to model the release rate and DRIFT 2.31 to model the subsequent dispersion of the resulting vapour plume.

The dispersion and possible flash fire from flashing releases from pipelines transporting flammable substances were previously modelled by HSE using CRUNCH [9]. The inputs to CRUNCH are obtained by a specific release rate model depending on the substance: for natural gas, the release rate model is HSE's in-house model LOSSP [26]; for all other substances, the release rate model is PipeTech [27], developed by University College London. HSE does not model flash fires for releases of natural gas and consequently no dispersion modelling is required for the assessment of such cases. LOSSP and another in-house model LOSSESP were both historically used by HSE for modelling pipeline releases of flammable substances other than natural gas. LOSSP has been used by HSE in the past for calculating the release rates from holes in pipelines transporting gaseous substances, and LOSSESP [26] has been used in the past to calculate release rates from holes in pipelines transporting liquid substances. PipeTech was used historically by HSE in conjunction with the two in-house models to calculate the release rates for all pipeline ruptures, whether the substance was gaseous or liquid.

CRUNCH is a dispersion model for continuous releases of denser than air vapour into the atmosphere that was developed for HSE in the early 1980s. CRUNCH was a precursor to DRIFT; it was state of the art in the 1980s, but has not been developed or enhanced since that time, with the last release being in 1991. DRIFT 3 is considered to give more realistic dispersion modelling results than those generated by CRUNCH.

Pipelines are assessed under the Pipeline Safety Regulations (PSR) using a risk based procedure, rather than the hazard based assessments that are performed for sites storing and processing flammable substances. Two PSR assessments have been reassessed using DRIFT 3.6.14. It should be noted that rainout has not previously been modelled in pipeline risk assessments, although this is being considered for the future.

When comparing plots of DRIFT 2.31 results to DRIFT 3.6.14 results, it should be noted that, for DRIFT 2.31, the maximum downwind and crosswind extents are used to form an isopleth of two half ellipses, which are joined along their major axes. The DRIFT 3.6.14 plots, in contrast, display the calculated crosswind extents at each downwind distance and represent the actual shape of the cloud predicted by DRIFT as opposed to an idealised shape².

For sites containing compressors, DRIFT 3.5 was used in conjunction with PFAF to generate a siting policy around gas compressor stations. This provided a recommended methodology for HSE for such sites. This has been recalculated using DRIFT 3.6.14. The hazard ranges obtained in the original assessments and the reassessments have been compared, to ensure that the results from DRIFT 3.6.14 do not differ significantly from the results obtained from the earlier DRIFT 3 version.

3.2 METHODOLOGY

Two recent PSR assessments, one for an ethylene pipeline and one for an LPG (liquefied petroleum gas) pipeline, have been recalculated using DRIFT 3.6.14. The results were incorporated into HSE's pipeline risk

² *The predicted cloud shape is sensitive to the concentration profiles of the model. DRIFT evolves the cloud from uniform profiles when dense, to Gaussian when passive.*

assessment tool, MISHAP, to assess the impact on the LUP zones. A siting policy for methane gas compressors that used DRIFT 3.5 has been reassessed using DRIFT 3.6.14 to ensure that the results from DRIFT 3.6.14 do not differ significantly. Ethylene, LPG and natural gas are all substances that are commonly considered by HSE. These types of releases are also important as they consider scenarios where a flammable substance is released under pressure, and the release continues until the supply of the substance can be isolated (unlike a vessel where the amount of substance released is constrained by the maximum capacity of the vessel).

Each scenario was initially reassessed in DRIFT 3.6.14 using input values chosen to replicate the assumptions used in CRUNCH, DRIFT 2.31 or DRIFT 3.5 as closely as possible. Sensitivity tests were undertaken for some of the inputs used in the modelling. This sensitivity analysis was used to inform recommendations on which inputs should be used. The outcomes of these tests were used with the results from previous work on DRIFT 3 [21, 22, 23] to give the recommended input values listed in Table 18.

Table 18 Recommended input values for use in DRIFT 3 for flashing releases of flammable substances from holes in vessels, pipework or pipelines

<i>Input</i>	<i>Recommended value in DRIFT 3 for Major Hazards Installations</i>	<i>Recommended value in DRIFT 3 for Major Accident Hazard Pipelines</i>
Release type	Finite duration	Finite duration
Phase	Dependent on the substance	Dependent on the substance and the output from the release rate model
Substance	As output by the release rate model	As output by the release rate model
Temperature	As output by the release rate model	As output by the release rate model
Pressure (for two-phase flows)	As output by the release rate model	As output by the release rate model
Liquid fraction (for two-phase flows)	Calculated from the output of the release rate model	Calculated from the output of the release rate model
Rainout fraction (for two-phase flows)	As determined by RAIN V2.0 if appropriate	As determined by RAIN V2.0 if appropriate
Contaminant fraction	1	1
Release rate and release duration	The release rate is output from the release rate model. A release duration of 1800 s can be used for vessels. The release duration for pipework will depend on the type of shut-off valve assumed (typically 60 s is assumed for an automatic shut-off valve and 1200 s is assumed for a manual shut-off valve).	Output by the release rate model
Location	(0,0,2)	(0,0,0) for buried pipelines unless specified otherwise. (0,0,2) for above ground pipelines unless specified otherwise.
Source type	Momentum jet	Momentum jet
Orifice diameter	Corresponding to hole size	Corresponding to hole size
Discharge coefficient	0.95 for ruptures, 0.8 for gaseous releases from holes, 0.61 for liquid releases from holes	0.95 for ruptures, 0.8 for gaseous releases from holes, 0.61 for liquid releases from holes
Angle from horizontal	0°	0°
Angle from north	90°	90°

Input	Recommended value in DRIFT 3 for Major Hazards Installations	Recommended value in DRIFT 3 for Major Accident Hazard Pipelines
Weather scheme	Pasquill	Pasquill
Input inversion height	No (the model determines this from a look-up table when the Pasquill weather scheme is selected)	No (the model determines this from a look-up table when the Pasquill weather scheme is selected)
Temperature	288.15 K (D5); 278.15 K (F2)	288.15 K (D5); 278.15 K (F2)
Relative humidity	60%	60%
Reference height	10 m	10 m
Roughness length	0.1 m (rural); 0.3 m (urban)	0.1 m (rural); 0.3 m (urban)
Wind angle from North ¹	270° (towards the positive x direction)	270° (towards the positive x direction)
Pasquill stability	D (day) or F (night)	D (day) or F (night)
Wind speed	5 m/s (day) or 2 m/s (night) ²	5 m/s (day) or 2 m/s (night) ²
User input flammability limits	No, as these should be read in automatically from the SPI file	No, as these should be read in automatically from the SPI file
Levels of interest	Lower Flammable Limit (LFL)	Lower Flammable Limit (LFL)

¹In DRIFT 3, the wind direction is defined as the direction from which the wind is blowing. This is the convention used by the Met Office. In EJECT (the jet model used in conjunction with DRIFT 2.31), the wind direction is defined as the direction towards which the wind is blowing. DRIFT 3 automatically corrects for this when opening a legacy file.

²The wind speeds listed are used for flammable pipeline releases only. Other flammable releases and toxic releases use wind speeds of 2.4 m/s, 4.3 m/s and 6.7 m/s.

A full list of the DRIFT input values used in the original assessments and reassessments is provided in Section 6.2 of the Appendices. The values of the LFL for each substance are given in Section 6.4 of the Appendices.

3.3 ETHYLENE ASSESSMENT

The original ethylene assessment used in this study was performed to determine the LUP zone sizes that would apply around an 8" ethylene pipeline if a section was replaced with a thicker wall pipeline. For the flash fire element, both CRUNCH [9] and DRIFT 2.31 [1, 2] were used in the assessment and the results were compared. It was found that the choice of dispersion model had a minor impact on the zone sizes, although the results generated by DRIFT 2.31 were used to set the zones. Four release sizes were considered: guillotine rupture, 110 mm hole, 75 mm hole and 25 mm hole, in line with standard pipeline assumptions. D5 and F2 weather conditions were modelled in the assessment. The in-house jet source term model, CREATE [31] was used to derive the inputs for DRIFT 2 (e.g. the contaminant mass fraction), rather than running the separate jet model, EJECT (DRIFT 3 contains a jet model based on EJECT). A surface ground roughness length of 0.3 m was used, to model the release over an urban environment. A source location height of $z = 0$ was chosen to account for the fact that the pipeline is buried and any release from a rupture or a hole would be at ground level.

In reality, a release from a buried pipeline is likely to lead to the formation of a crater, which will affect the flow from the release point, unless the jet is vertical. It is not possible to model this effect in DRIFT, or in the previous model, CRUNCH.

The pipeline details are given in Table 19.

Table 19 Ethylene pipeline details

<i>Parameter</i>	<i>Value</i>
Diameter (mm)	219.1
Wall thickness (mm)	7.04
Maximum operating pressure (barg)	98.6
Depth of cover (m)	0.9
Pipe material specification ¹	API 5L
Pipe material grade ¹	X42

¹The pipe material specification and material grade refer to the standards and quality of the pipeline steel

In the original assessment, the release rates were calculated using PipeTech for ruptures and LOSSP for the holes. The release rates used in the original assessment are given in Table 20 and the release duration was 120 s. A temperature of 256.5 K was assumed for the rupture release in DRIFT 2.31, which was the temperature output by CREATE. The temperature for the hole releases was assumed to be 243 K in DRIFT 2.31. CRUNCH uses the jet temperature, which is set to the boiling point, as its initial temperature.

Table 20 Release rates for the different hole sizes from the failure of an ethylene pipeline

<i>Scenario</i>	<i>Release rate (kg/s)</i>
Rupture	327
110 mm hole	298
75 mm hole	138
25 mm hole	15

In the reassessment, PipeTech version 54 has been used to recalculate the release rate and to generate the exit temperature, pressure and the liquid fraction for the rupture scenario. The revised values are given in Table 21. In the original assessment, ethylene was treated as gaseous only in the dispersion modelling. In the reassessment, the output from PipeTech indicates that the release from the rupture of the pipeline should be modelled as two-phase and therefore it has been modelled as two-phase in DRIFT 3.

Table 21 shows that the release rate calculated using PipeTech version 54 is slightly different from that obtained using an earlier version of the model. The difference is small, however, allowing for a comparison of DRIFT results with those from the previous analysis.

Table 21 Outputs from PipeTech for rupture in an ethylene pipeline

<i>Parameter</i>	<i>New PipeTech output</i>	<i>Previous PipeTech output</i>
Release rate (kg/s)	323.8	327.1
Exit temperature (K)	218.0	219.4
Exit pressure (bar)	8.9	9.36
Liquid fraction	0.57	Treated as gaseous so assumed 0

A different approach has been used for the releases from holes. The release rates calculated in the original assessment have been used in the reassessment together with a release duration of 120 s and the previously derived release temperature of 243 K. As DRIFT 3.6.14 incorporates a jet dispersion model, a contaminant mass fraction value of 1 has been input, rather than the value that was calculated using CREATE. The release has been assumed to be gaseous, which is consistent with the results generated by PipeTech for each of the hole sizes.

In the original assessment, a coefficient of discharge of 0.8 was used for all the releases. Standard HSE practice is to use a coefficient of discharge of 0.95 for ruptures, 0.8 for holes for a gaseous release, and 0.61

for holes for a liquid release. In the reassessment, 0.8 has been used for all release sizes for consistency with the original assessment.

The finite duration model has been used in all cases for the reassessment.

3.3.1 Lower Flammable Limit (LFL) isopleths in D5 weather conditions

The LFL isopleths calculated in DRIFT 3.6.14 for a rupture, a 110 mm hole, a 75 mm hole and a 25 mm hole in an ethylene pipeline in D5 weather are shown in Figure 62 to Figure 65. The DRIFT 3 results are generated using the finite duration model option. Results obtained from the DRIFT 2 continuous model, which was used in the original assessment, are also shown in these figures. The instantaneous model in DRIFT 2 was not run. The maximum downwind distances to the LFL predicted by DRIFT 3.6.14 and DRIFT 2.31 are given in Table 22. Table 22 also shows the output from CRUNCH, which was obtained as part of the original assessment but was not used to set the LUP zones.

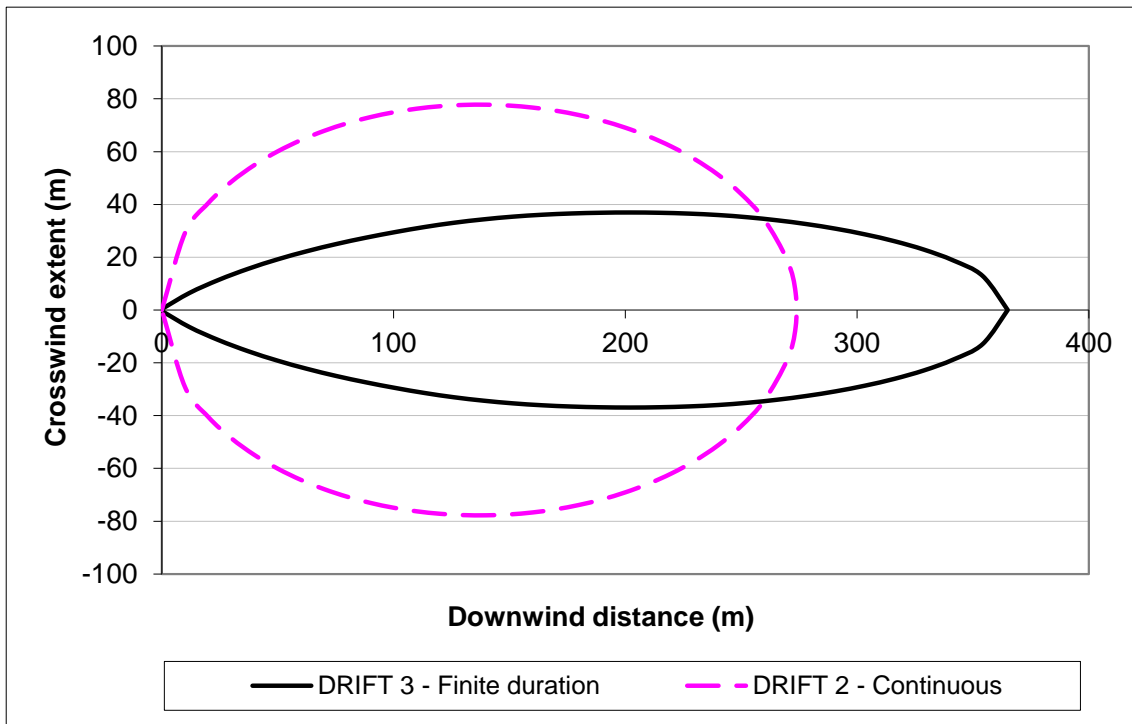


Figure 62 LFL isopleths for rupture of an ethylene pipeline in D5 weather

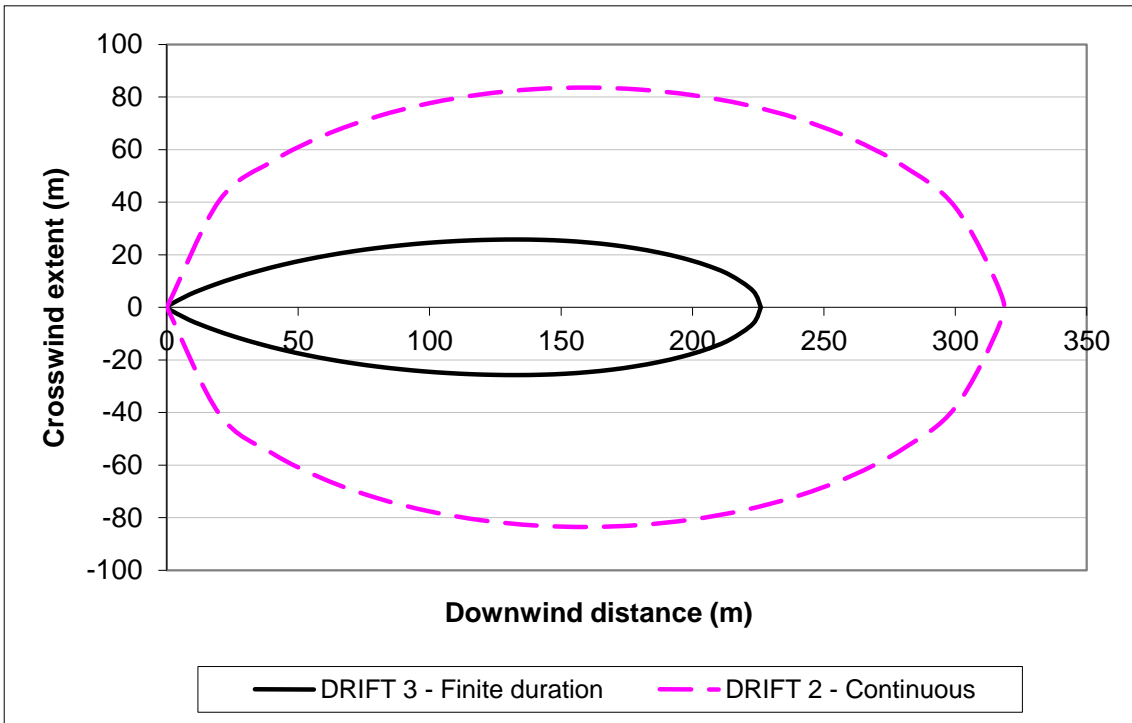


Figure 63 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in D5 weather

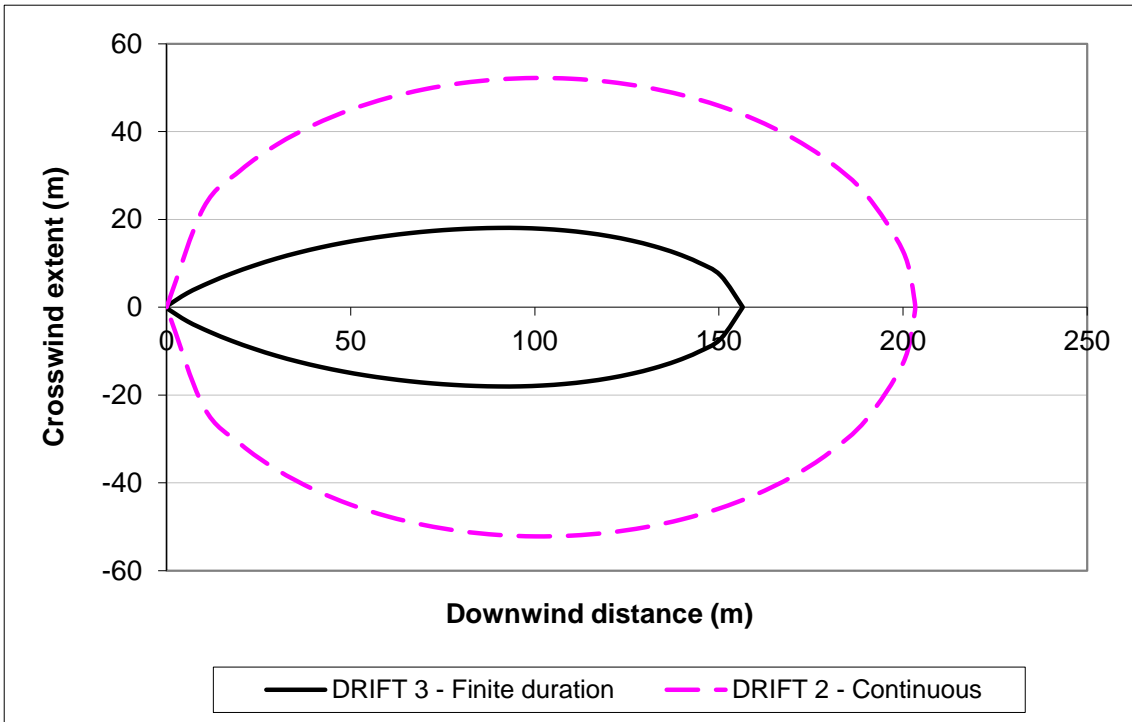


Figure 64 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in D5 weather

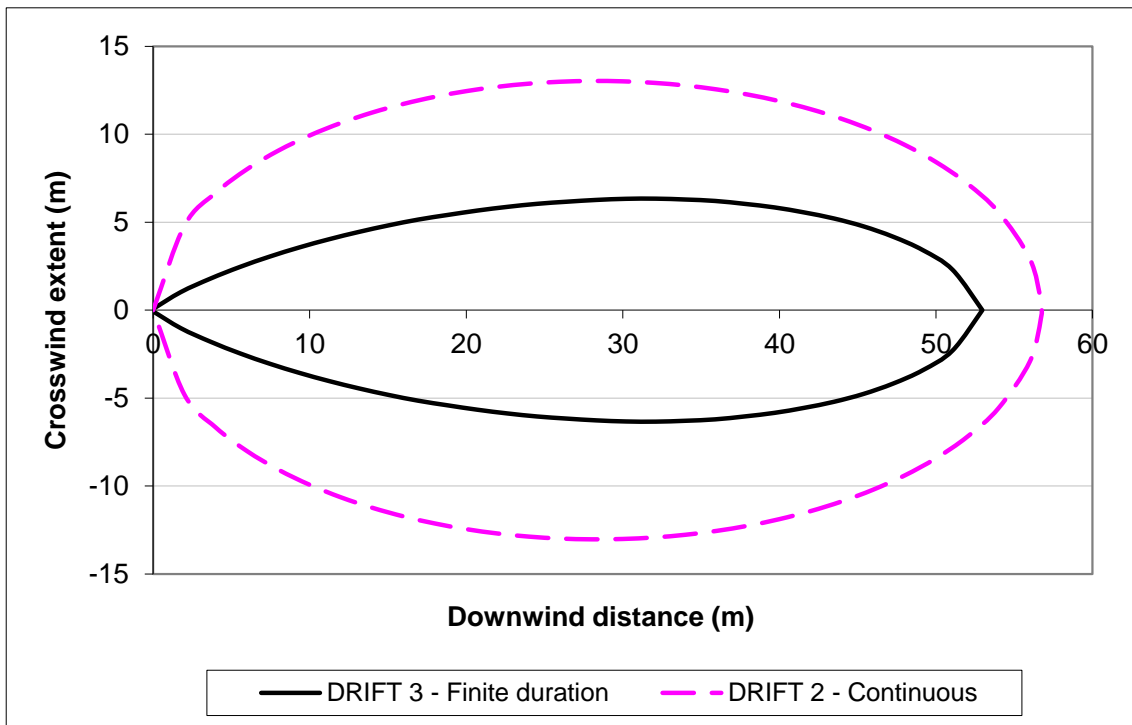


Figure 65 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in D5 weather

Table 22 shows the maximum downwind distances to the LFL for the different release sizes from an ethylene pipeline in D5 weather.

Table 22 Maximum downwind distances to the LFL for an ethylene release in D5 weather from a pipeline

Scenario	Maximum downwind distance to the LFL (m)		
	DRIFT 3 – Finite Duration	DRIFT 2 – Continuous	CRUNCH
Rupture	365	274	350
110 mm hole	226	317	310
75 mm hole	156	203	220
25 mm hole	53	57	72

Figure 62 shows that for the rupture scenario, DRIFT 3 predicts a larger downwind distance, but DRIFT 2 predicts a larger crosswind extent. For the releases through holes, Figure 63 to Figure 65 show that DRIFT 3 produces smaller downwind LFL distances and crosswind extents than DRIFT 2. As the hole size decreases (and the release rate reduces), the maximum downwind distance to the LFL predicted by DRIFT 2 decreases more rapidly than that predicted by DRIFT 3. The closest agreement between the downwind LFL distances predicted by the two models is therefore obtained for the 25 mm hole.

The maximum downwind distance to the LFL predicted by DRIFT 2 is greater for a 110 mm hole than for a rupture release. CREATE (the in-house jet model used to produce a source term for DRIFT 2) predicts a larger contaminant mass fraction for the holes than for the rupture (0.1 as opposed to 0.0715). The effect of the larger contaminant mass fraction in DRIFT 2 is to increase the downwind LFL distances. This is why a larger distance is predicted for a 110 mm hole than for a rupture. Additional modelling approximations were made previously by HSE due to limitations with both CREATE and computing power. These will also have had an impact on the DRIFT 2 outputs.

The different DRIFT 3 behaviour seen for the rupture scenario (i.e. the rupture produces longer downwind distances than the 110 mm hole) is likely to be due to the change in the treatment of the release from gaseous in DRIFT 2 to two-phase in DRIFT 3. To confirm this point, the rupture was modelled as gaseous in DRIFT 3. In this instance, the maximum downwind distance to the LFL is 234 m, which is less than the distance calculated by DRIFT 2.

There are other differences in the modelling worth highlighting. DRIFT 2 requires inputs from a source term jet model, e.g. CREATE or EJECT. The original assessment used CREATE rather than EJECT as it was considered that this better represented the crater that would be formed on pipeline rupture. DRIFT 3 has an integrated jet model, derived from the EJECT model, that is part of the dispersion calculations. This means that the jet phase is included in the isopleth outputs generated by DRIFT 3. In addition, the continuous model was used in DRIFT 2 whereas the finite duration model was used in DRIFT 3. These different models can have an effect on the results as, although the same basic equations are used in both models, the cloud is treated differently in post-processing. The finite duration model includes dilution of the leading and trailing edges of the plume, which means that the cloud spreads longitudinally. The larger the travel time, the greater the effect of this dilution.

Table 22 shows that DRIFT 3 produces shorter downwind LFL extents than CRUNCH for the three hole sizes, although there is less than a factor of 2 between the two sets of results. DRIFT 3 produces a larger maximum downwind distance to the LFL than CRUNCH for the rupture release. The results from DRIFT 2 were similar to those from CRUNCH for the 110 mm and 75 mm holes, but the maximum downwind extents predicted by DRIFT 2 for ruptures and 25 mm holes were significantly smaller than those predicted by CRUNCH.

3.3.2 Lower Flammable Limit (LFL) isopleths in F2 weather conditions

The LFL isopleths calculated in DRIFT 3.6.14 for a rupture, a 110 mm hole, a 75 mm hole and a 25 mm hole in F2 weather are shown in Figure 66 to Figure 69. The outputs of the DRIFT 2 continuous and instantaneous models are also shown, although it is the results from the continuous model that were ultimately used in the assessment. The maximum downwind distances to the LFL predicted by DRIFT 3.6.14 are given in Table 23, together with the results from DRIFT 2 and CRUNCH.

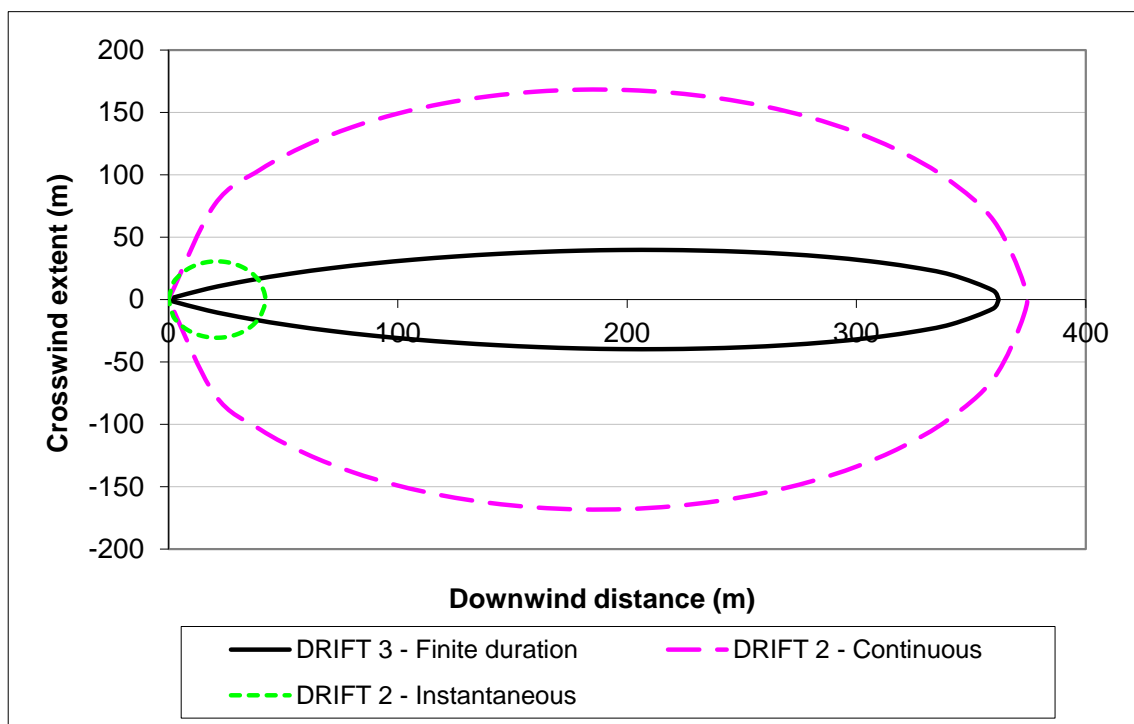


Figure 66 LFL isopleths for rupture of an ethylene pipeline in F2 weather

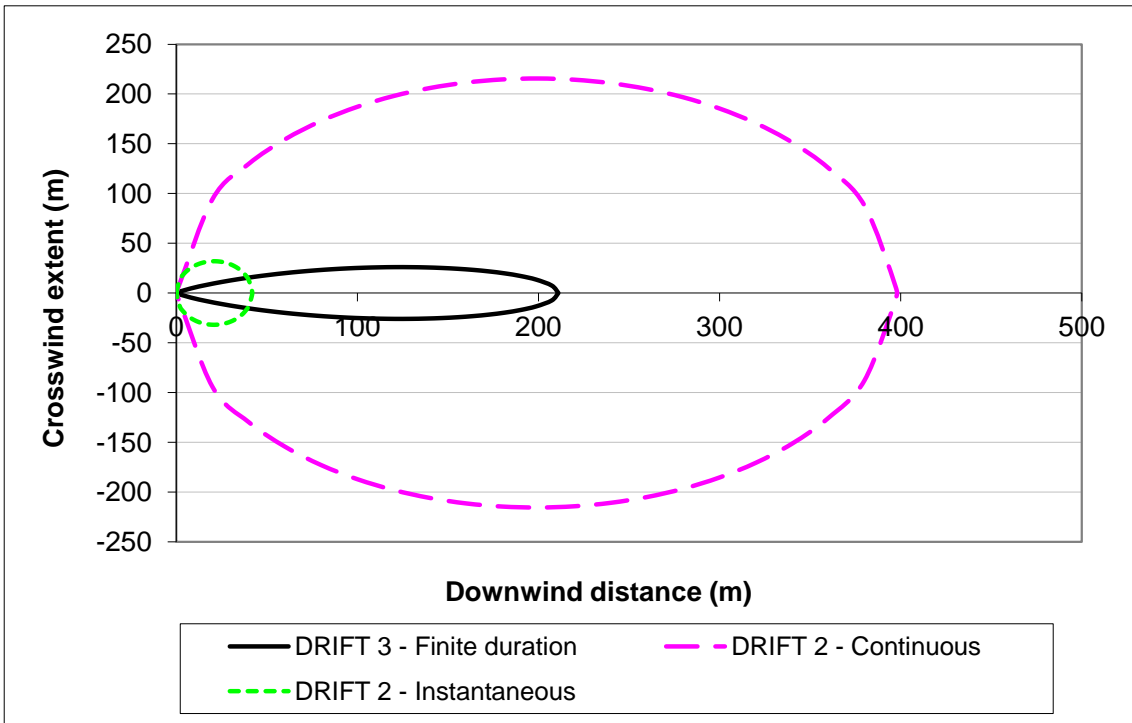


Figure 67 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in F2 weather

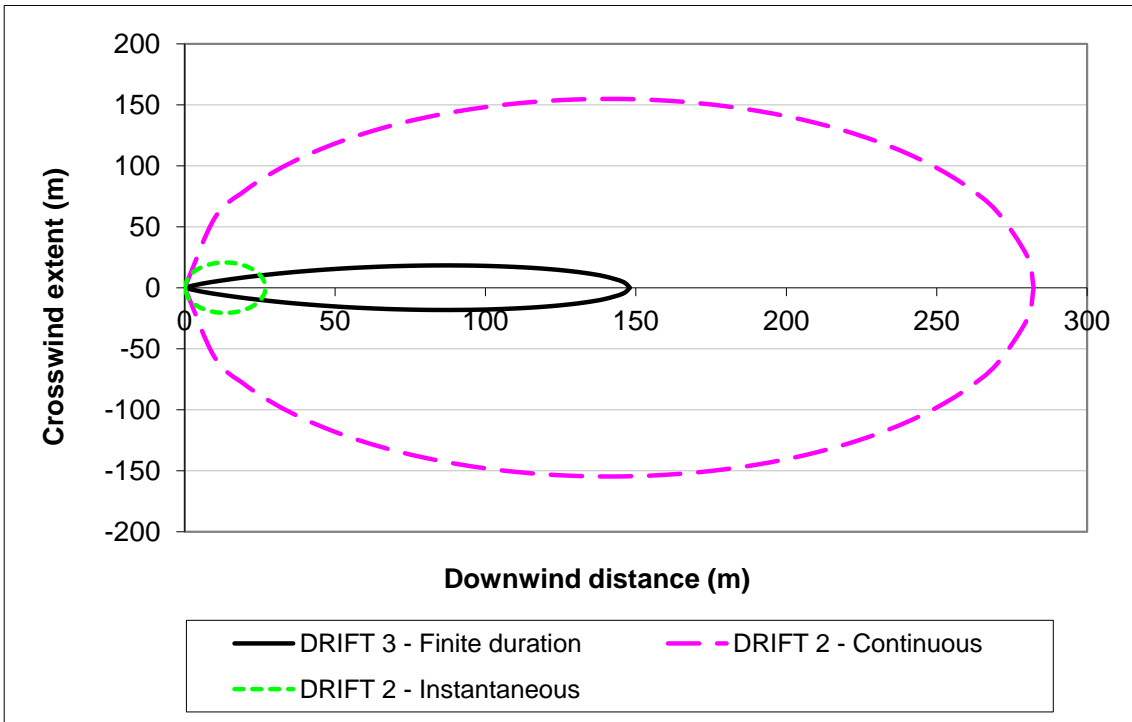


Figure 68 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in F2 weather

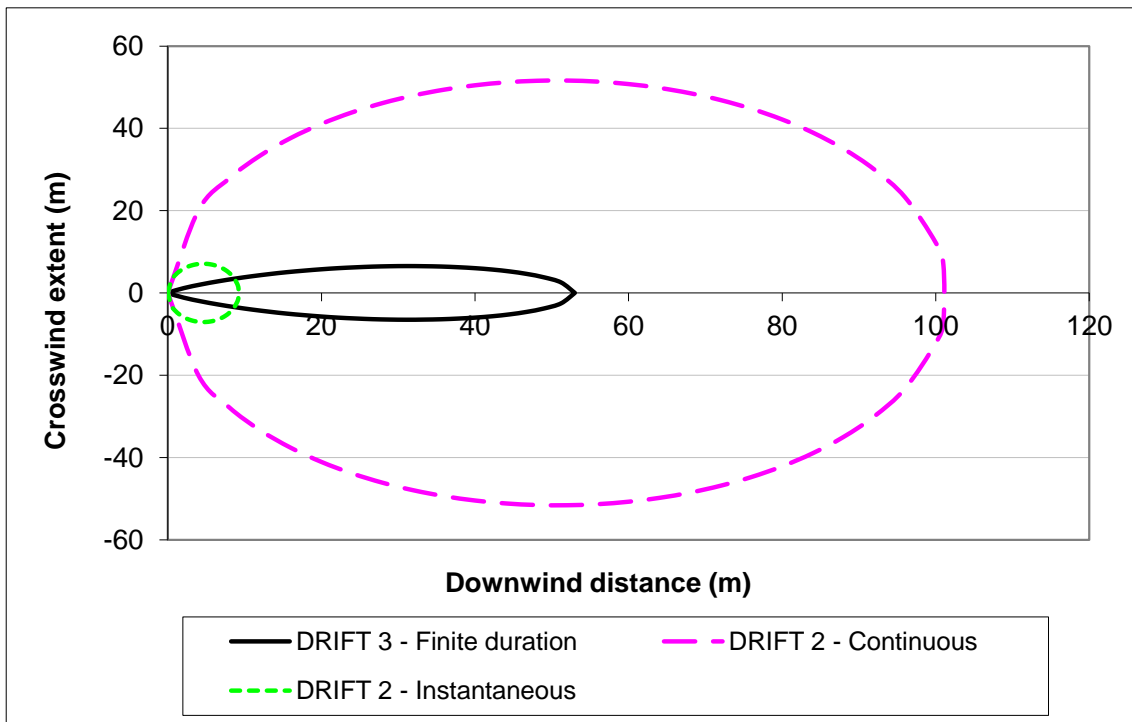


Figure 69 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in F2 weather

Table 23 shows the maximum downwind distances to the LFL for the different release sizes from an ethylene pipeline in F2 weather.

Table 23 Maximum downwind distances to the LFL from an ethylene release from a pipeline in F2 weather

Scenario	Maximum downwind distance to the LFL (m)			
	DRIFT 3 – Finite Duration	DRIFT 2 – Continuous	DRIFT 2 – Instantaneous	CRUNCH
Rupture	362	374	42	780
110 mm hole	211	397	42	690
75 mm hole	148	282	27	520
25 mm hole	53	101	9	200

As in the D5 weather case, for the three hole sizes modelled, the maximum downwind LFL distances and crosswind extents predicted by DRIFT 3 are considerably smaller than those predicted by the continuous model in DRIFT 2. This is not the case for the rupture release, where the maximum downwind extent predicted by DRIFT 3 is similar to that generated by modelling a continuous release in DRIFT 2. For all the hole sizes, the plume velocity had to be increased to enable the DRIFT 2 continuous model to run in F2 weather conditions. No issues were encountered when running DRIFT 3 for these scenarios.

The DRIFT 2 instantaneous model predicts small LFL isopleths. This is because the entire release mass is initially assumed to form a vertical cylindrical cloud. The cloud is predicted to slump under the effect of gravity, reducing its height and increasing its radius. This process leads to increased dilution associated with spreading (edge entrainment). The greatly enhanced edge entrainment associated with the instantaneous model gives rise to a rapid dilution before the cloud moves any distance. This leads to unrealistically short downwind LFL distances for the scenarios considered here. The instantaneous model results have been shown for comparison purposes but were discounted in the original assessment.

The DRIFT 2 continuous model predicts a larger maximum downwind distance to the LFL for the 110 mm hole than for the rupture. This is analogous to the results obtained in D5 weather. As explained previously, this is likely to be due to the fact that the CREATE source term model predicts a larger contaminant mass fraction for the holes than for the rupture. In contrast, the rupture release produces the largest downwind LFL distance in DRIFT 3. In DRIFT 3, the rupture release was modelled as two-phase, whereas in DRIFT 2 it was assumed to be gaseous.

CRUNCH predicts maximum downwind distances to the LFL that are several times the size of those predicted by DRIFT 3, and the differences between the outputs of the two models are significantly larger than the differences observed when modelling the releases in D5 weather. According to Jagger [9], the CRUNCH model is more suitable for high wind speed conditions, where high wind speed is defined as being ≥ 5 m/s. This is likely to explain why such large differences are observed between DRIFT 3 and CRUNCH in F2 weather, but much smaller differences are seen in D5 weather. It should also be noted that, unlike DRIFT 3, CRUNCH does not contain a jet element. The downwind distances to the LFL predicted by DRIFT 3 are likely to be smaller than those predicted by CRUNCH due to the dilution caused by the turbulent interactions between the jet and the atmosphere.

A comparison of Table 23 and Table 22 shows that the maximum downwind LFL distances predicted by DRIFT 3 are slightly shorter in F2 weather than in D5 weather. This is likely to be due to the velocity of the jet release modelled in DRIFT 3 being significantly greater than the ambient wind speed, which will lead to turbulence and increased mixing of the gas with the surrounding air at the leading edge of the jet. At lower wind speeds, the difference between the two velocities is greater meaning that the amount of turbulent mixing is likely to be greater. The net effect of this is that the pollutant is dispersed more quickly at the lower wind speed leading to shorter downwind LFL distances. This was not considered in CRUNCH as it is a much simpler model, which does not model the jet phase. CRUNCH produced much greater distances to the LFL in F2 weather than in D5 weather, as would normally be expected.

When the revised DRIFT 3 distances are put into MISHAP01 [34, 35], the pipeline risk assessment model used in the original assessment, the risk based LUP zones are reduced in size. This is shown in Table 24 if the pipeline is treated as suburban, and in Table 25 if the pipeline is treated as rural. Suburban pipelines have higher failure rates associated with them due to the increased frequency with which they are struck by machinery, and therefore have larger risk based LUP zones than rural pipelines. The reductions in zone size are significant, particularly for the middle and outer zones, which reduce by a factor of approximately 2 in the suburban case. In the rural case, the outer zone is reduced by a factor of less than 2, whilst the middle zone is reduced by a factor of more than 2.

Since the original risk based LUP zones were derived, HSE has replaced MISHAP01 with MISHAP12 [26]. The risk based zone sizes have been recalculated in MISHAP12 using both CRUNCH and DRIFT 3 outputs, and these zones are also shown in Table 24 and Table 25 for suburban and rural pipelines respectively. In this case, the outer and middle risk based zones predicted for the suburban pipeline using the DRIFT 3 outputs are almost a factor of 2 smaller than the zones predicted using the CRUNCH outputs, but there is a smaller reduction in the risk based inner zone. For the rural pipeline, the risk based outer zone is reduced by a factor of 1.8, there is a small reduction in the risk based middle zone, and the risk based inner zone is 0 m in both cases.

It should be emphasised that the zone sizes given in Table 24 and Table 25 are the risk based zones calculated by MISHAP01 or MISHAP12 and not the final LUP zones. For ease of reference they have been referred to in this report as the inner, middle and outer zones, but they are actually the distances to a 10 cpm/yr (chances per million per year) risk of receiving a dangerous dose, a 1 cpm/yr risk of receiving a dangerous dose and a 0.3 cpm/yr risk of receiving a dangerous dose, respectively. The final LUP zones use the greater of the risk based zones and a hazard based distance. They are also rounded according to HSE's agreed rounding policy [26].

Table 24 Comparing risk based LUP zones (m) from two versions of MISHAP using DRIFT 3 or CRUNCH for flash fires and assuming the pipeline is suburban

<i>Flash fire model</i>	<i>LUP Zone</i>		
	<i>Inner Zone</i>	<i>Middle Zone</i>	<i>Outer Zone</i>
MISHAP01			
CRUNCH	65	432	668
DRIFT 3 Finite Duration	55	234	324
MISHAP12			
CRUNCH	37	197	443
DRIFT 3 Finite Duration	32	104	241

Table 25 Comparing risk based LUP zones (m) from two versions of MISHAP using DRIFT 3 or CRUNCH for flash fires and assuming the pipeline is rural

<i>Flash fire model</i>	<i>LUP Zone</i>		
	<i>Inner Zone</i>	<i>Middle Zone</i>	<i>Outer Zone</i>
MISHAP01			
CRUNCH	10	169	395
DRIFT 3 Finite Duration	8	69	216
MISHAP12			
CRUNCH	0	68	184
DRIFT 3 Finite Duration	0	65	100

3.4 SENSITIVITY ANALYSES FOR THE ETHYLENE PIPELINE

3.4.1 Coefficient of discharge

In both the original assessment and the reassessment, a coefficient of discharge of 0.8 was used for all the releases. Standard HSE practice is to use a coefficient of discharge of 0.95 for ruptures, 0.8 for holes for a gaseous release, and 0.61 for holes for a liquid release. The rupture scenarios have been rerun in DRIFT 3 using a coefficient of discharge of 0.95. The results indicate that this has no effect on the maximum predicted downwind distance to the LFL.

3.4.2 Steady continuous model

The scenarios have been rerun in DRIFT 3 as steady continuous releases rather than using the finite duration model, to determine what effect this has on the results. Changing the model was found to have no impact on the downwind LFL distances calculated. The steady continuous model uses the same basic equations as the finite duration model, but with differences in the post-processing. When the release duration is long compared with the cloud travel time, then the concentration profiles tend to those of the steady continuous model. This is the case in the ethylene pipeline scenarios as the cloud travel time to reach the maximum distance to the LFL is approximately 20 s or less, depending on the specific scenario, whilst the release duration modelled is 120 s.

3.4.3 Relative humidity

In the reassessment, the relative humidity was assumed to be 60%, as this is the standard value used by HSE. To test the sensitivity of the results to relative humidity, a set of scenarios were run using a relative humidity of 80%. When the results were compared to those obtained using a relative humidity of 60%, it

was found that there was no significant difference for the releases from holes, with a maximum difference of 1 m in the maximum predicted downwind distance to the LFL. A larger difference in the predicted dispersion distances was observed in the rupture cases with decreases of 14 m in D5 weather and 7 m in F2 weather, when the relative humidity was set to 80%. This represents a decrease of approximately 4% in the D5 scenario and 2% in the F2 scenario, neither of which can be considered to be significant. The larger differences are due to the treatment of the release as two-phase in the rupture case rather than as gaseous as is the case for the holes. If the release is treated as gaseous, no difference is seen in the results when the relative humidity is modified.

The difference observed between a purely gaseous release and a two-phase release is likely to be due to some of the release being liquid for the two-phase scenario. The two-phase release cools to much lower temperatures than the vapour release due to latent heat being removed when the liquid ethylene vaporises. By this mechanism the two-phase release cools to below the normal boiling temperature of 169 K before increasing in temperature due to mixing with air. In comparison, the vapour release continuously warms from its initial temperature 218 K by mixing with air. This leads to the two-phase release producing a significantly denser cloud than the vapour release. For a ground-based cloud, mixing with overlying air is suppressed by the stabilising effect of the dense cloud lying below warmer air. This suppression of mixing increases with cloud density and cloud size. Water vapour from moist air mixed into the cold cloud will condense releasing its latent heat. This latent heat warms the cloud and reduces the density, hence reducing the density suppression effect on mixing. Due to the cloud from the two-phase release being significantly colder and denser than the cloud from the vapour release, a much greater amount of water vapour is condensed in the two-phase cloud with a greater effect on the density-dependent mixing.

3.4.4 Release height

In the original assessment, a release height of 0 m was used in DRIFT. Sensitivity tests have been undertaken in DRIFT 3.6.14 using release heights of 0.2 m, 0.5 m, 1 m and 2 m. The pipeline is buried underground and in reality there will be effects from any crater formed. This interaction between release and crater produces a complex source that cannot be taken into account by integral models such as DRIFT and CRUNCH. Although it may appear that the best approximation is to assume a ground-based jet, there may be interactions occurring within the surface roughness length (0.3 m in this scenario) that impact on the results. The results in D5 weather are shown in Figure 70 to Figure 73 for ruptures, 110 mm holes, 75 mm holes and 25 mm holes in the ethylene pipeline. The equivalent plots in F2 weather are shown in Figure 74 to Figure 77. The maximum downwind distances to the LFL are given in Table 26.

The isopleths are smaller in all cases when a height of $z = 2$ m or $z = 1$ m is used. This applies to both the maximum downwind LFL distances and crosswind extents. This reflects differences in the behaviour of the elevated and grounded regions of the jet. Elevation plots indicate that the cloud is immediately grounded at the lower release heights, but, at the higher release heights, the cloud travels a few metres before touching the ground. When the release is along the ground, only the upper surface and sides of the jet interact with the atmosphere. Within the jet region the ground surface roughness will act to slow the jet down if the release is at ground level. This, in turn, means that the difference in velocities between the jet and the wind is less, which leads to less turbulence at the edge of the jet. Also, when grounded, the lateral spreading of the jet is enhanced and vertical mixing suppressed due to the stabilising effect of the dense cloud at ground-level. The net effect is that less mixing occurs for the dense ground-level jet and the cloud extends further, both in the cross wind and downwind directions in this case.

In an actual pipeline release, the jet will interact with the crater formed, depending on the angle of release. The jet is then likely to become angled slightly upwards, but may then reattach to the ground due to the

Coandă effect³. The closest approximation within DRIFT is to assume a release height of 0 m. This is the recommended release height for modelling buried pipelines in DRIFT 3 for HSE assessments.

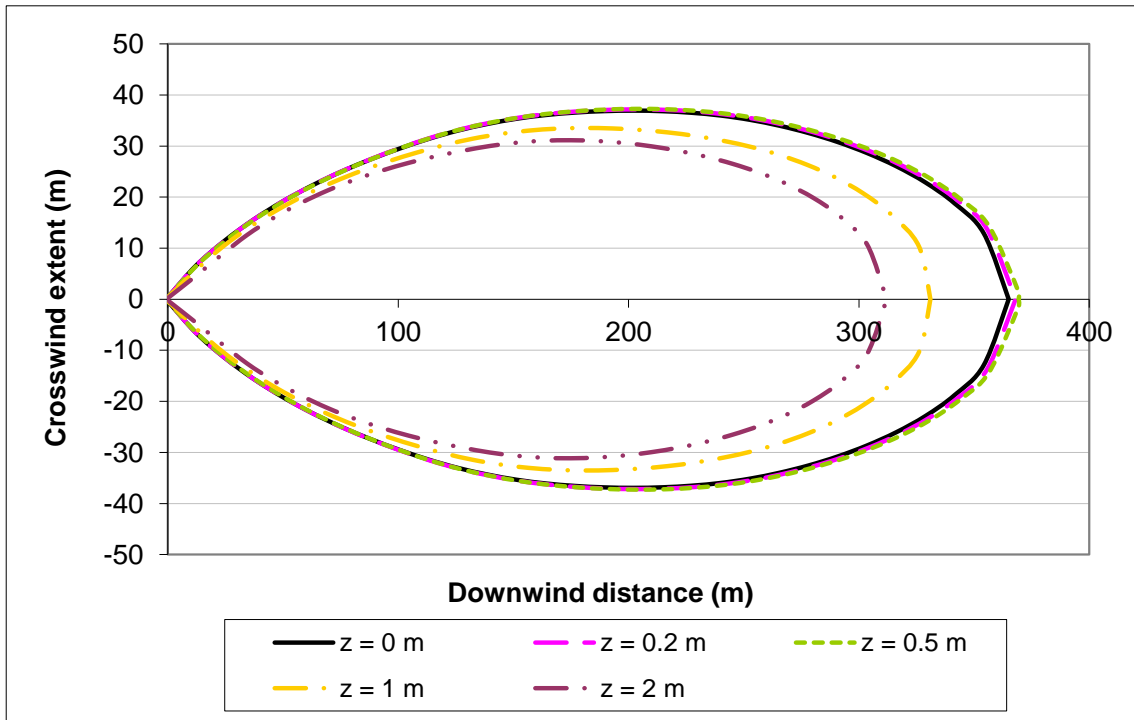


Figure 70 LFL isopleths for rupture of an ethylene pipeline in D5 weather, varying the release height

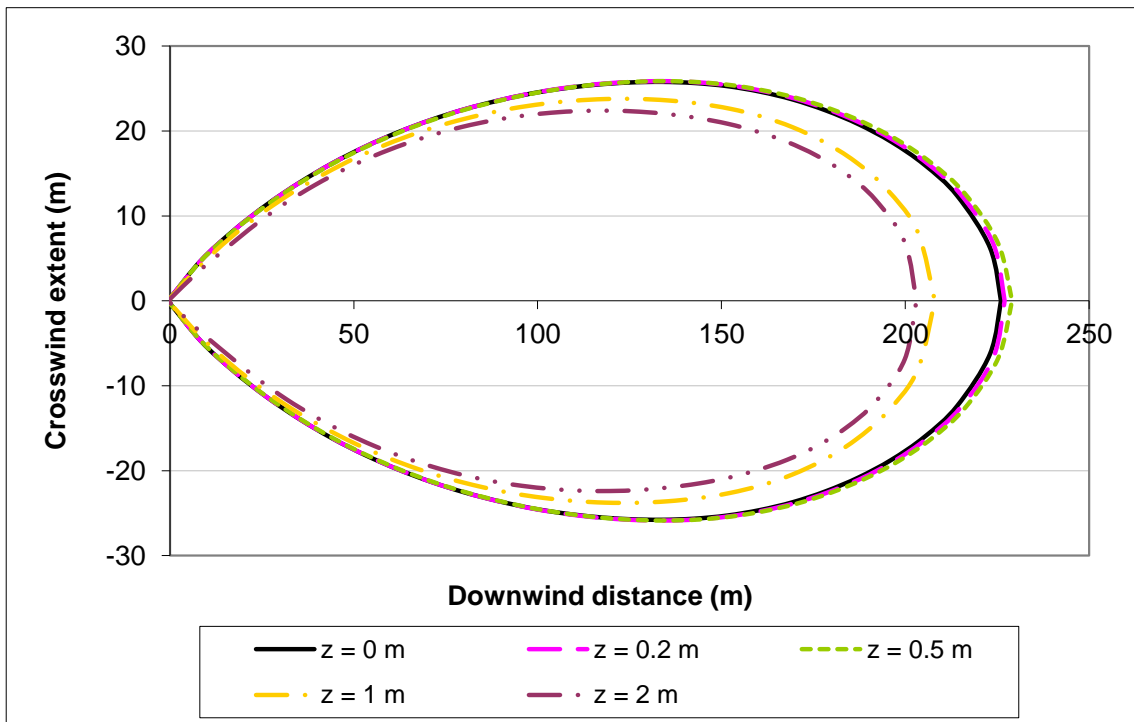


Figure 71 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in D5 weather, varying the release height

³ The Coandă effect is the tendency of a fluid jet to attach itself to a nearby surface and to remain attached, even if the surface curves away from the initial jet direction.

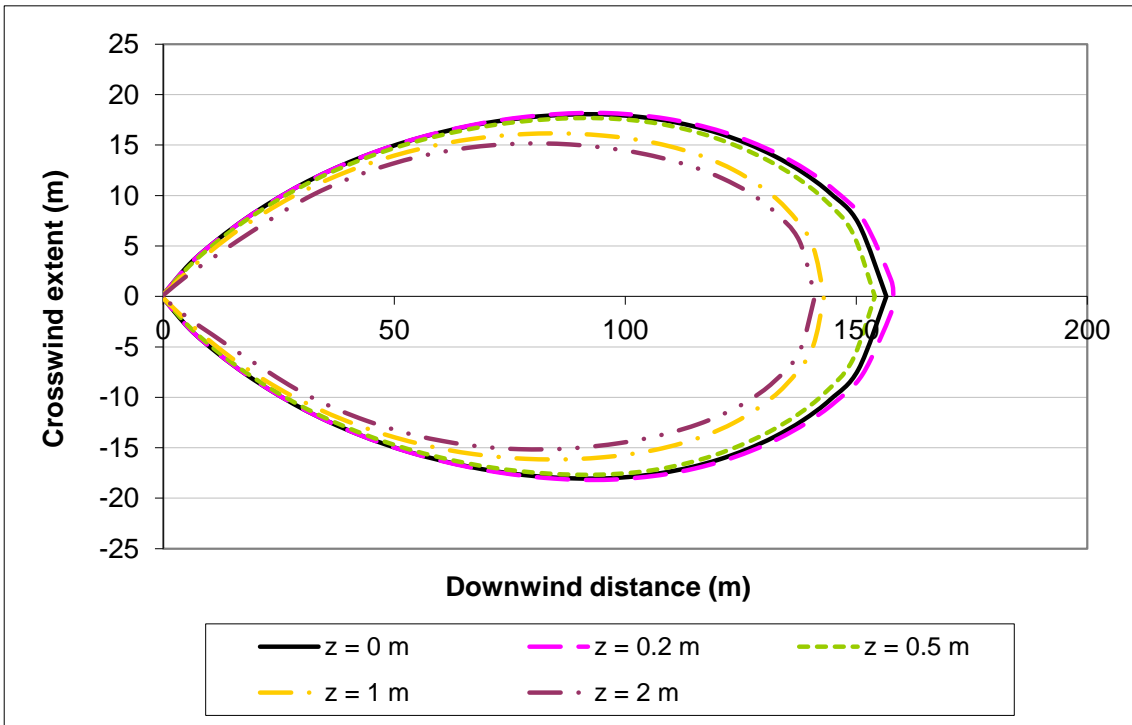


Figure 72 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in D5 weather, varying the release height

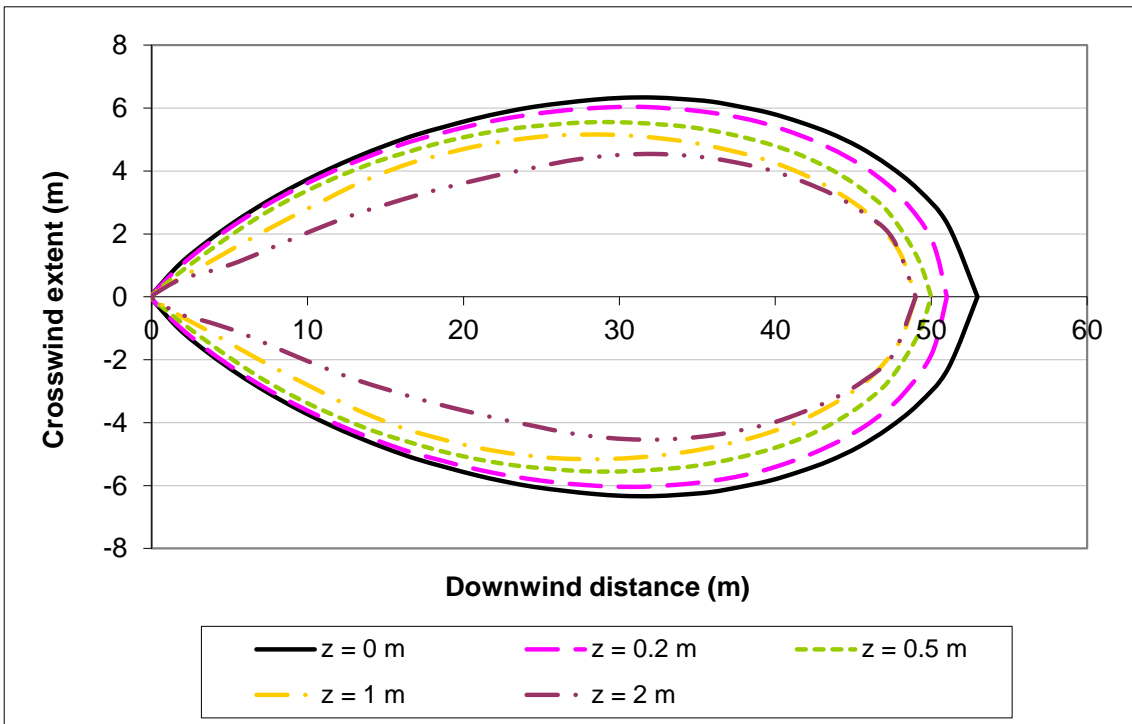


Figure 73 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in D5 weather, varying the release height

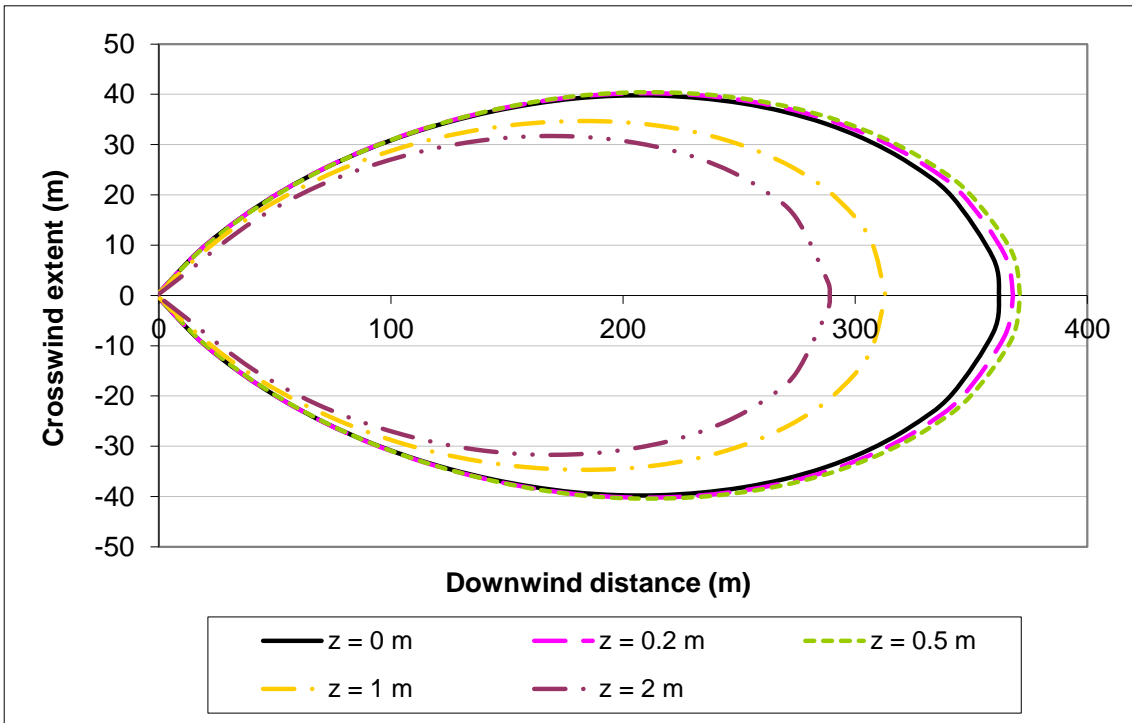


Figure 74 LFL isopleths for rupture of an ethylene pipeline in F2 weather, varying the release height

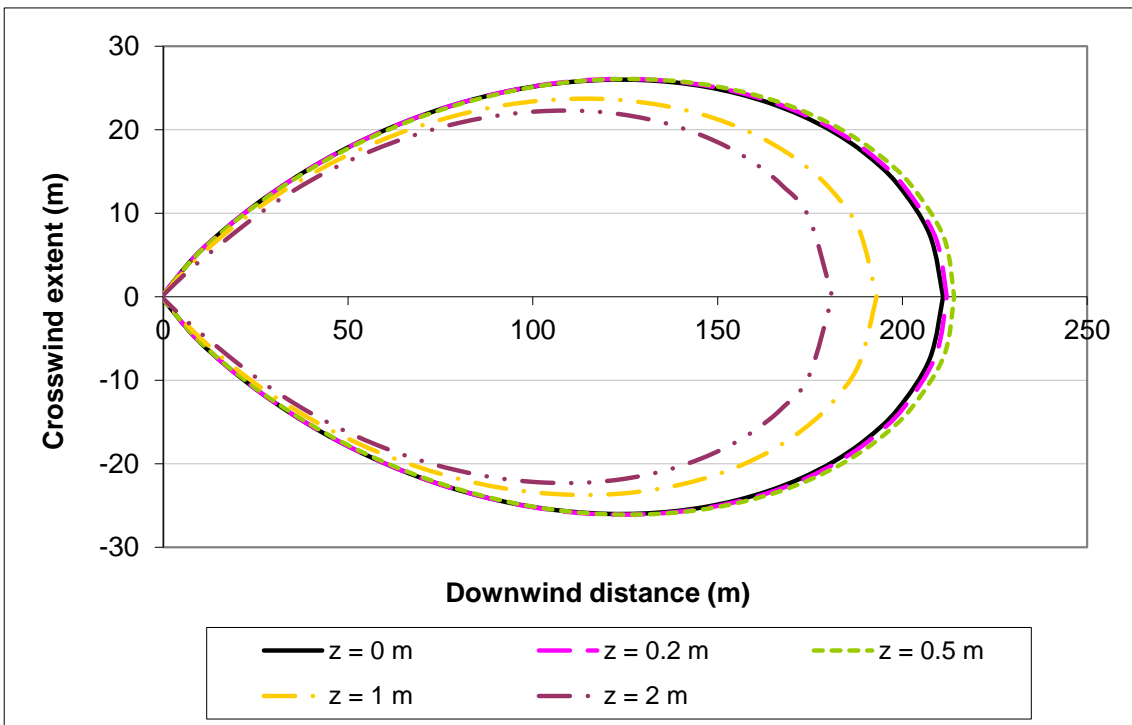


Figure 75 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in F2 weather, varying the release height

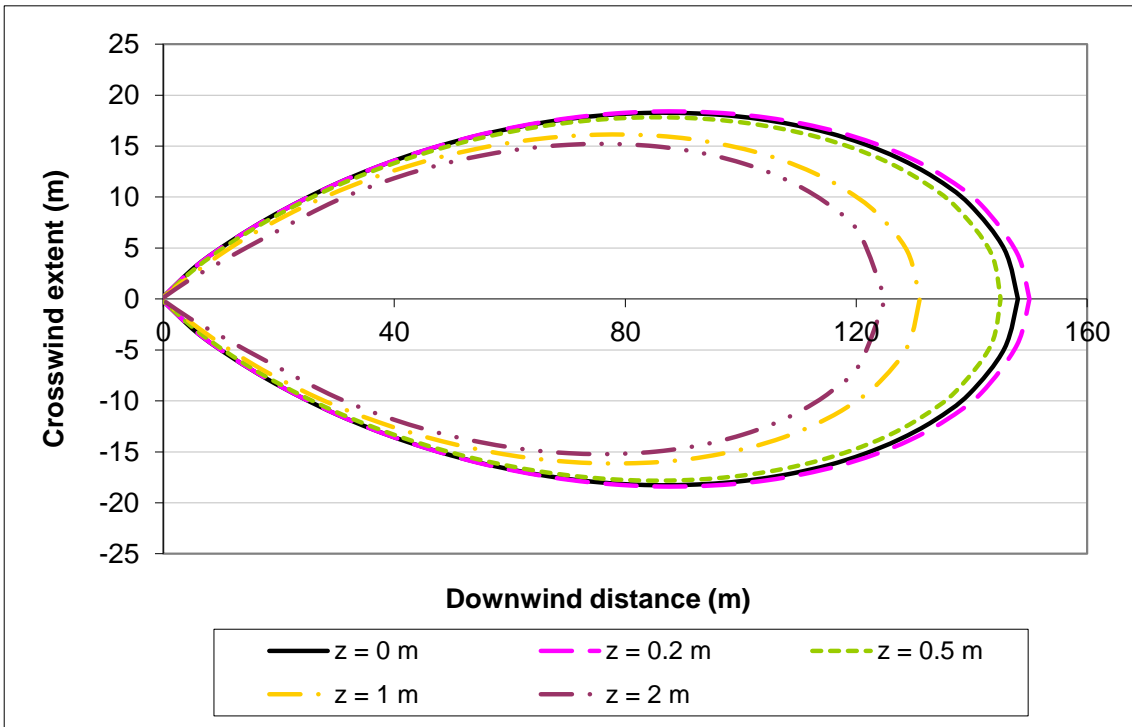


Figure 76 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in F2 weather, varying the release height

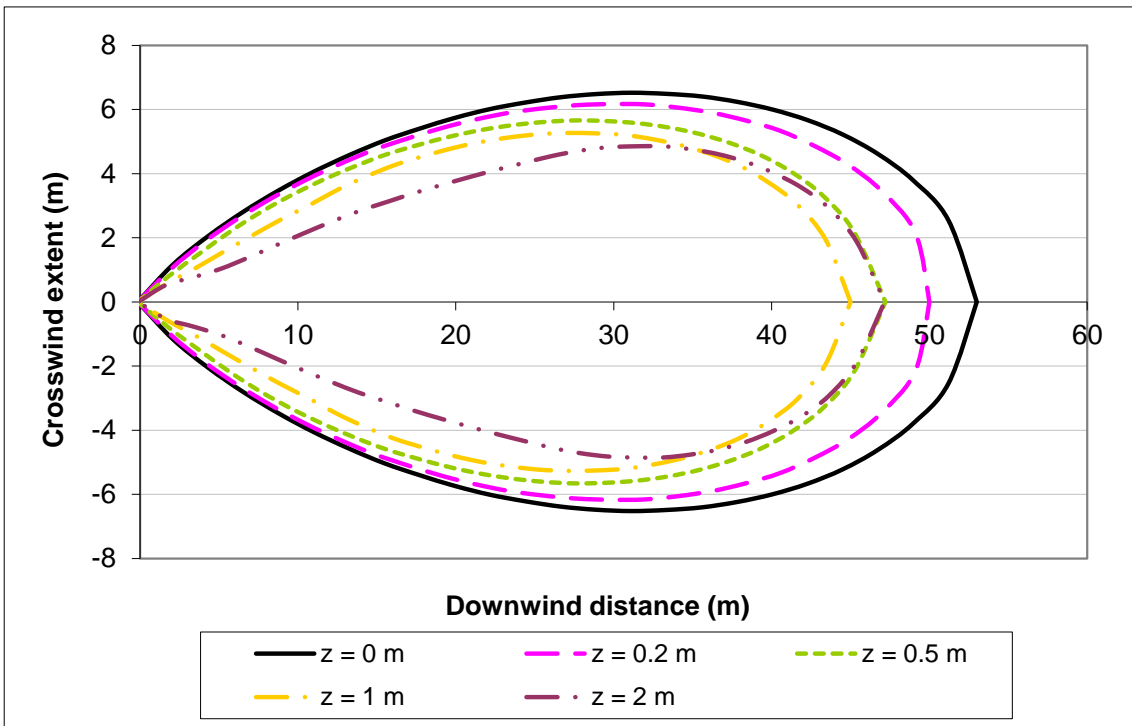


Figure 77 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in F2 weather, varying the release height

The maximum downwind distances to the LFL following a release from an ethylene pipeline at various release heights are shown in Table 26.

Table 26 Maximum downwind distances to the LFL for an ethylene release from a pipeline, varying the release height

<i>Scenario</i>	<i>Maximum downwind distance to the LFL (m) at specified release height</i>				
	<i>0 m</i>	<i>0.2 m</i>	<i>0.5 m</i>	<i>1 m</i>	<i>2 m</i>
<i>D5 weather</i>					
Rupture	365	368	369	331	312
110 mm hole	226	227	229	208	203
75 mm hole	156	158	154	143	141
25 mm hole	53	51	50	49	49
<i>F2 weather</i>					
Rupture	362	368	371	313	289
110 mm hole	211	212	214	193	181
75 mm hole	148	150	145	131	125
25 mm hole	53	50	47	45	47

3.4.5 Ground surface roughness length

In the original assessment, a ground surface roughness length of 0.3 m was used, which corresponds to an urban environment and is used by HSE when modelling releases from suburban pipelines. Sensitivity tests have been performed to assess the effect of moving to a value of 0.1 m, which is the surface roughness assumed by HSE for a rural environment and is used by HSE when modelling releases from rural pipelines. The results are shown in Figure 78 to Figure 81 for the various release sizes modelled in D5 weather and in Figure 82 to Figure 85 for the equivalent F2 scenarios. The maximum downwind distances to the LFL are given in Table 27. A release height of 0 m has been assumed.

The maximum predicted downwind distances to the LFL are reduced in all cases modelled when the ground surface roughness length is reduced to 0.1 m, except when modelling the rupture in D5 weather. The figures show that the crosswind extents are also reduced slightly. These effects are due to the decrease in friction between the release and the ground as the surface roughness length is decreased. The effect of the decrease in friction is that the jet does not slow down as quickly, leading to increased turbulent mixing with the atmosphere and hence shorter distances to the cloud concentration falling below the criterion concentration.



Figure 78 LFL isopleths for rupture of an ethylene pipeline in D5 weather for suburban and rural ground surface roughness lengths

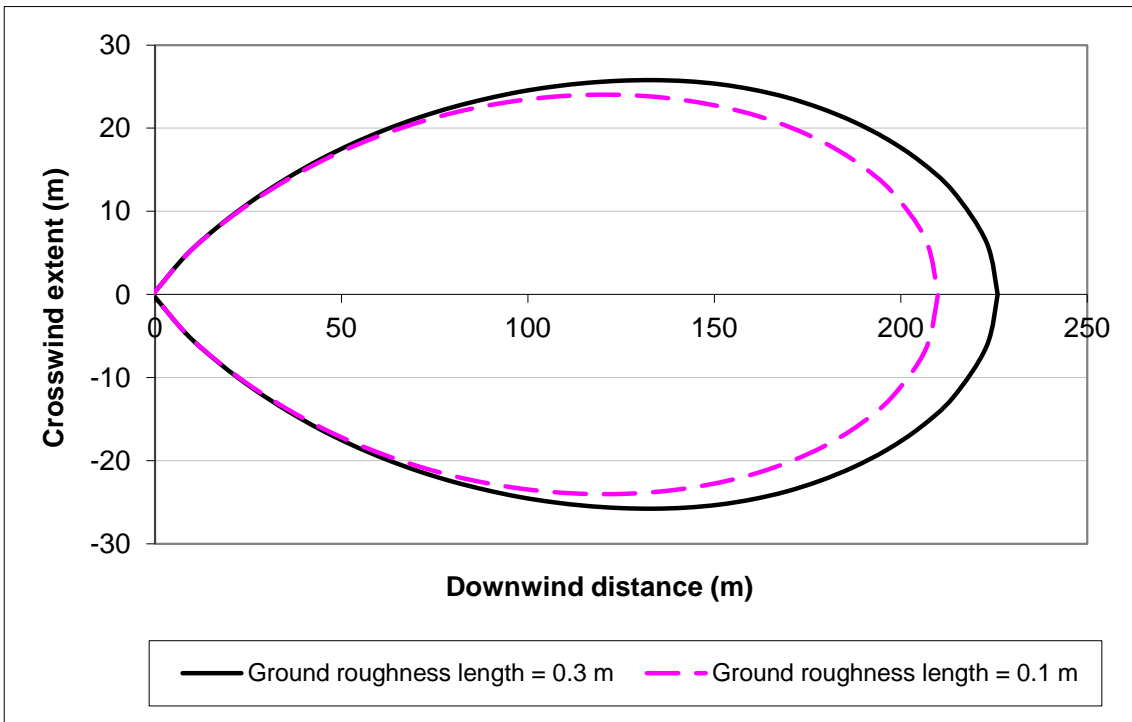


Figure 79 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in D5 weather for suburban and rural ground surface roughness lengths

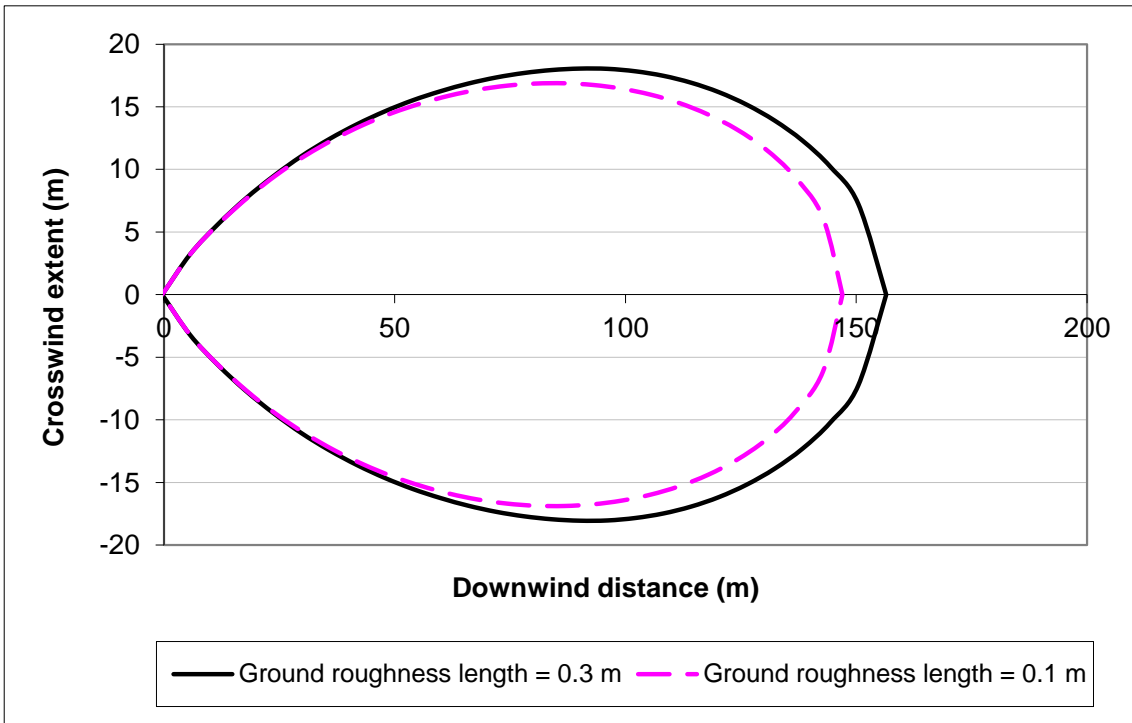


Figure 80 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in D5 weather for suburban and rural ground surface roughness lengths

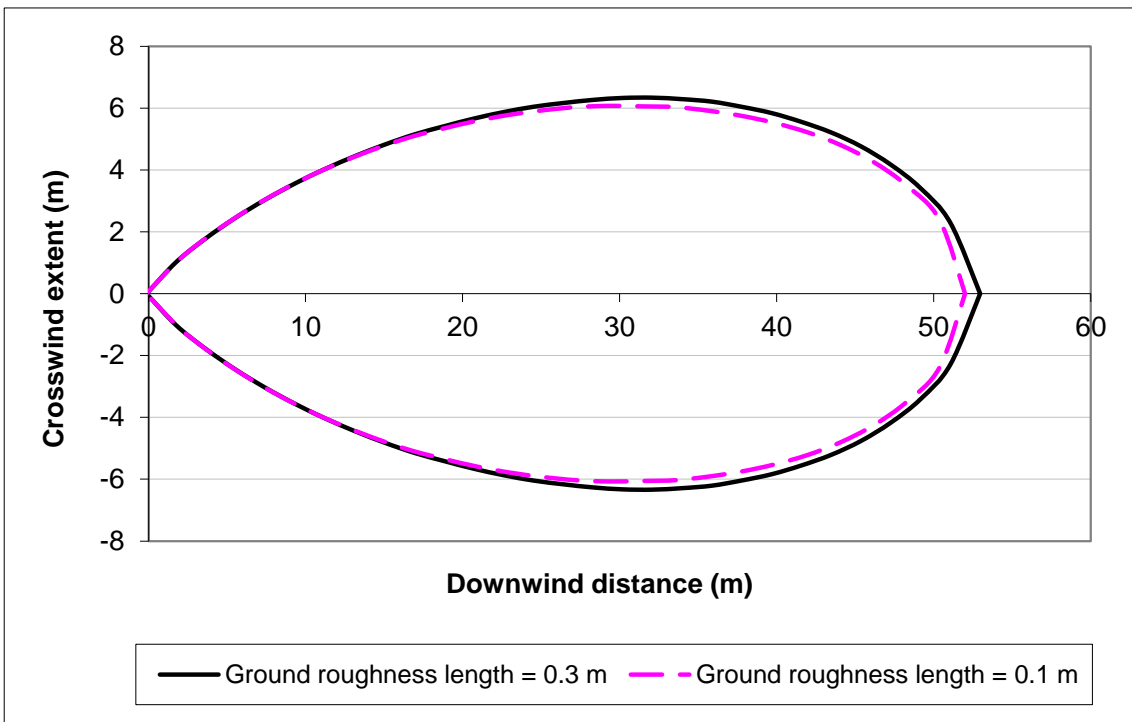


Figure 81 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in D5 weather for suburban and rural ground surface roughness lengths

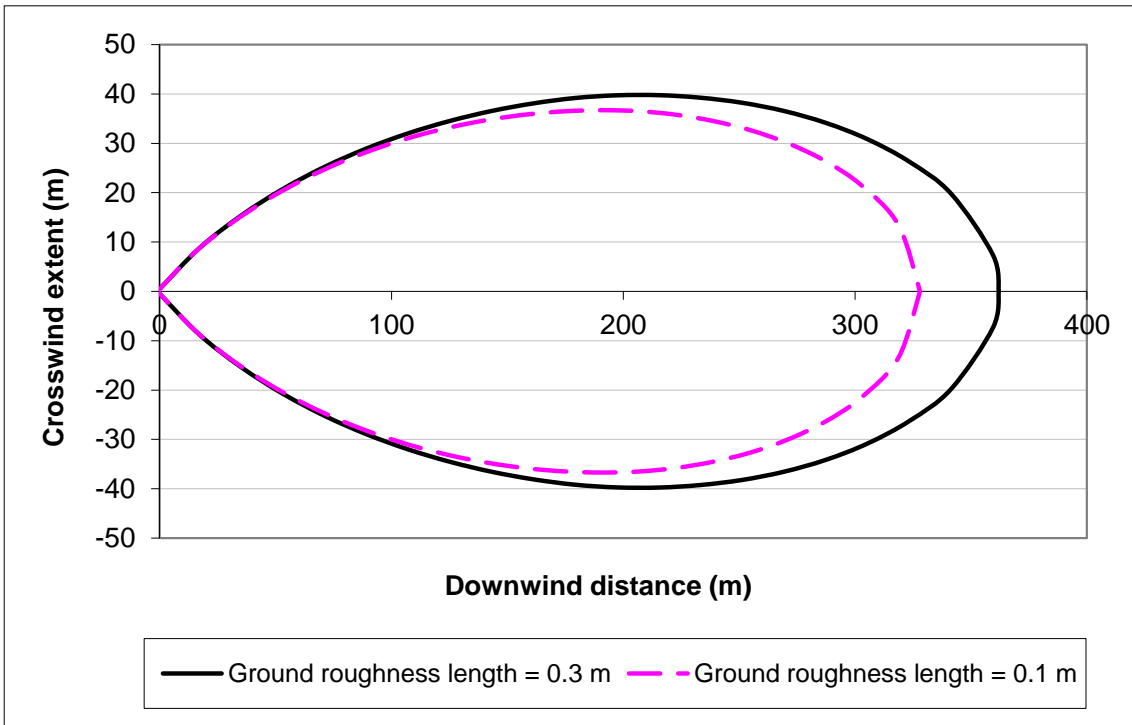


Figure 82 LFL isopleths for rupture of an ethylene pipeline in F2 weather for suburban and rural ground surface roughness lengths

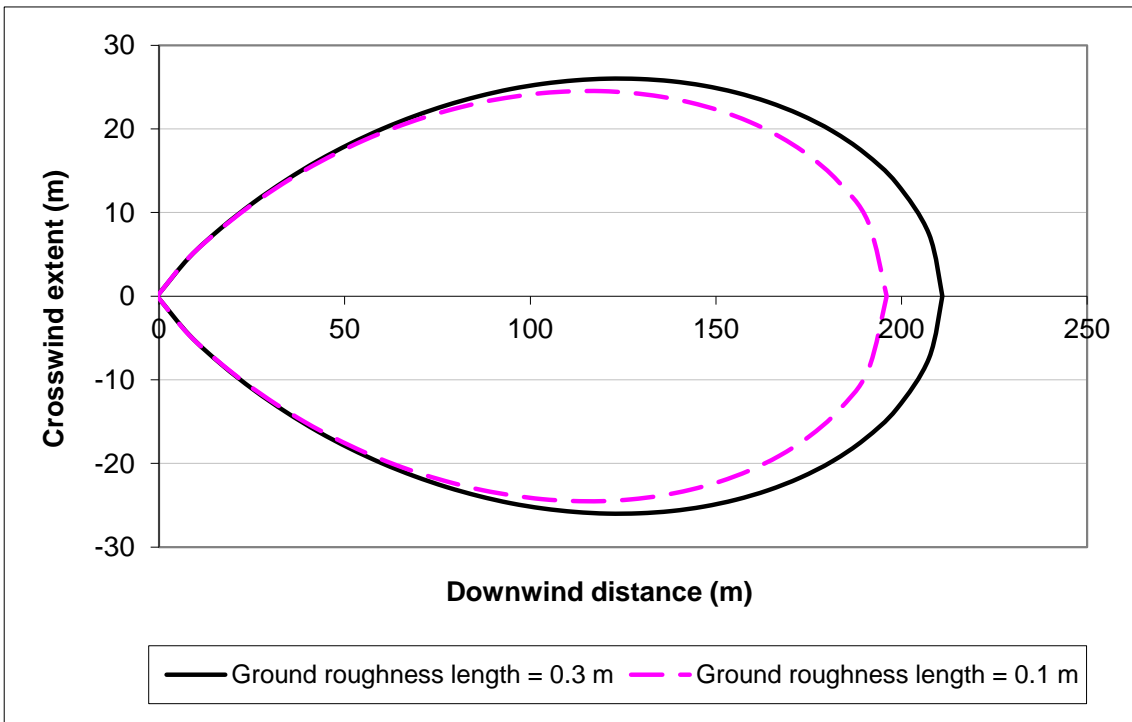


Figure 83 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in F2 weather for suburban and rural ground surface roughness lengths

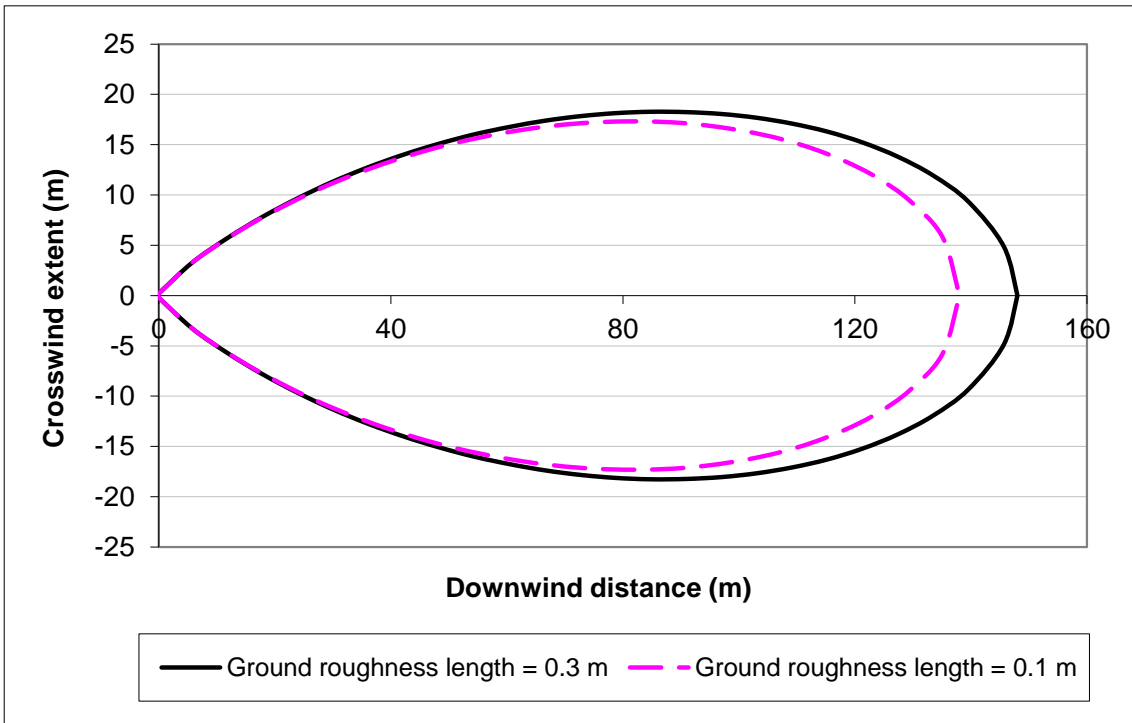


Figure 84 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in F2 weather for suburban and rural ground surface roughness lengths



Figure 85 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in F2 weather for suburban and rural ground surface roughness lengths

Table 27 shows the maximum downwind distances to the LFL following a release from an ethylene pipeline, assuming suburban and rural ground surface roughness lengths.

Table 27 Maximum downwind distances to the LFL for an ethylene release from a pipeline for two ground surface roughness lengths

<i>Scenario</i>	<i>Maximum downwind distance to the LFL (m) using specified ground surface roughness length</i>	
	<i>0.3 m</i>	<i>0.1 m</i>
<i>D5 weather</i>		
Rupture	365	373
110 mm hole	226	210
75 mm hole	156	147
25 mm hole	53	52
<i>F2 weather</i>		
Rupture	362	328
110 mm hole	211	196
75 mm hole	148	138
25 mm hole	53	50

3.4.6 Angle of release

In the original assessment, it was assumed that the release was horizontal. Sensitivity tests were performed in DRIFT 3.6.14 using release angles of 45° and 90° from the horizontal, assuming a release height of $z = 0$ m and a ground roughness length of 0.1 m. Results could not be obtained for the 90° case as the termination criteria in DRIFT 3 were never satisfied. The results for the 45° case are shown in Figure 86 to Figure 89 for the D5 weather scenarios and in Figure 90 to Figure 93 for the F2 weather scenarios, together with the results for the base case release angle of 0° from horizontal. The maximum predicted downwind distances to the LFL are shown in Table 28.

There is a significant reduction in the size of the contours when the angle of release is modelled as 45° from horizontal when compared to when the jet is modelled as horizontal (0°). This is as expected given that there is a vertical component to the jet momentum when modelling a 45° jet that is not present for the horizontal release. Additionally, releasing a jet into an ambient cross-flow greatly enhances its mixing rate with air.

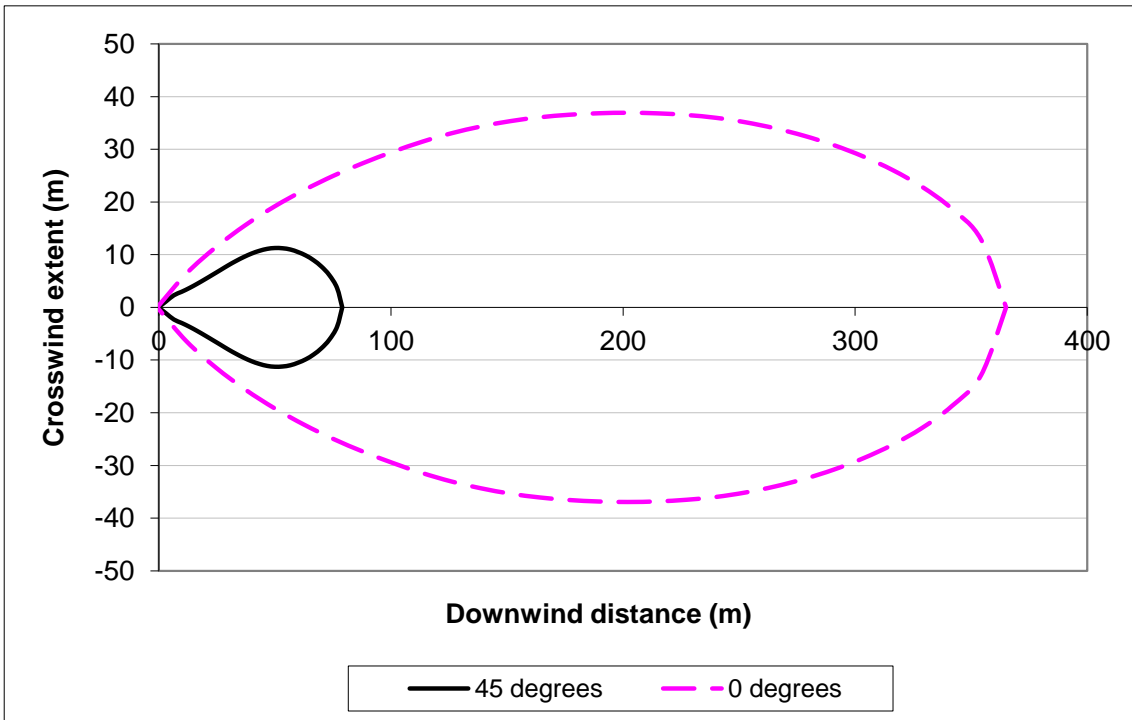


Figure 86 LFL isopleths for rupture of an ethylene pipeline in D5 weather for two release angles

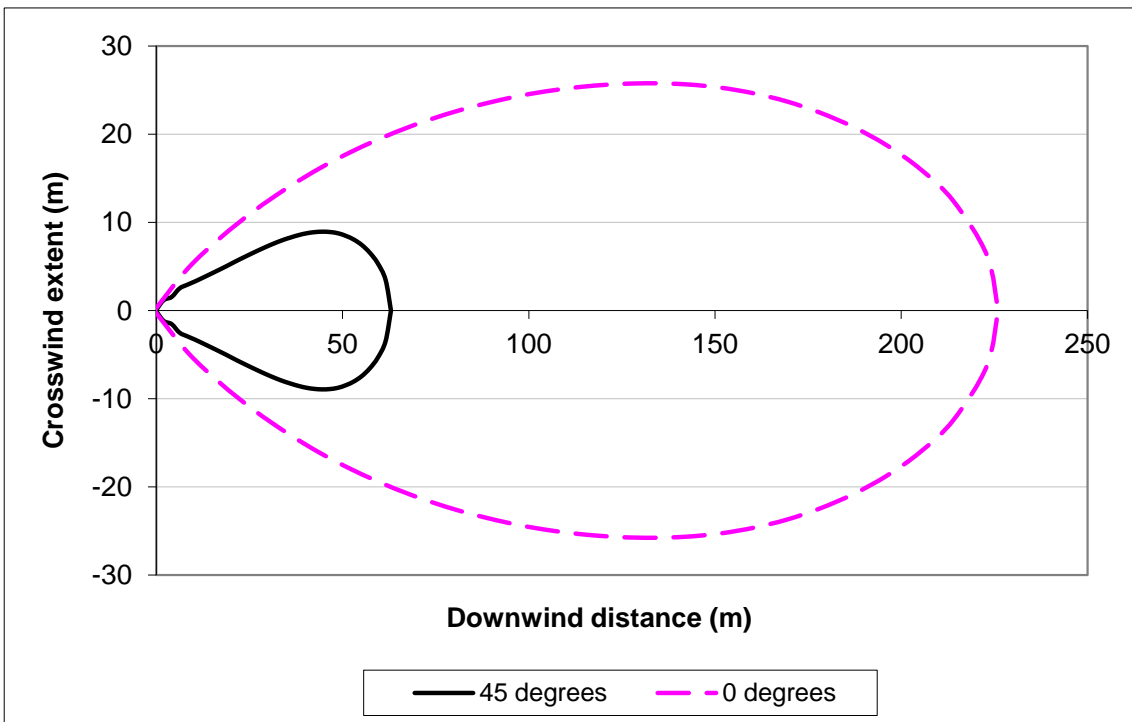


Figure 87 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in D5 weather for two release angles

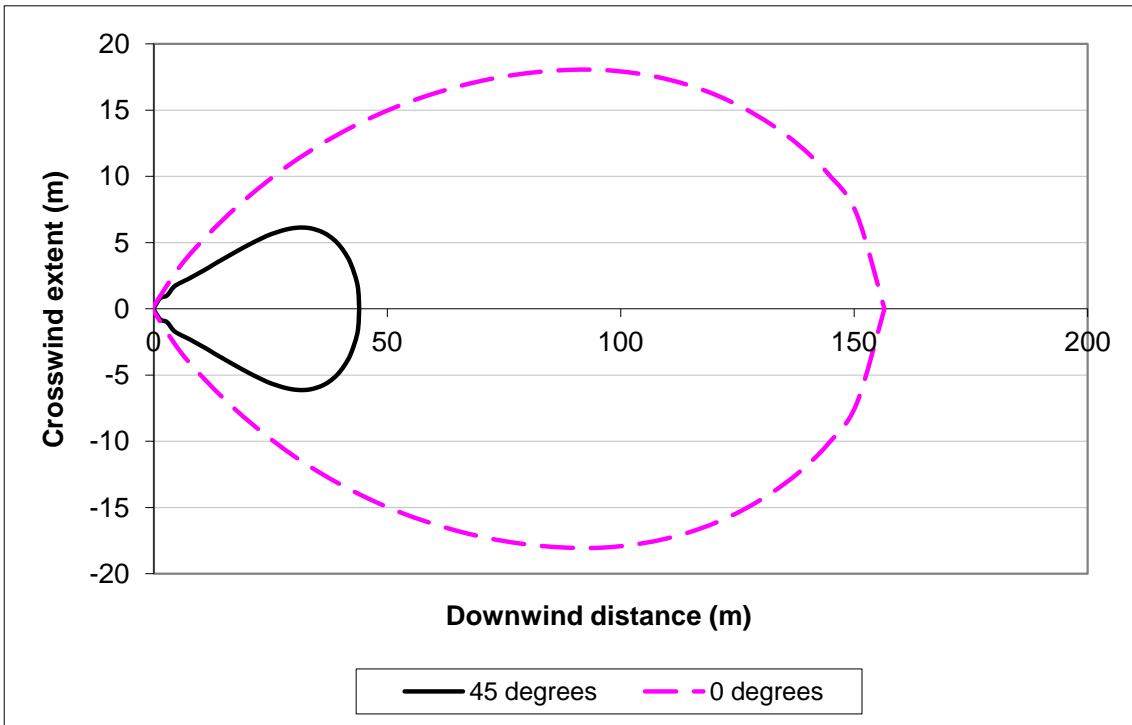


Figure 88 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in D5 weather for two release angles

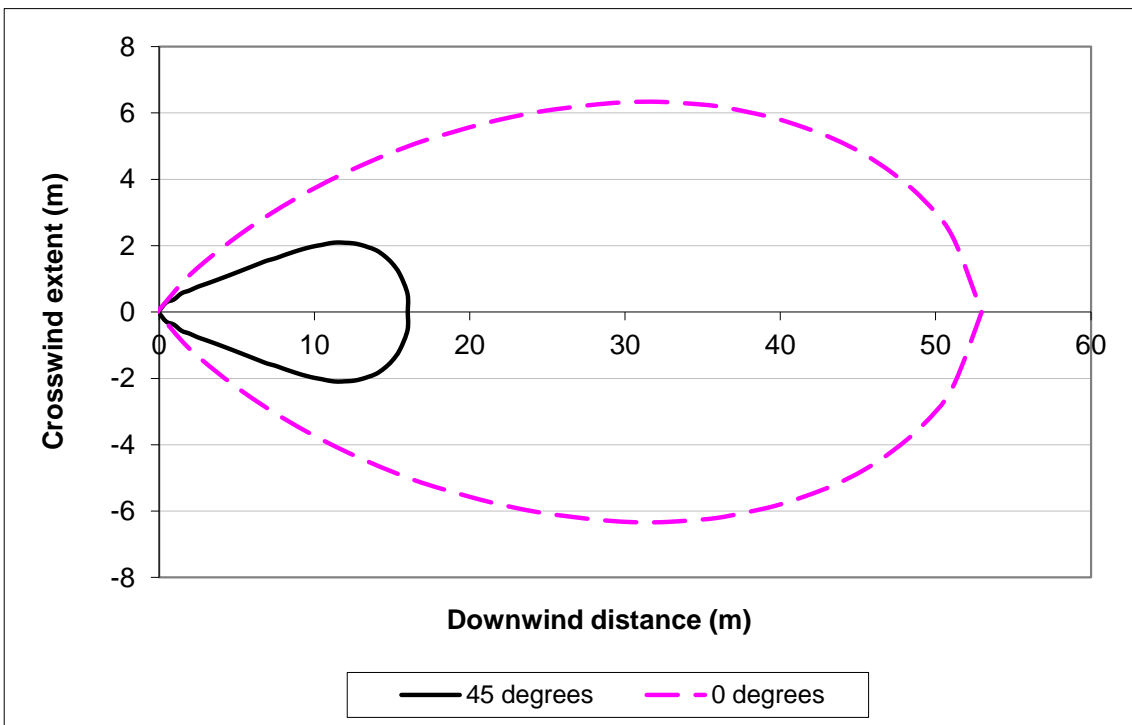


Figure 89 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in D5 weather for two release angles

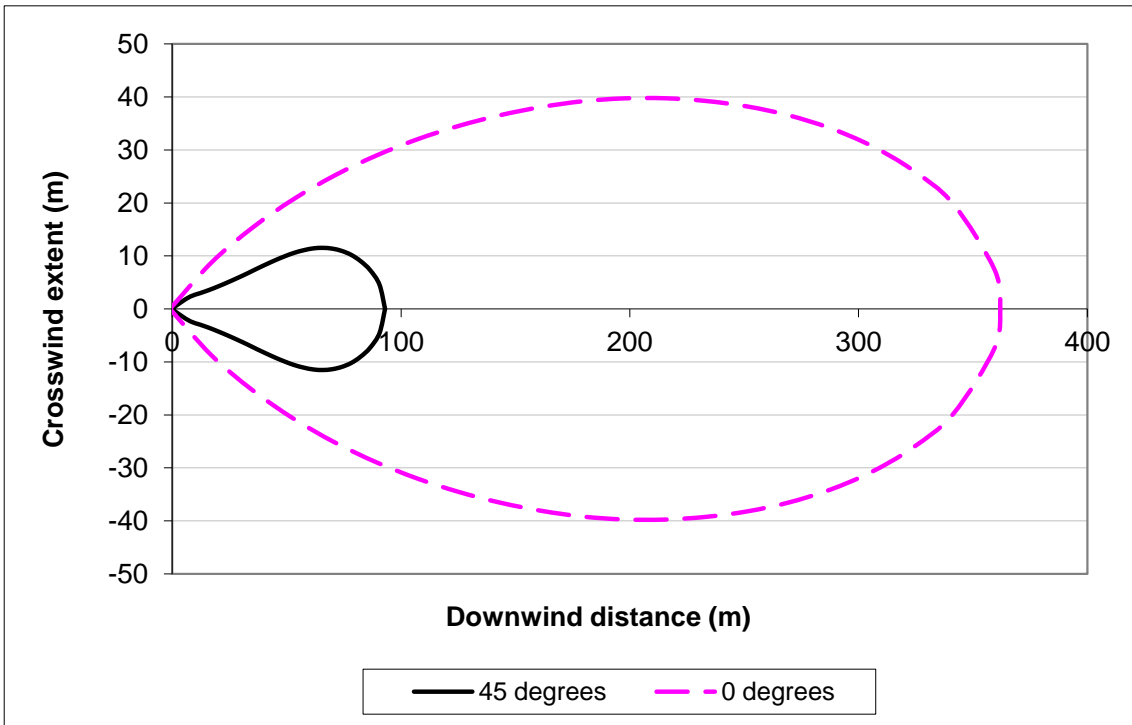


Figure 90 LFL isopleths for rupture of an ethylene pipeline in F2 weather for two release angles

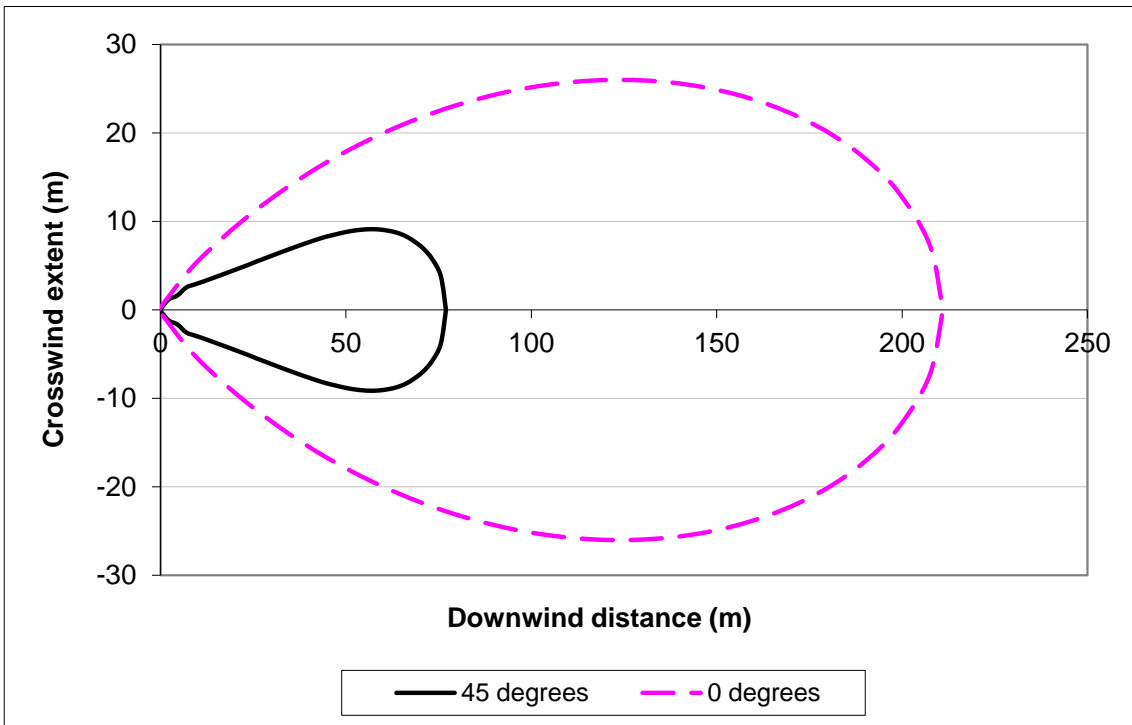


Figure 91 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in F2 weather for two release angles

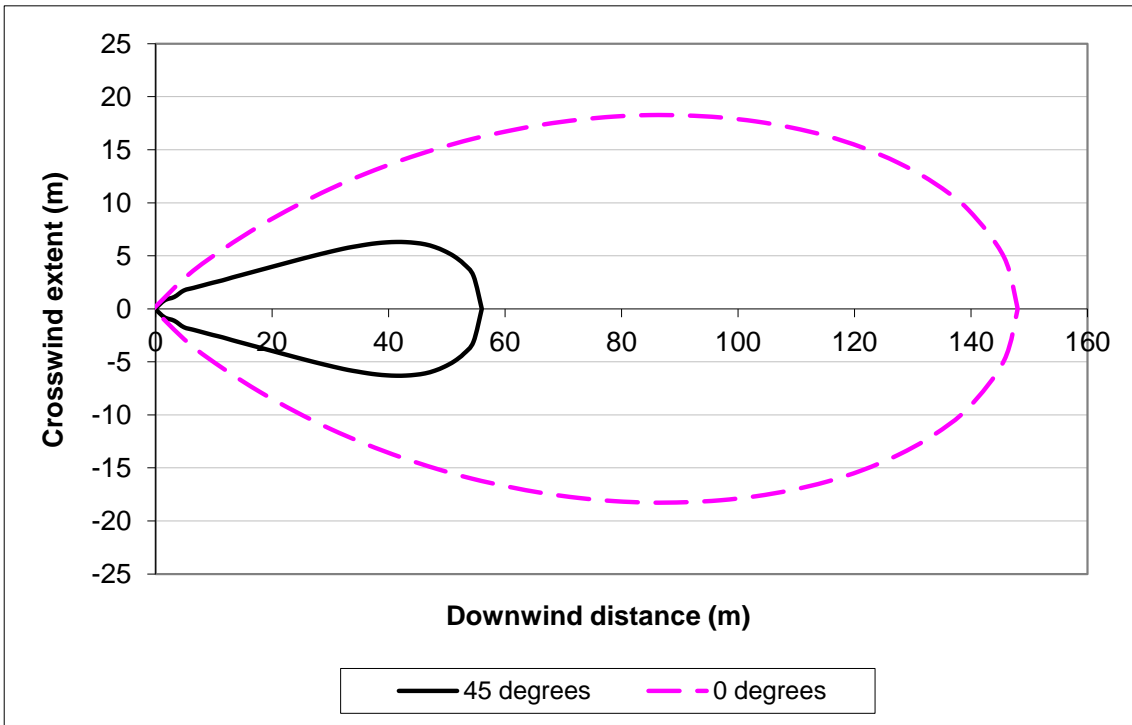


Figure 92 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in F2 weather for two release angles

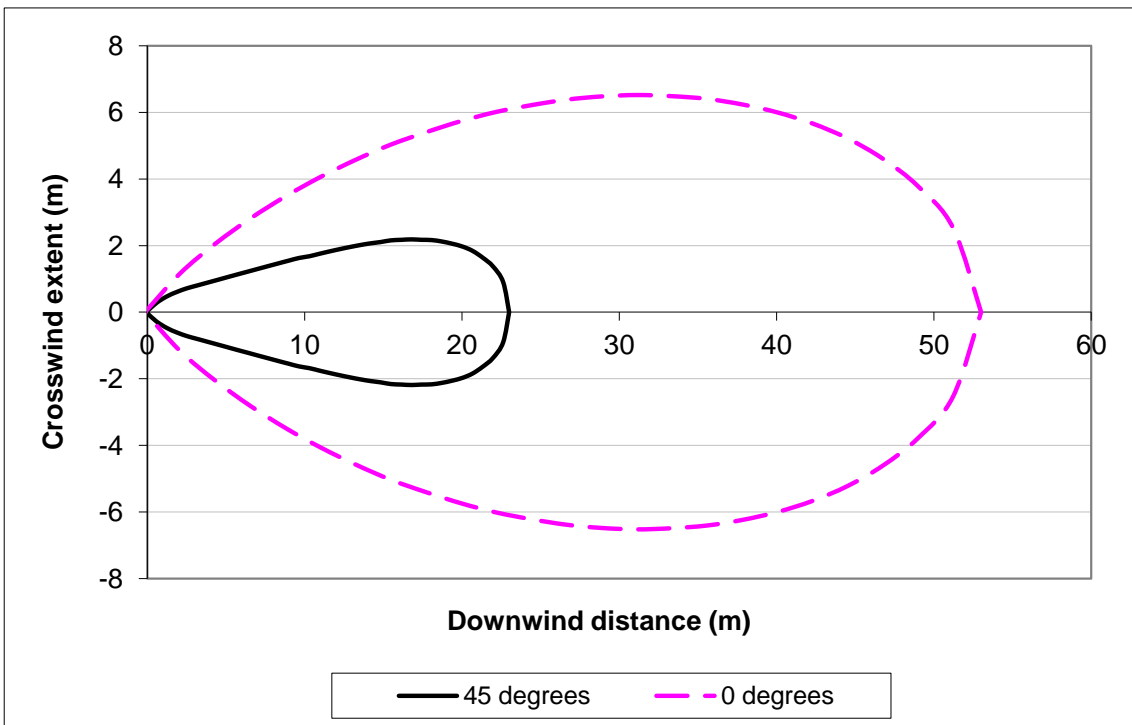


Figure 93 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in F2 weather for two release angles

The maximum downwind distances to the LFL following a release from an ethylene pipeline at two release angles are shown in Table 28.

Table 28 Maximum downwind distances to the LFL from an ethylene release from a pipeline for two angles of release

<i>Scenario</i>	<i>Maximum downwind distance to the LFL (m) using specified release angle from horizontal</i>	
	<i>0°</i>	<i>45°</i>
<i>D5 weather</i>		
Rupture	365	79
110 mm hole	226	63
75 mm hole	156	44
25 mm hole	53	16
<i>F2 weather</i>		
Rupture	362	93
110 mm hole	211	77
75 mm hole	148	56
25 mm hole	53	23

3.4.7 Release temperature

In the original assessment and the reassessment, the input temperature for DRIFT for ruptures was taken as the output from CREATE (256.5K), as used in the original assessment. The equivalent value for the three hole sizes was 243 K. This is lower than the temperature of the substance as it travels along the pipeline (283 K) but higher than the temperature of the substance at the exit point (218 K for ruptures, as calculated by PipeTech). Sensitivity tests have been performed to determine the effect of modifying the temperature on the maximum downwind LFL distances calculated by DRIFT 3. Temperatures of 270 K (the approximate mid-point between the 256.5 K used for ruptures and the critical temperature of ethylene) and 283 K (close to the critical temperature of 282.3 K) have been tested and the results from DRIFT 3 have been compared with those generated using either the temperature output from PipeTech (218 K) when modelling the rupture scenarios or using the value calculated by CREATE (243 K) when modelling the releases from the three hole sizes.

The results in D5 weather are shown in Figure 94 to Figure 97 and the results in F2 weather are shown in Figure 98 to Figure 101. As the release temperature increases, the maximum downwind LFL distances decrease. This implies that using the temperature at the exit point is a cautious approach.

Table 29 gives the maximum downwind distances to the LFL for all the scenarios. The maximum downwind distances to the LFL predicted for a release temperature of 283 K are significantly smaller than those predicted for a release temperature of 270 K, despite the relatively small increase in temperature. This is due to the fact that the release temperature of 283 K is very close to the critical temperature of ethylene (282.3 K). At colder temperatures the cloud is denser than air but, at 283 K, the cloud becomes less dense than air, leading to buoyancy. Mixing is suppressed for denser than air dispersion, but enhanced for buoyant dispersion.

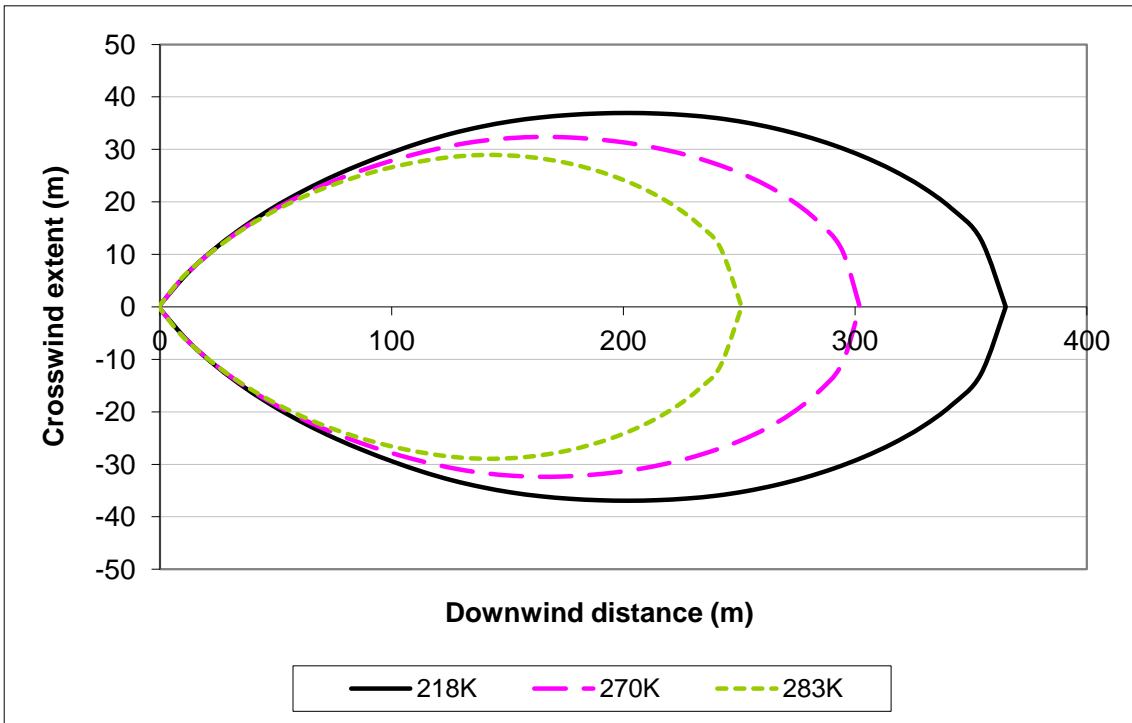


Figure 94 LFL isopleths for rupture of an ethylene pipeline in D5 weather, varying the release temperature

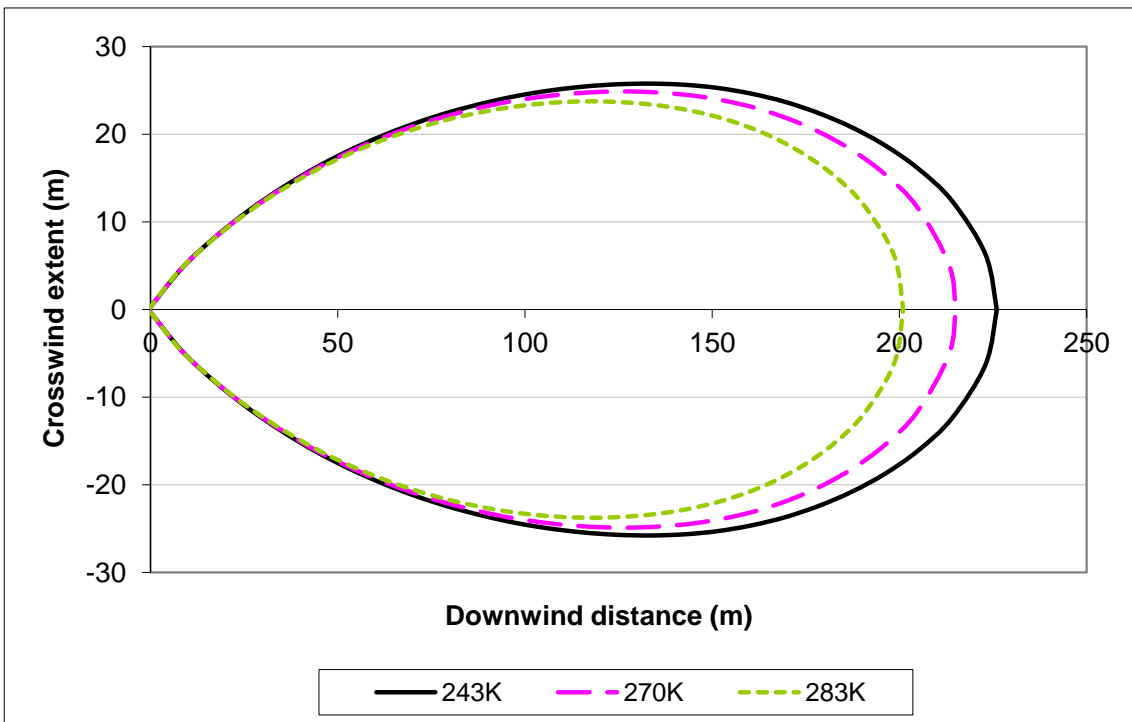


Figure 95 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in D5 weather, varying the release temperature

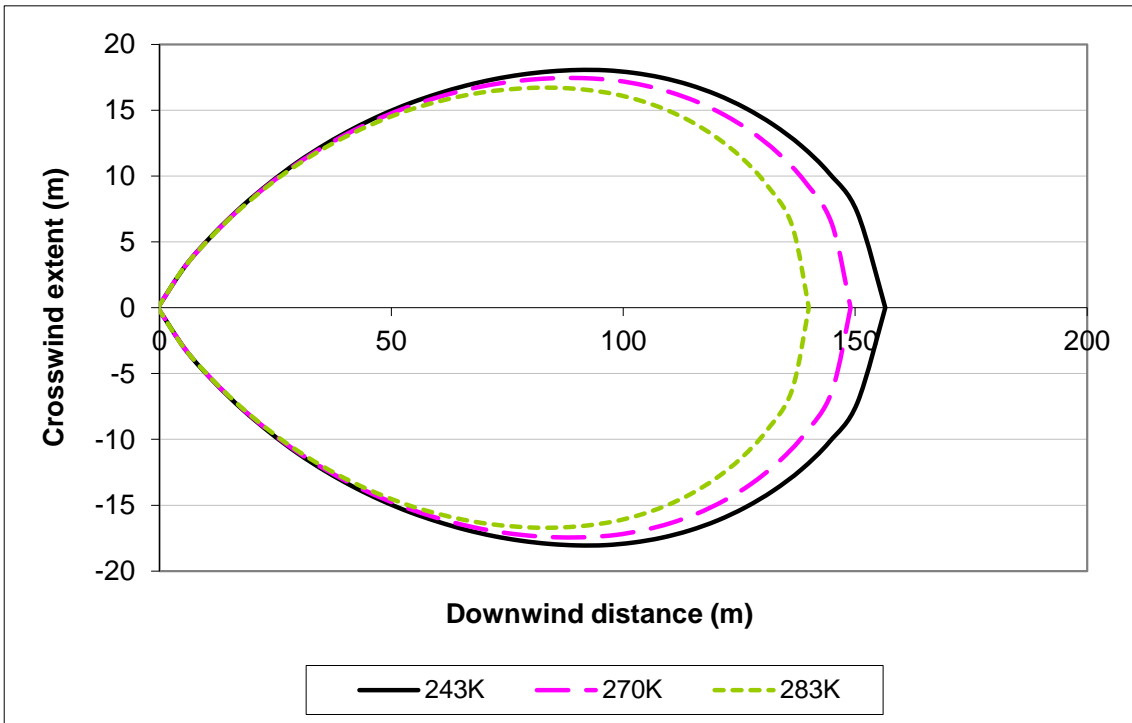


Figure 96 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in D5 weather, varying the release temperature

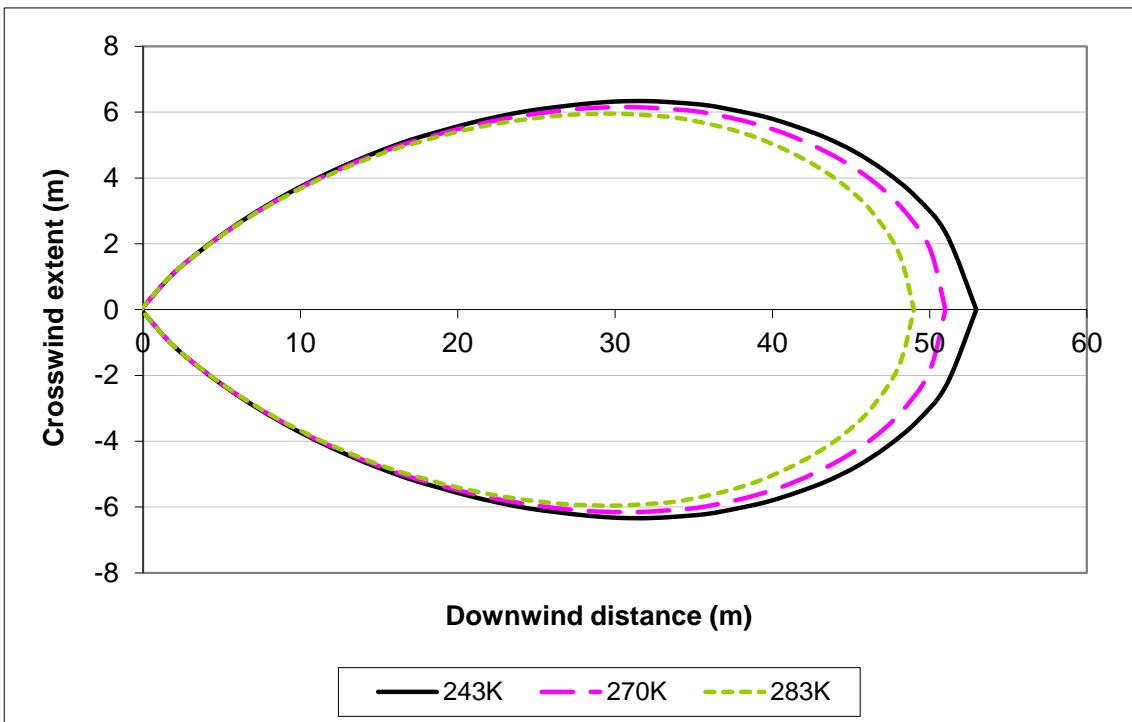


Figure 97 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in D5 weather, varying the release temperature

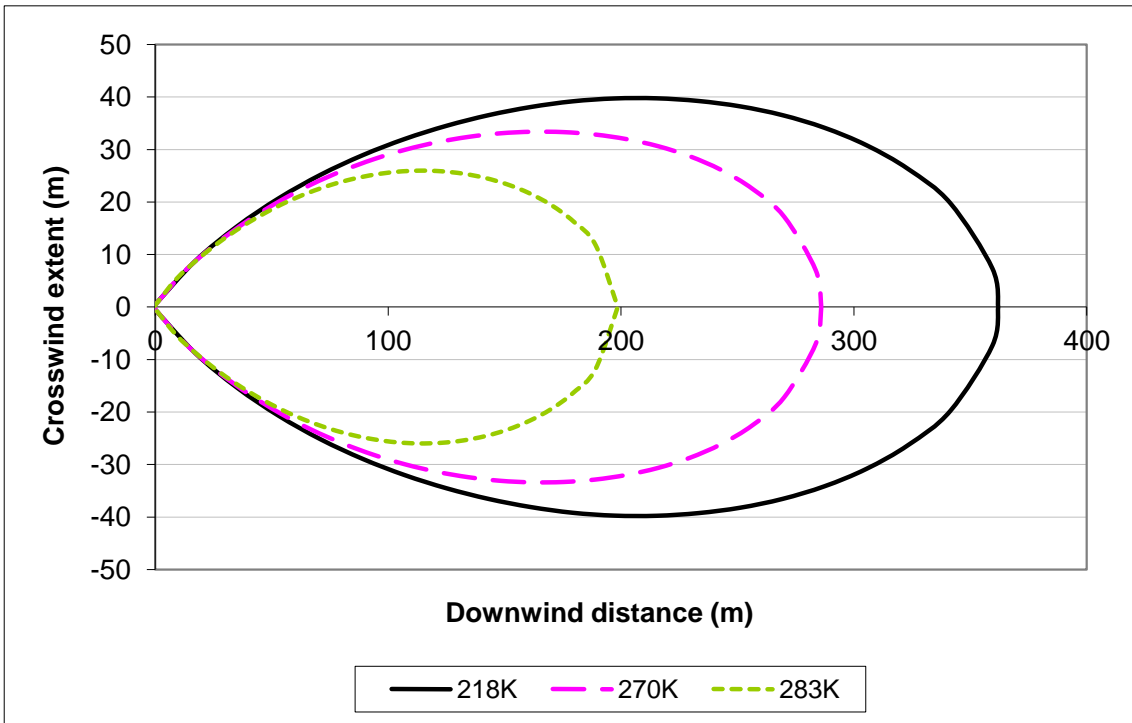


Figure 98 LFL isopleths for rupture of an ethylene pipeline in F2 weather, varying the release temperature

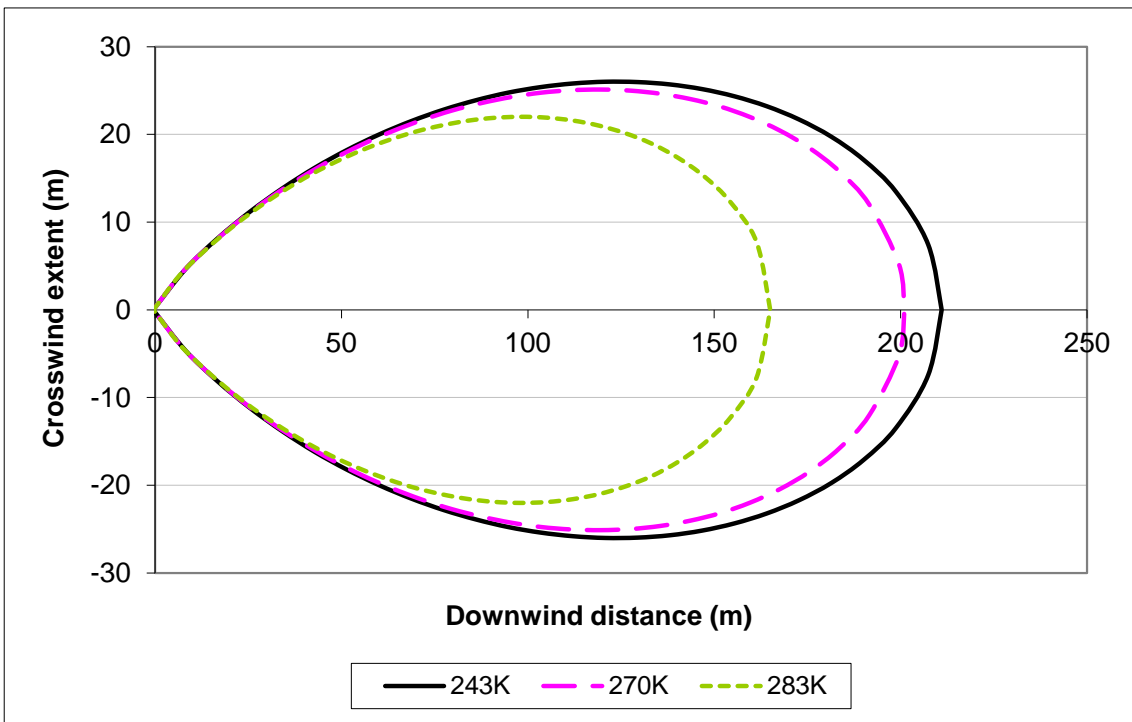


Figure 99 LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in F2 weather, varying the release temperature

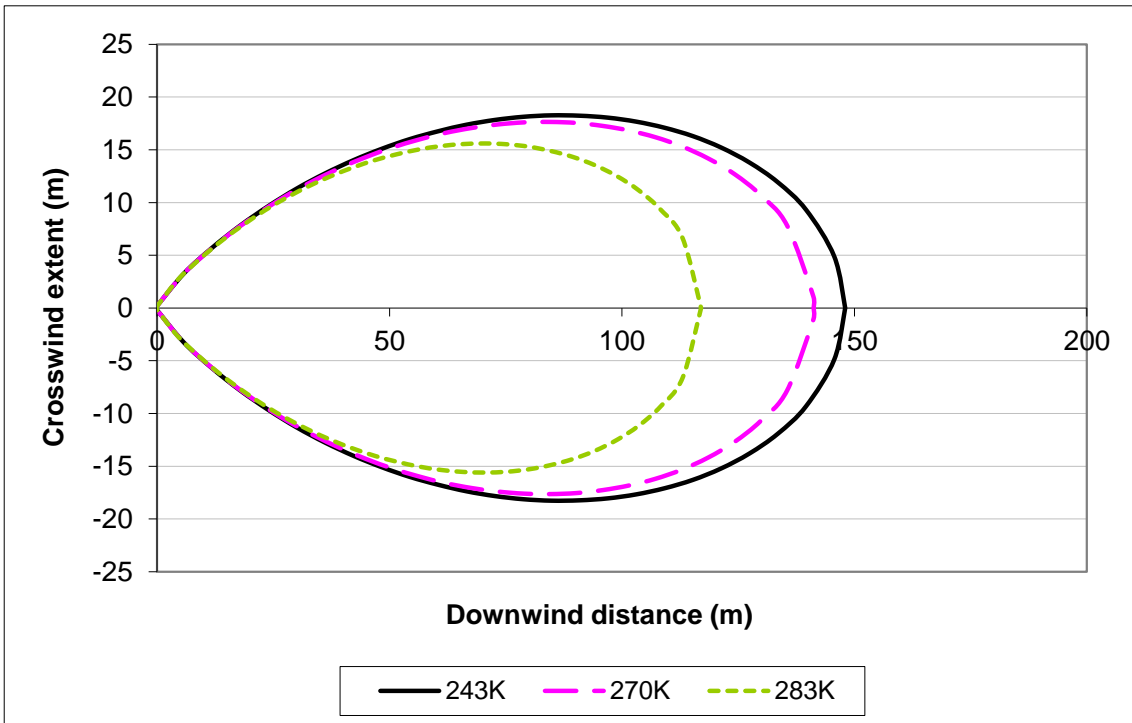


Figure 100 LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in F2 weather, varying the release temperature

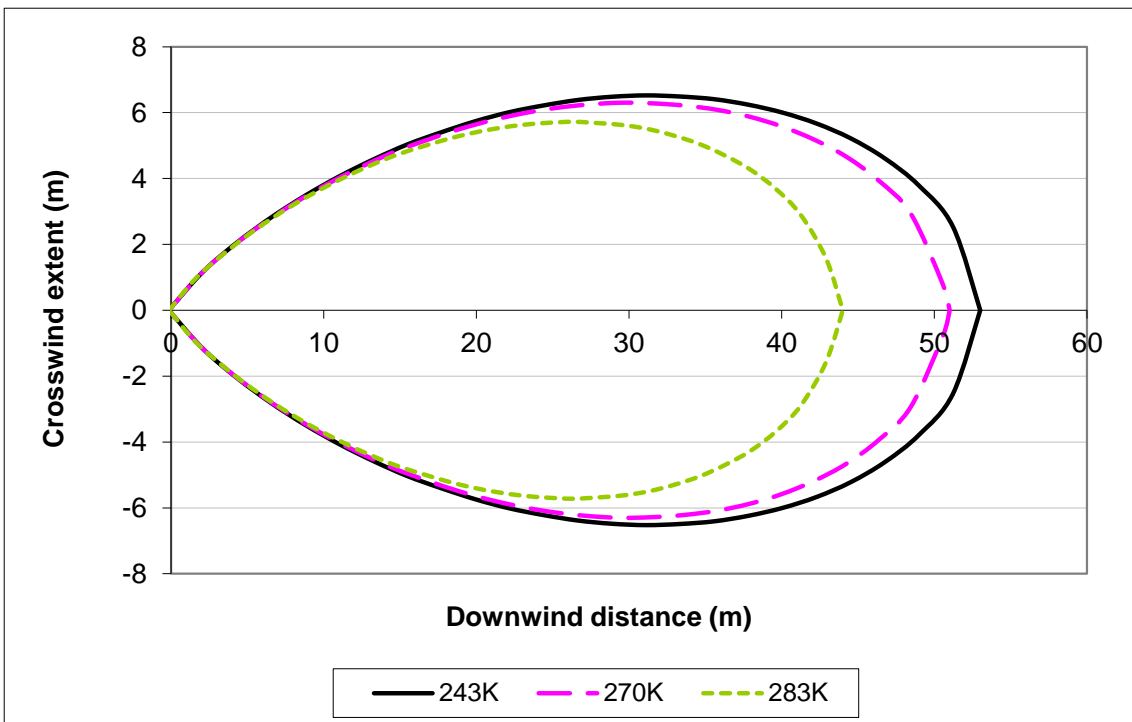


Figure 101 LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in F2 weather, varying the release temperature

Table 29 shows the maximum predicted downwind distances to the LFL following a release from an ethylene pipeline, at various release temperatures.

Table 29 Maximum downwind distances to the LFL from an ethylene release from a pipeline varying the temperature of release

<i>Scenario</i>	<i>Maximum downwind distance to the LFL (m) using specified release temperature</i>			
	<i>218K</i>	<i>243 K</i>	<i>270 K</i>	<i>283 K</i>
<i>D5 weather</i>				
Rupture	365	N/A	302	251
110 mm hole	N/A	226	215	201
75 mm hole	N/A	156	149	140
25 mm hole	N/A	53	51	49
<i>F2 weather</i>				
Rupture	362	N/A	286	199
110 mm hole	N/A	211	201	165
75 mm hole	N/A	148	141	117
25 mm hole	N/A	53	51	44

3.4.8 PipeTech version 54 outputs for pipeline holes

In the original assessment and the reassessment, PipeTech was used to generate the release rates for the rupture scenario but LOSSP was used for the three hole sizes modelled. It was also assumed in the original assessment that the release was purely gaseous for all the release sizes. In the reassessment, the rupture releases have been assumed to be two-phase, as indicated by the PipeTech outputs.

Sensitivity tests have been performed to assess the impact of moving to using the outputs from PipeTech for all the release sizes modelled i.e. ruptures and holes. Using PipeTech is now the recommended practice for HSE for pipeline assessments, but was not the case when the original assessment was undertaken. The release rates and temperatures for the three hole sizes are given in Table 30. The output from PipeTech indicates that the releases from the hole sizes modelled are all gaseous and so this is the option that has been used in DRIFT 3.6.14.

Table 30 Release rates from PipeTech and LOSSP and temperatures from PipeTech for holes in an ethylene pipeline

<i>Hole size</i>	<i>Release rate (kg/s)</i>		<i>Temperature (K) (PipeTech)</i>	<i>Flow type</i>
	<i>PipeTech</i>	<i>LOSSP</i>		
110 mm	225.68	298	266.65	Gaseous
75 mm	166.63	138	265.62	Gaseous
25 mm	25.05	15	264.50	Gaseous

The results for D5 weather are shown in Figure 102 to Figure 104 and for F2 weather in Figure 105 to Figure 107. Table 31 gives the maximum downwind distances to the LFL. The figures and table indicate that the maximum downwind LFL distances decrease for the 110 mm holes when using the PipeTech inputs, but increase for the other two hole sizes. If the release rates from PipeTech are compared to those from LOSSP in Table 30, PipeTech predicts a lower flow rate than LOSSP for the 110 mm hole scenario, but higher flow rates for the other two hole sizes modelled.

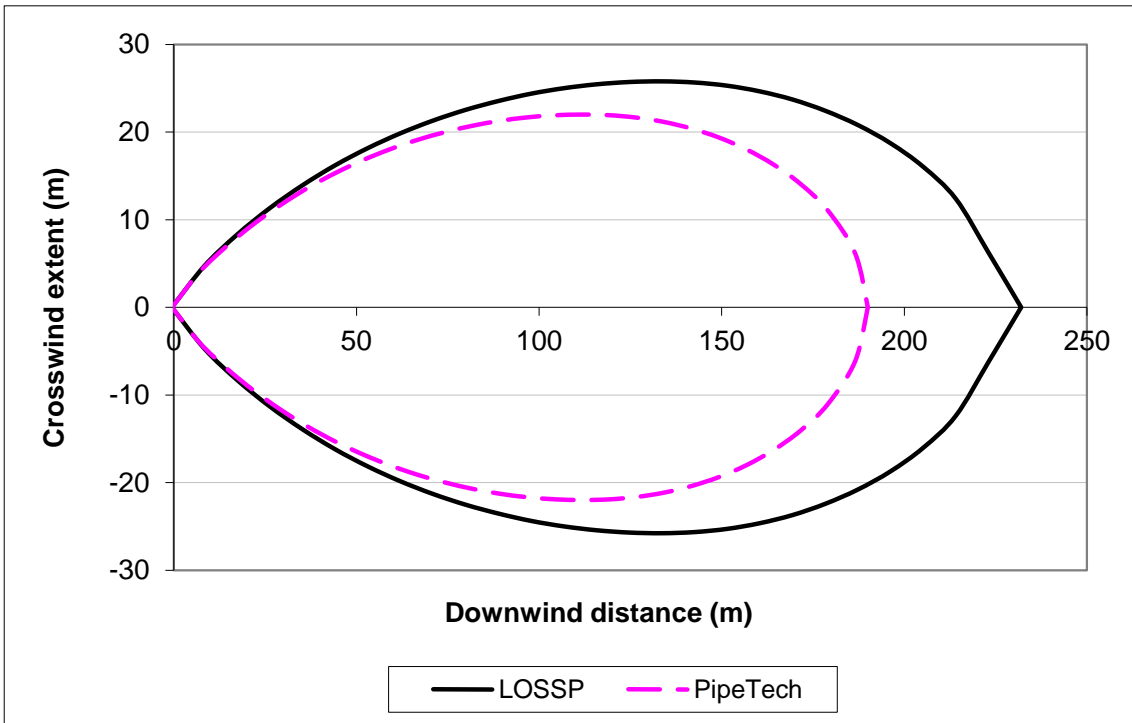


Figure 102 Comparison of LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in D5 weather for different flow rate source models

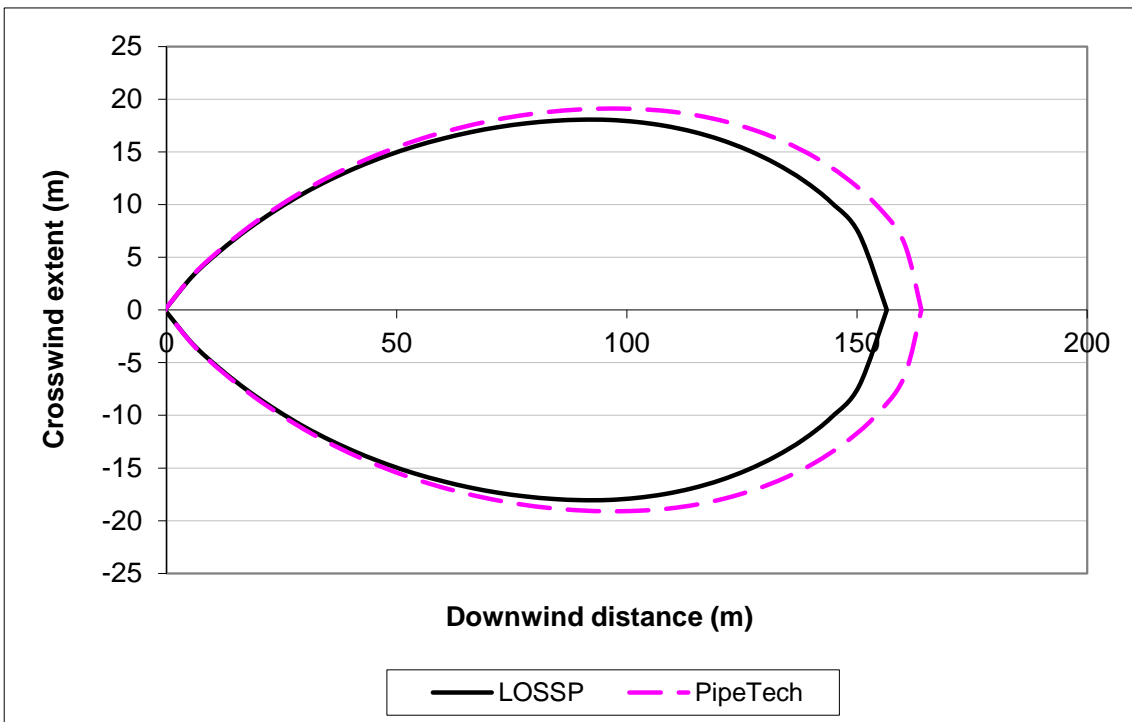


Figure 103 Comparison of LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in D5 weather for different flow rate source models

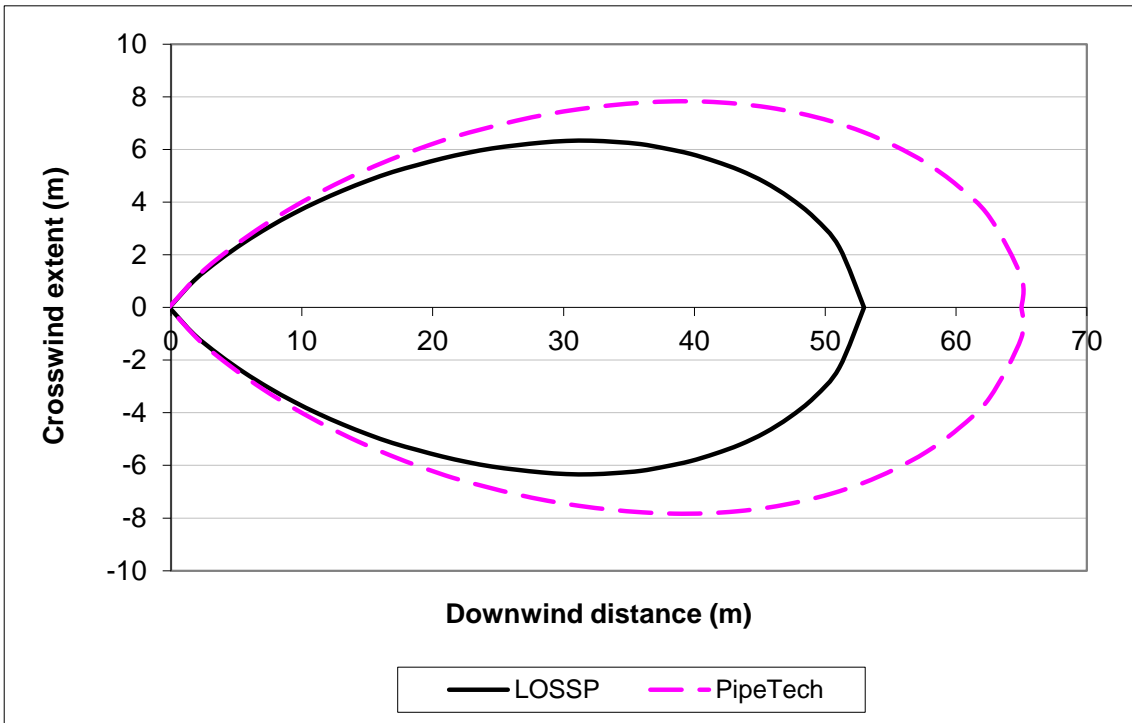


Figure 104 Comparison of LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in D5 weather for different flow rate source models

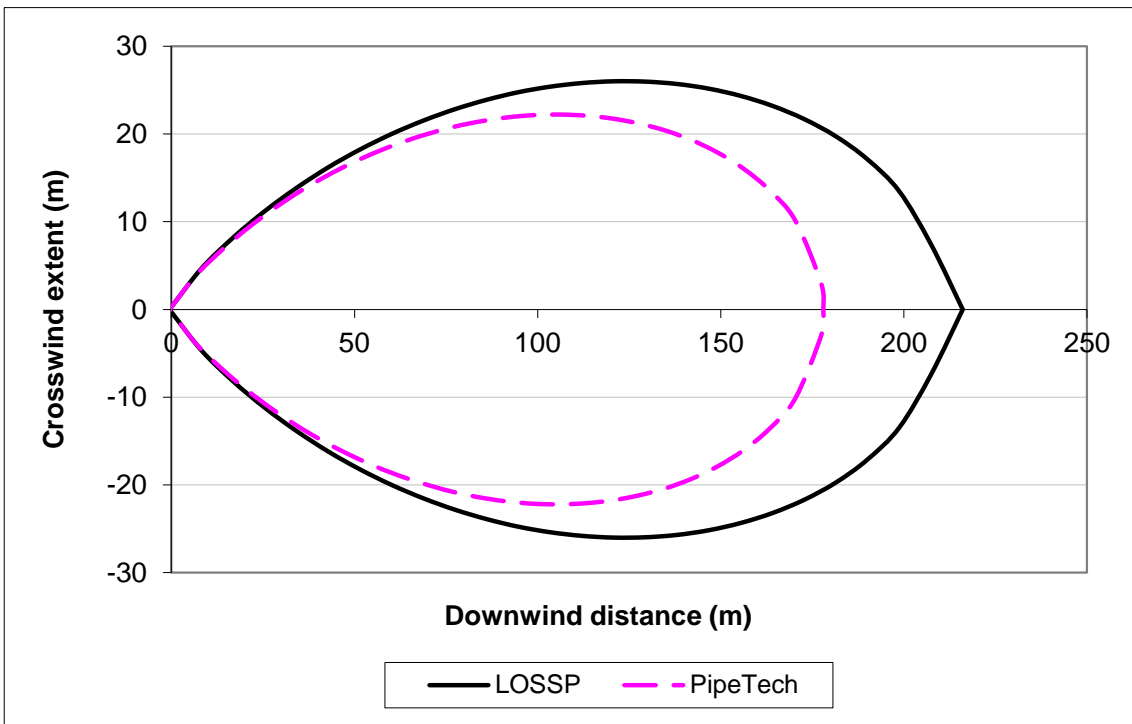


Figure 105 Comparison of LFL isopleths for a release from a 110 mm hole in an ethylene pipeline in F2 weather for different flow rate source models

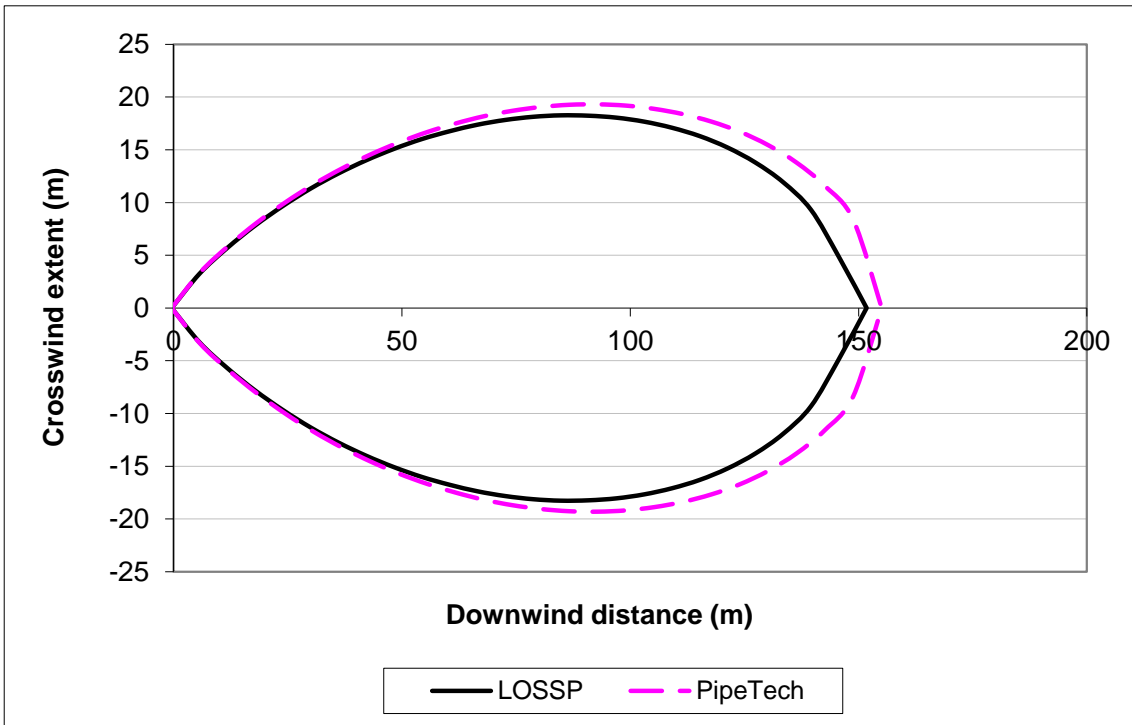


Figure 106 Comparison of LFL isopleths for a release from a 75 mm hole in an ethylene pipeline in F2 weather for different flow rate source models

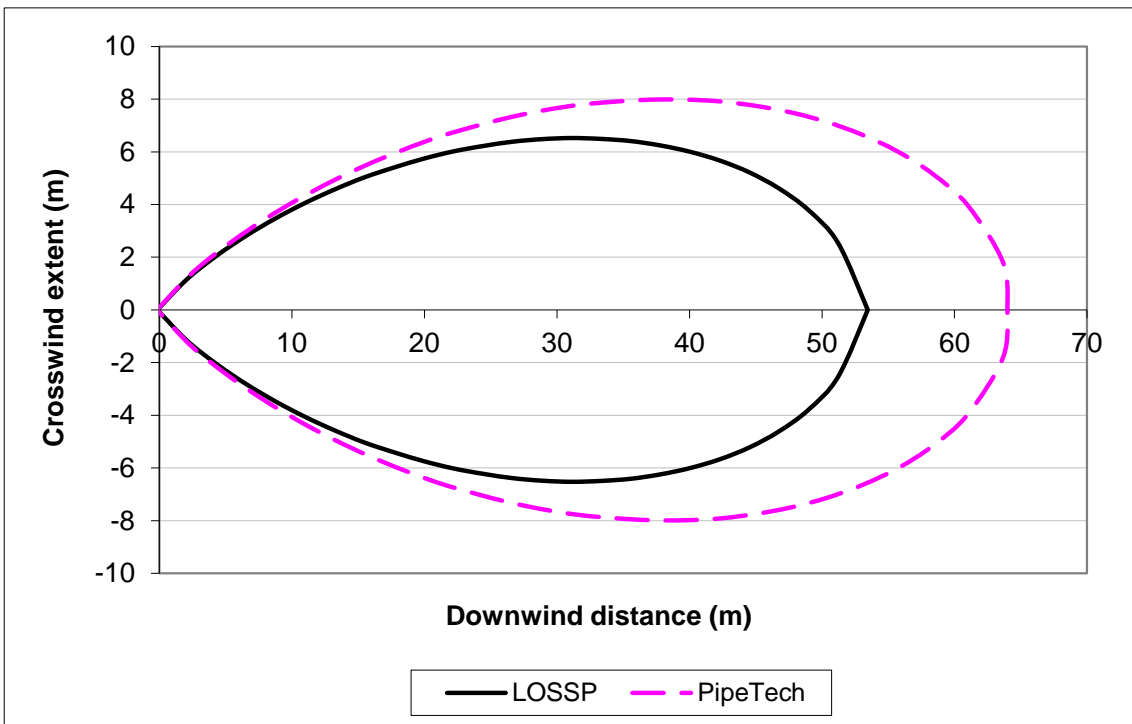


Figure 107 Comparison of LFL isopleths for a release from a 25 mm hole in an ethylene pipeline in F2 weather for different flow rate source models

Table 31 shows the maximum predicted downwind distances to the LFL following a release from an ethylene pipeline, using different flow rate source models.

Table 31 Maximum predicted downwind distances to the LFL from an ethylene release from a pipeline for different flow rate source models

<i>Scenario</i>	<i>Maximum downwind distance to the LFL (m) using specified flow rate source model</i>	
	<i>LOSSP</i>	<i>PipeTech</i>
<i>D5 weather</i>		
110 mm hole	226	190
75 mm hole	156	164
25 mm hole	53	65
<i>F2 weather</i>		
110 mm hole	211	178
75 mm hole	148	155
25 mm hole	53	64

The effects of using PipeTech for all the hole sizes, rather than just ruptures, on the risk based LUP zones are shown in Table 32 for the suburban pipeline and in Table 33 for the rural pipeline. Suburban pipelines have higher failure rates associated with them due to the increased likelihood of being struck by digging equipment. The results indicate that there is a negligible impact on the zone sizes.

Table 32 Comparing risk based LUP zones (m) assuming the pipeline is suburban and using different flow rate source models for the holes

<i>Flow rate model for holes</i>	<i>Land Use Planning Zone (m)</i>		
	<i>Inner Zone</i>	<i>Middle Zone</i>	<i>Outer Zone</i>
LOSSP	32	104	241
PipeTech	32	105	241

Table 33 Comparing risk based LUP zones (m) assuming the pipeline is rural and using different flow rate source models for the holes

<i>Flow rate model for holes</i>	<i>Land Use Planning Zone (m)</i>		
	<i>Inner Zone</i>	<i>Middle Zone</i>	<i>Outer Zone</i>
LOSSP	0	65	100
PipeTech	0	65	100

3.5 LIQUEFIED PETROLEUM GAS (LPG) PIPELINE ASSESSMENT

The original assessment was undertaken to modify the LUP zone sizes that would apply around a 114.3 mm (4.5") LPG pipeline, as a consequence of receiving revised information about the pipeline parameters. Two different wall thicknesses, 6.02 mm and 5.02 mm, were considered. PipeTech was used to generate the release rates for the rupture scenario and LOSSP was used to generate release rates for the three hole sizes modelled. The large hole size was revised to be equivalent to 100 mm diameter, rather than the 110 mm hole size that is usually used by HSE, as it would otherwise be larger than the internal diameter of the pipeline. MISHAP01 was used to generate the LUP zones. CRUNCH was the dispersion model used for the flash fire dispersion modelling.

For the reassessment, the same inputs as were used in MISHAP01 have been assumed, but DRIFT 3 has been used for the dispersion modelling for the flash fire calculations. As the pipeline is buried, an initial location height of $z = 0$ m has been used in DRIFT 3, rather than the standard height of $z = 2$ m used by HSE to model releases from chemical sites. A release duration of 1800 s has been assumed and the finite duration model in DRIFT 3 has been used. The release has been modelled as two-phase in DRIFT 3.

The pipeline details are given in Table 34. A discharge coefficient of 1 was assumed for the rupture scenarios, as opposed to the standard value of 0.95, to be consistent with the earlier assessments.

Table 34 LPG pipeline details

<i>Parameter</i>	<i>Value</i>
Diameter (mm)	114
Wall thickness (mm)	6.02 or 5.02
Maximum operating pressure (barg)	19
Depth of cover (m)	1.0
Pipe material specification	API 5L
Pipe material grade ¹	X42

¹The pipe material specification and material grade refer to the standards and quality of pipeline steel

The release rates used in the assessment are given in Table 35.

Table 35 Release rates for the different hole sizes from the failure of an LPG pipeline

<i>Scenario</i>	<i>Release rate (kg/s)</i>	
	<i>Wall thickness = 6.02 mm</i>	<i>Wall thickness = 5.02 mm</i>
Rupture	30.34	33.14
100 mm hole	80.28	86.69
75 mm hole	85.98	88.29
25 mm hole	13.19	13.20

The flow rates used are calculated after 30 seconds. This is to allow a steady jet fire to be formed, which is modelled in conjunction with the flash fire. In the rupture case, the initial flow rate is significantly larger, but the flow decays very quickly. For the holes, the initial flow rate is much lower, but the decay rate is also significantly lower than in the rupture case. This leads to flow rates after 30 s that are higher in the 100 mm hole and 75 mm hole cases than for the rupture scenario. The same effect explains why the 100 mm hole flow rate is lower than the 75 mm hole flow rate.

The temperature and pressure at the release point, which are required as inputs to DRIFT 3, are given in Table 36 for each of the hole sizes and the pipeline wall thicknesses, noting that the inputs are the same for each of the hole sizes used in the assessment. The values for the ruptures are taken from PipeTech and those for the holes are taken from LOSSESP.

Table 36 Temperatures (K), pressures (Pa) and liquid fractions at the release point for ruptures and holes from the failure of an LPG pipeline

<i>Scenario</i>	<i>Temperature (K)</i>		<i>Absolute pressure (Pa)</i>		<i>Liquid fraction</i>	
	<i>Wall thickness = 6.02 mm</i>	<i>Wall thickness = 5.02 mm</i>	<i>Wall thickness = 6.02 mm</i>	<i>Wall thickness = 5.02 mm</i>	<i>Wall thickness = 6.02 mm</i>	<i>Wall thickness = 5.02 mm</i>
Rupture	253.01	253.81	245000	252000	0.828	0.840
Holes	231.1	231.1	101325	101325	0.774	0.774

3.5.1 Lower Flammable Limit (LFL) isopleths

The LFL isopleths predicted by DRIFT 3 have been plotted for both wall thicknesses modelled and both weather conditions in Figure 108 for a rupture, Figure 109 for a 100 mm hole, Figure 110 for a 75 mm hole and Figure 111 for a 25 mm hole. The maximum downwind distances to the LFL are reported in Table 37, together with those from CRUNCH.

For the rupture scenario, the maximum downwind LFL distances calculated are smaller for the larger wall thickness modelled. This is related to the decrease in internal pipeline diameter with the thicker walled pipe, which, in turn, leads to lower flow rates.

For the releases through holes, the maximum downwind LFL distances predicted in F2 weather conditions are slightly shorter than those predicted in D5 weather. As explained previously in the ethylene pipeline case, this is likely to be due to the interaction of the jet with the surrounding atmosphere. The jet speed will be higher than the wind speed, leading to shear induced turbulence along the edges of the jet, which increases the mixing and hence causes the cloud to disperse more rapidly. The difference between the wind speed and jet speed will be less in D5 weather than in F2, leading to less turbulence and therefore longer downwind dispersion distances.

In contrast, the LFL isopleths predicted for the pipeline rupture scenario are smaller in D5 weather than in F2 weather. This is because the rupture release behaves less like a jet than the hole releases. The initial velocity of the fluid exiting the pipeline in a rupture scenario is calculated to be approximately an order of magnitude lower than the velocities calculated for the hole release scenarios, possibly due to choked flow. This means that the dispersion from a rupture will be affected more by the cloud density and wind than dispersion from a hole. As a result, the lower wind speed, the further the cloud generated by the rupture will travel before diluting below the criterion value.

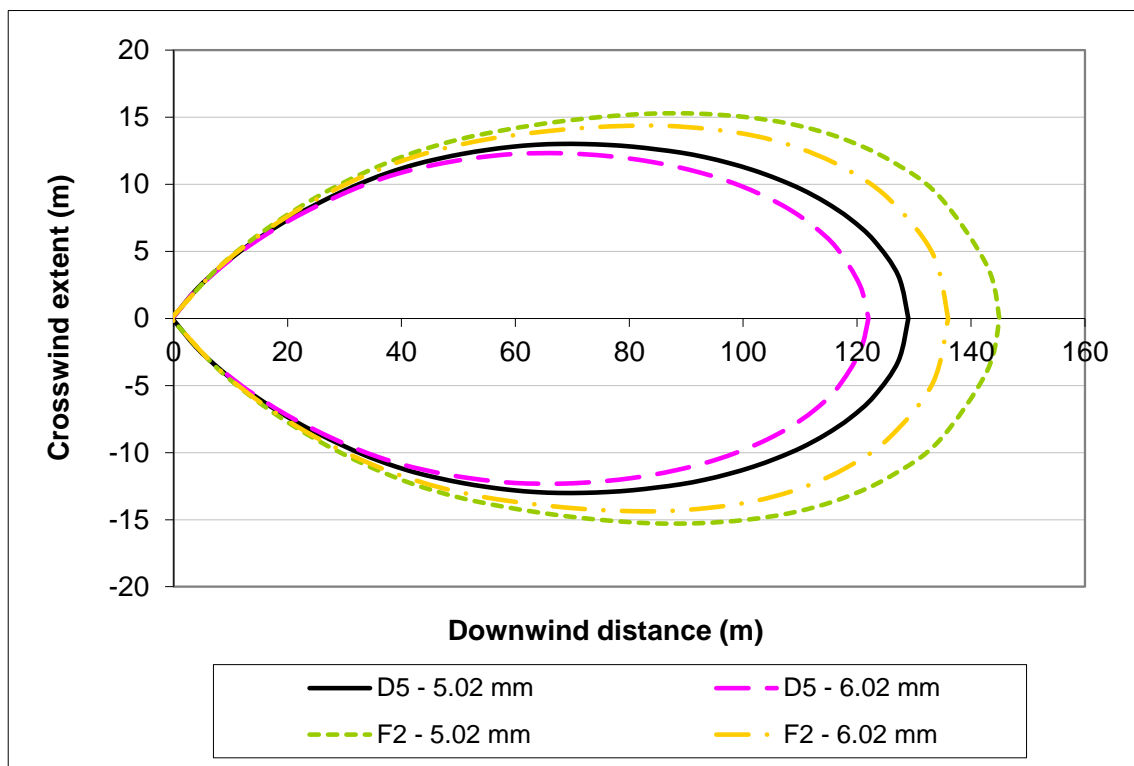


Figure 108 LFL isopleths for rupture of an LPG pipeline in D5 and F2 weather for two wall thicknesses

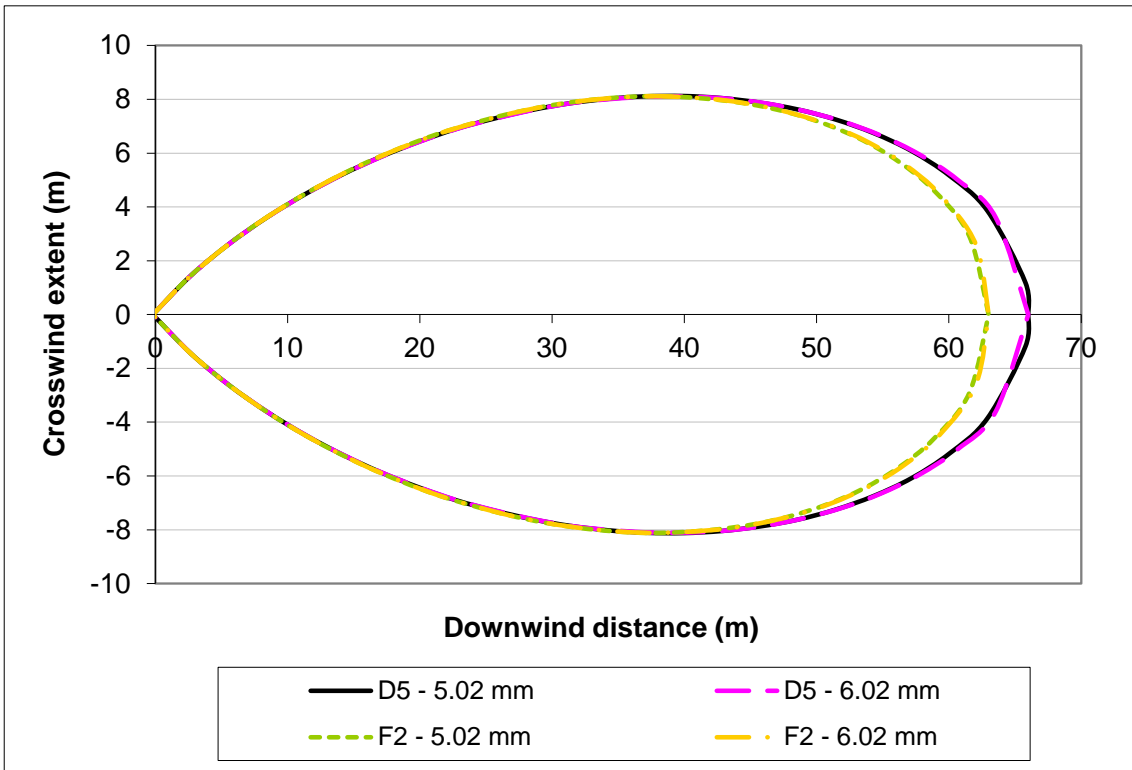


Figure 109 LFL isopleths for a release from a 100 mm hole in an LPG pipeline in D5 and F2 weather for two wall thicknesses

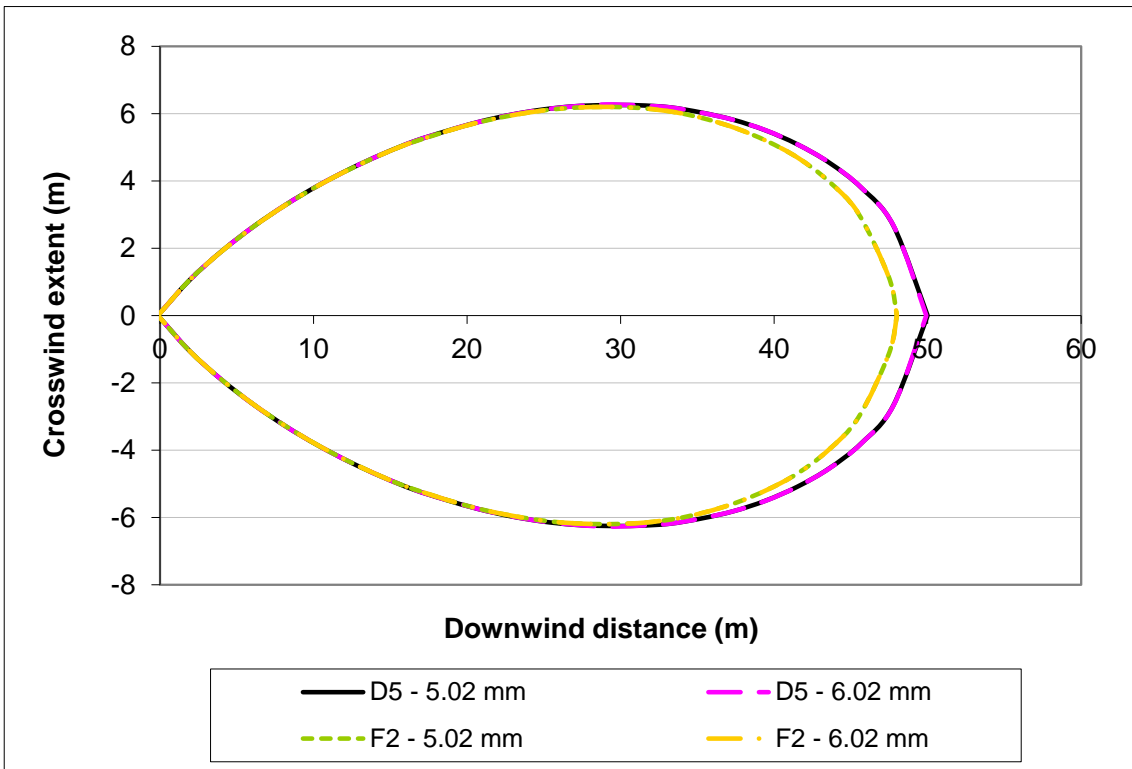


Figure 110 LFL isopleths for a release from a 75 mm hole in an LPG pipeline in D5 and F2 weather for two wall thicknesses

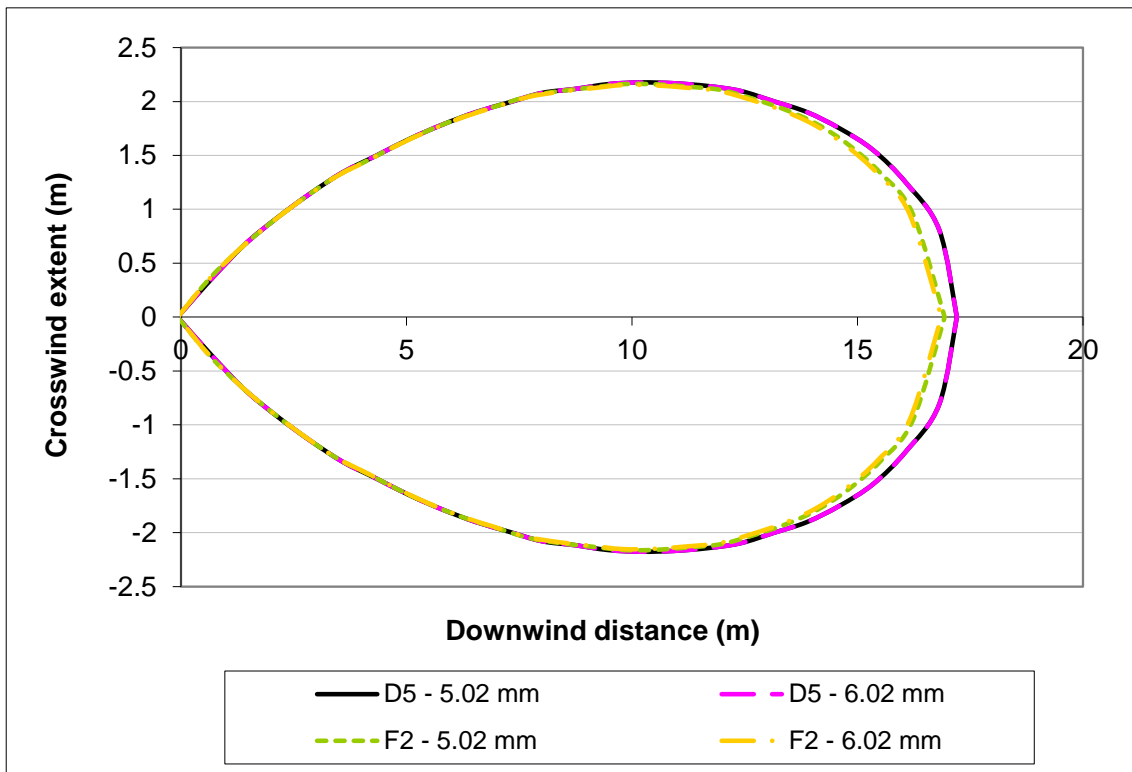


Figure 111 LFL isopleths for a release from a 25 mm hole in an LPG pipeline in D5 and F2 weather for two wall thicknesses

The maximum predicted downwind distances to the LFL following a release from an LPG pipeline are shown in Table 37.

Table 37 Maximum downwind distances to the LFL from an LPG release from a pipeline

Scenario	Maximum downwind distance to the LFL (m) for specified dispersion model and wall thickness			
	DRIFT 3 – Finite Duration		CRUNCH	
	6.02 mm	5.02 mm	6.02 mm	5.02 mm
D5 weather				
Rupture	122	129	110	120
100 mm hole	66	66	180	190
75 mm hole	50	50	190	190
25 mm hole	17	17	71	71
F2 weather				
Rupture	136	145	210	210
100 mm hole	63	63	310	320
75 mm hole	48	48	320	320
25 mm hole	17	17	140	140

CRUNCH predicts much larger maximum downwind distances to the LFL, particularly in F2 weather, than are predicted by DRIFT 3. The only exception to this is the rupture scenario in D5 weather where the maximum LFL distances are approximately the same from the two models. Turbulence resulting from the interaction between the jet and the wind cannot be considered in CRUNCH as it does not contain a jet model. This leads to CRUNCH calculating longer distances in F2 weather than in D5 weather, as would

generally be expected for releases that are not jet-like in character. According to Jagger [9], the CRUNCH model is more suitable for high wind speed conditions, where high wind speed is defined as being ≥ 5 m/s.

When the LFL distances predicted by DRIFT 3 are used in MISHAP01 [34, 35], the pipeline risk assessment model used in the original assessment, the risk based LUP zones are reduced in size. This is shown in Table 38 for the wall thickness of 6.02 mm and in Table 39 for the wall thickness of 5.02 mm. There is a significant reduction in the LUP outer zone size, in particular, whilst smaller reductions are seen in the inner and middle zones.

Since the original risk based LUP zones were derived, HSE has replaced MISHAP01 with MISHAP12 [26]. MISHAP12 has been used to calculate the zones using both CRUNCH and DRIFT 3. The MISHAP12 results are given in Table 38 for the wall thickness of 6.02 mm and in Table 39 for the wall thickness of 5.02 mm.

The trends in the zone sizes observed when using MISHAP12 are similar to those observed when using MISHAP01.

Table 38 Comparing risk based LUP zones (m) from two versions of MISHAP using DRIFT 3 or CRUNCH for flash fires for an LPG pipeline with a wall thickness of 6.02 mm

<i>Risk model/ Dispersion model</i>	<i>Land Use Planning Zone (m)</i>		
	<i>Inner Zone</i>	<i>Middle Zone</i>	<i>Outer Zone</i>
MISHAP01			
CRUNCH	14	62	101
DRIFT 3	12	52	67
MISHAP12			
CRUNCH	14	63	111
DRIFT 3	8	49	65

Table 39 Comparing risk based LUP zones (m) from two versions of MISHAP using DRIFT 3 or CRUNCH for flash fires for an LPG pipeline with a wall thickness of 5.02 mm

<i>Flash fire model</i>	<i>Land Use Planning Zone (m)</i>		
	<i>Inner Zone</i>	<i>Middle Zone</i>	<i>Outer Zone</i>
MISHAP01			
CRUNCH	20	66	115
DRIFT 3	18	53	69
MISHAP12			
CRUNCH	26	71	135
DRIFT 3	23	54	70

3.6 SENSITIVITY ANALYSES FOR THE LIQUEFIED PETROLEUM GAS (LPG) PIPELINE

3.6.1 Relative humidity

The original assessment used the HSE standard relative humidity value of 60%. Sensitivity tests were performed to assess the effects of using a relative humidity of 80% on the 6.02 mm wall thickness pipeline. It was found that the scenarios were not sensitive to the value of the relative humidity as a maximum difference of 3 m was observed in the predicted maximum downwind distances to the LFL for the two relative humidities modelled.

3.6.2 Steady continuous model

Sensitivity tests were performed on the 6.02 mm wall thickness pipeline to assess the effect of modelling the releases as steady continuous in DRIFT 3 rather than using the finite duration model. Modelling a steady continuous release in DRIFT 3 can give an indication of some of the differences that are likely to be observed between results from DRIFT 2 and DRIFT 3 for other, similar releases.

It was found that moving from the finite duration model to the steady continuous model had no impact on the isopleths generated for the scenarios modelled. As explained previously, this is because the same basic equations are used in both models, with differences occurring at the post-processing stage. When the release time is long compared with the cloud travel time, as in this case, then the concentration profiles obtained using the finite duration model tend to those of the steady continuous model. This implies that any differences seen between DRIFT 2 and DRIFT 3 outputs for similar scenarios are not directly related to the change from using the continuous model in DRIFT 2 to using the finite duration model in DRIFT 3 (noting that DRIFT 2 results were not available for this assessment).

3.6.3 Release height

The assessment assumed a release height of 0 m as the pipeline is buried and this assumption was to simulate a ground-based release. If a buried pipeline fails, a crater is likely to be formed that will affect the direction of the release. It is possible that the jet will not be immediately grounded and so sensitivity tests have been performed to assess the impact of varying the release height on the results output by DRIFT 3. In the tests, a wall thickness of 6.02 mm has been assumed in all cases.

The results for D5 weather are shown in Figure 112 for a pipeline rupture, in Figure 113 for a 100 mm hole, in Figure 114 for a 75 mm hole and in Figure 115 for a 25 mm hole. The results for F2 weather are not shown as the trends are very similar to those in D5 weather. The maximum downwind distances to the LFL are given in Table 40, where the results are shown for both D5 and F2 weather.

The maximum distances to the LFL tend to decrease as the release height increases, up to a release height of 1 m. Using a release height of 2 m generally increases the maximum LFL distances when compared to the results generated using a release height of 1 m.

Different trends are observed for the 25 mm hole, for which the shortest maximum LFL distance occurs at a release height of 0.2 m (i.e. the 0 m release extends longer downwind). The maximum LFL distances increase as the release height increases above 0.2 m, up to a release height of 1 m. The maximum distance to the LFL at a release height of 2 m is less than that at a release height of 1 m.

Figure 116 contains plots of the elevation at different release heights for the 100 mm hole and the 25 mm hole. They illustrate how the downwind distance changes as the release height increases and show that the releases from a 100 mm hole follow different trends to those from a 25 mm hole. The plots also show how the plume has to travel a larger distance before touching down, as the release height increases.

In all cases considered the $z = 0$ m release height is predicted to give rise to the largest LFL isopleth. Increasing release height causes the model to transition from the ground-based jet model to the elevated jet model. As already discussed, the grounded and elevated jet models display different behaviours due to the following factors a) grounded jets spread more laterally and less vertically compared with elevated jets, b) dense grounded jets have suppressed vertical mixing due to the stabilising effect of having a dense gas below the lighter ambient air, c) ground surface drag acts to slow down grounded jets. For the rupture case, there is only a small region that is elevated before the jet becomes grounded – in this case increasing the height of the release increases the amount of dilution due to the elevated jet which then shortens the ground-based LFL contour. For the 25 mm hole case, increasing the release height eventually leads to the case where the entire dilution is due to the elevated jet – the fully elevated jet is axi-symmetric and much

narrower than the grounded jet, yet it has a similar downstream distance to the LFL. Intermediate hole sizes show this effect to a lesser extent.

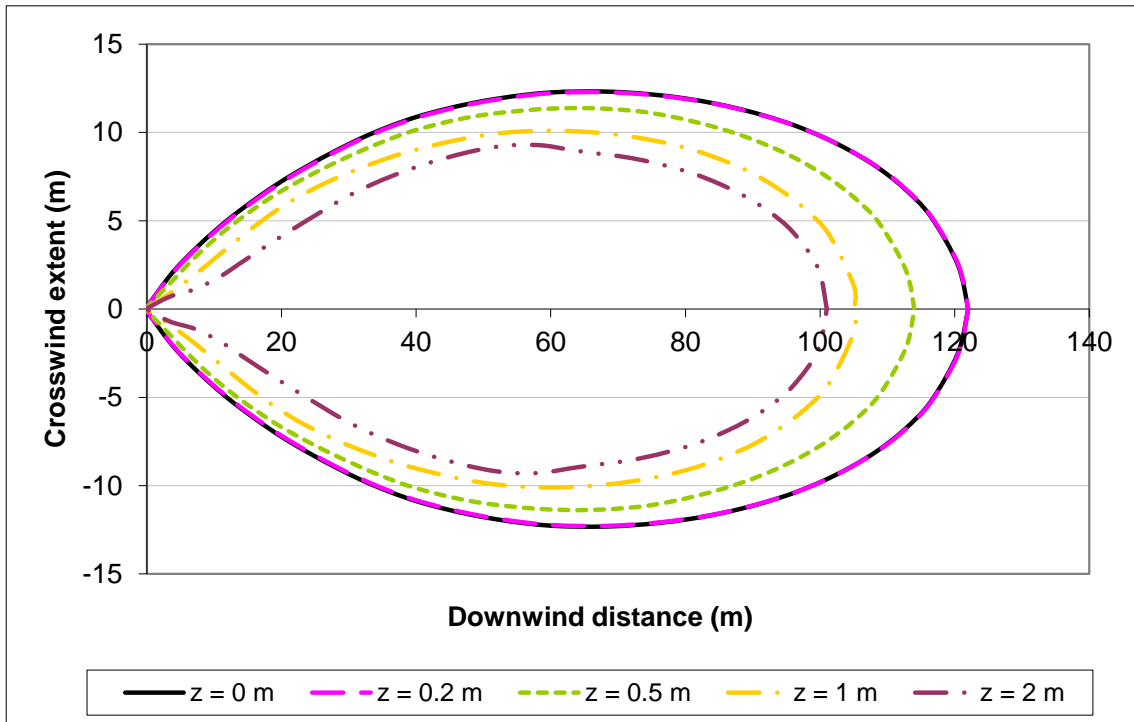


Figure 112 LFL isopleths for rupture of an LPG pipeline in D5 weather, varying the release height

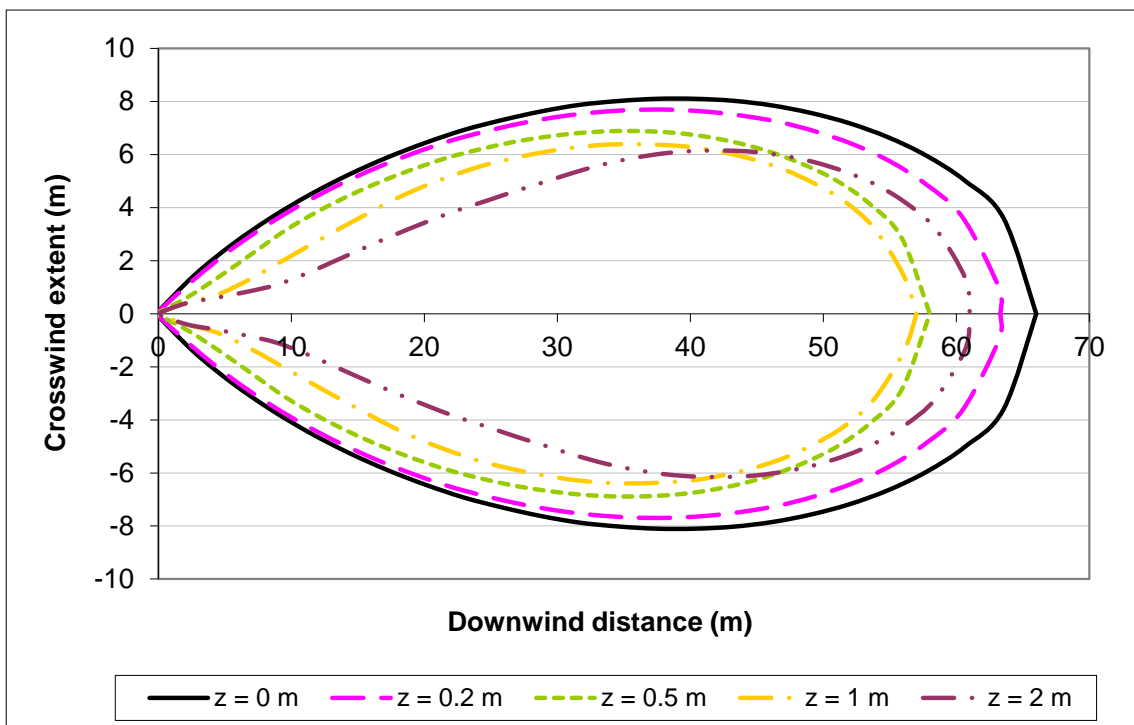


Figure 113 LFL isopleths for a release from a 100 mm hole in an LPG pipeline in D5 weather, varying the release height

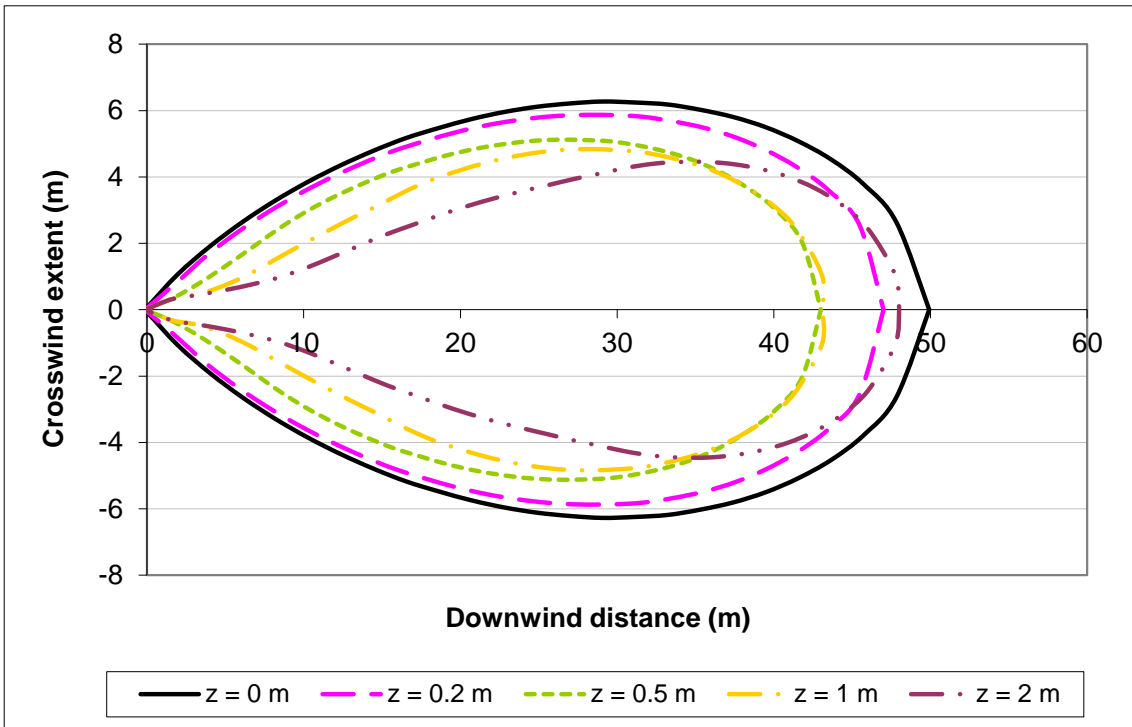


Figure 114 LFL isopleths for a release from a 75 mm hole in an LPG pipeline in D5 weather, varying the release height

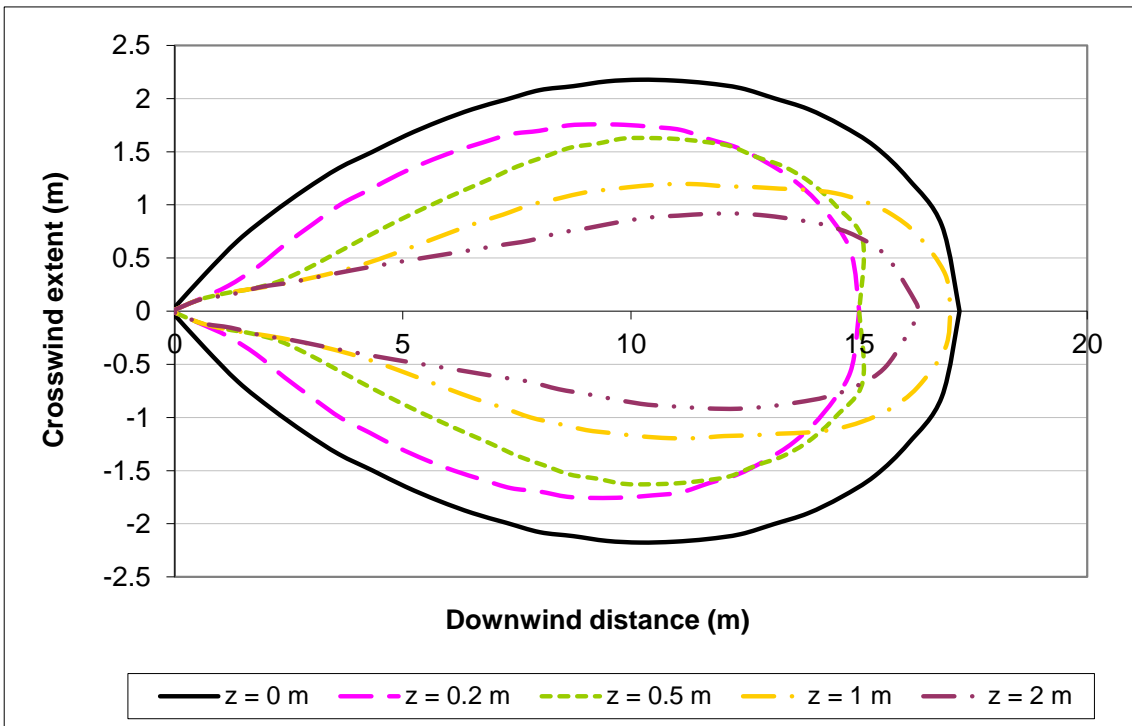
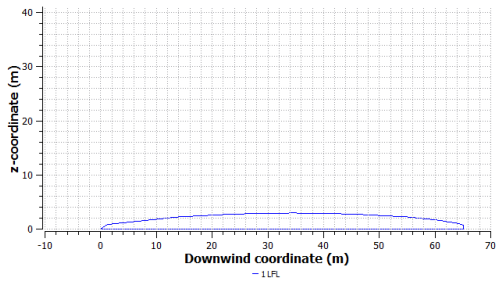
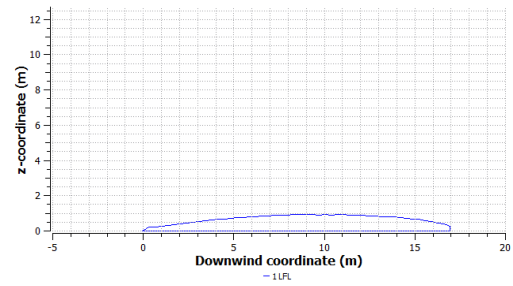


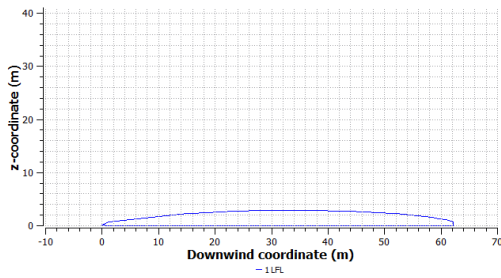
Figure 115 LFL isopleths for a release from a 25 mm hole in an LPG pipeline in D5 weather, varying the release height



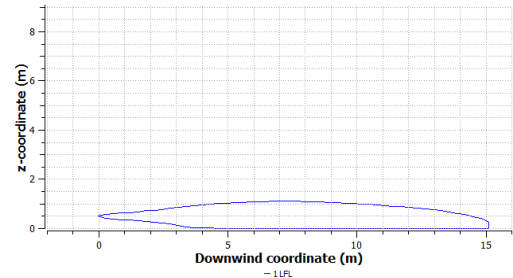
(a) Release from a 100 mm hole at a release height of 0 m



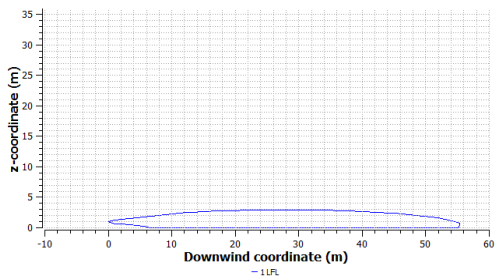
(b) Release from a 25 mm hole at a release height of 0 m



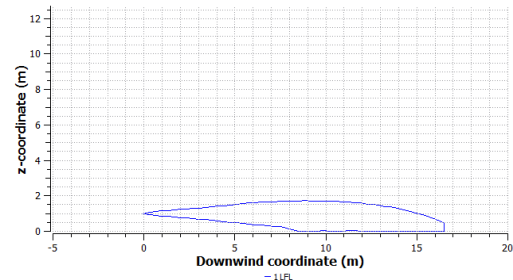
(c) Release from a 100 mm hole at a release height of 0.5 m



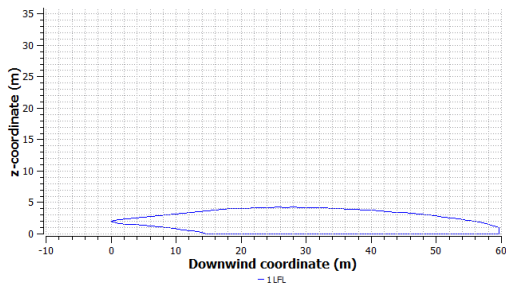
(d) Release from a 25 mm hole at a release height of 0.5 m



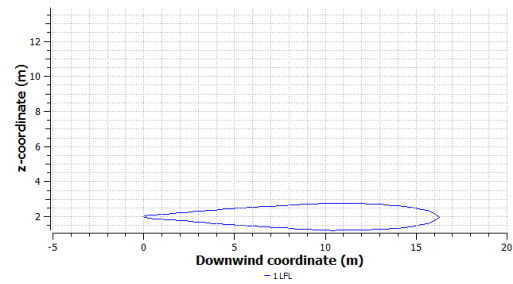
(e) Release from a 100 mm hole at a release height of 1 m



(f) Release from a 25 mm hole at a release height of 1 m



(g) Release from a 100 mm hole at a release height of 2 m



(h) Release from a 25 mm hole at a release height of 2 m

Figure 116 Elevation plots of the LFL isopleths for a release from an LPG pipeline in D5 weather at the specified hole size and release height

Table 40 shows the maximum downwind distances to the LFL predicted by DRIFT 3.6.14 for releases from an LPG pipeline at various release heights.

Table 40 Maximum downwind distances to the LFL predicted by DRIFT 3.6.14 for releases from an LPG pipeline at selected release heights

<i>Scenario</i>	<i>Maximum downwind distance to the LFL (m) at specified release height</i>				
	<i>0 m</i>	<i>0.2 m</i>	<i>0.5 m</i>	<i>1 m</i>	<i>2 m</i>
<i>D5</i>					
Rupture	122	122	114	105	101
100 mm hole	66	63	58	57	61
75 mm hole	50	47	43	43	48
25 mm hole	17	15	15	17	16
<i>F2</i>					
Rupture	136	137	118	106	103
100 mm hole	63	61	55	55	59
75 mm hole	48	46	41	42	47
25 mm hole	17	15	15	17	16

3.6.4 Release temperature

In the original assessment and the reassessment, the initial temperature used in CRUNCH and DRIFT 3 was taken from PipeTech for ruptures and LOSSESP for holes. The initial temperature is the temperature of the substance at the point it exits the pipe and is generally lower than the temperature of the substance as it travels along the pipeline. Sensitivity tests have been performed to determine the effect of modifying the initial temperature on the downwind LFL distances calculated by DRIFT 3 for the pipeline with a wall thickness of 6.02 mm. Temperatures of 265 K and 278 K (assumed to be the temperature within the pipeline) have been tested and the results from DRIFT 3 have been compared with the DRIFT 3 outputs obtained using the temperatures assumed in the original assessment (253.01 K for pipeline rupture releases and 231.1 K for pipeline hole releases). The ambient air temperature is assumed to be 278 K in F2 weather and 288 K in D5 weather.

The results are shown in Figure 117 to Figure 120 for F2 weather only and indicate that, as the temperature increases, the maximum downwind distance to the LFL decreases.

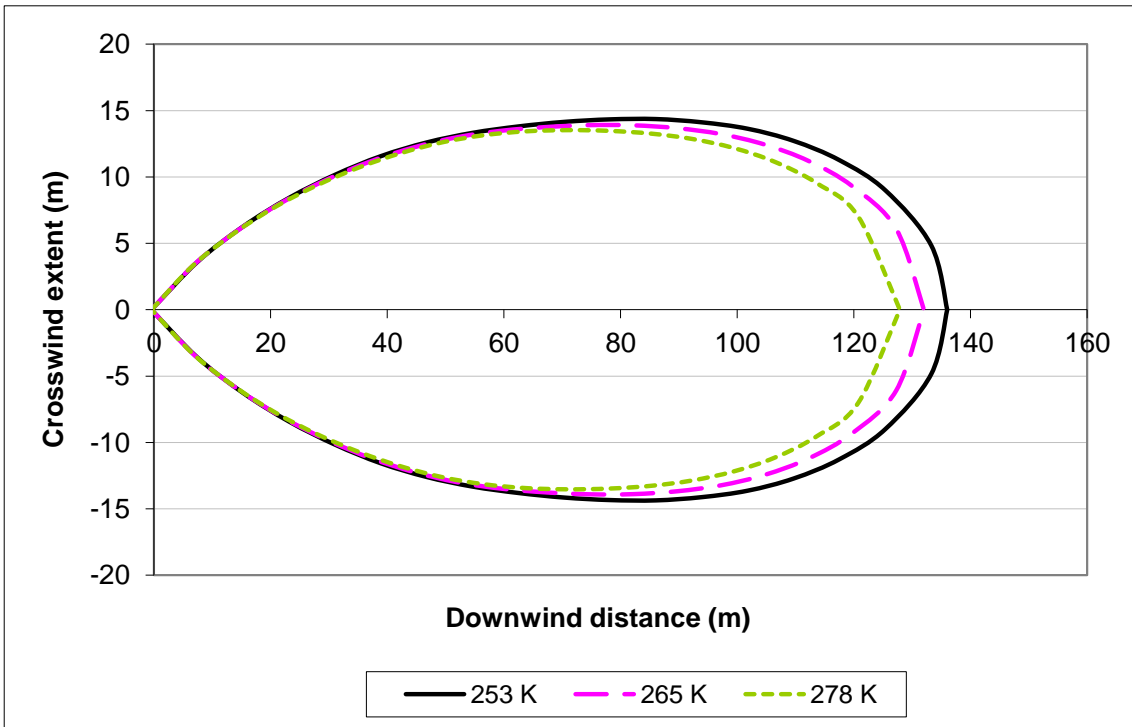


Figure 117 LFL isopleths for rupture of an LPG pipeline in F2 weather, varying the release temperature

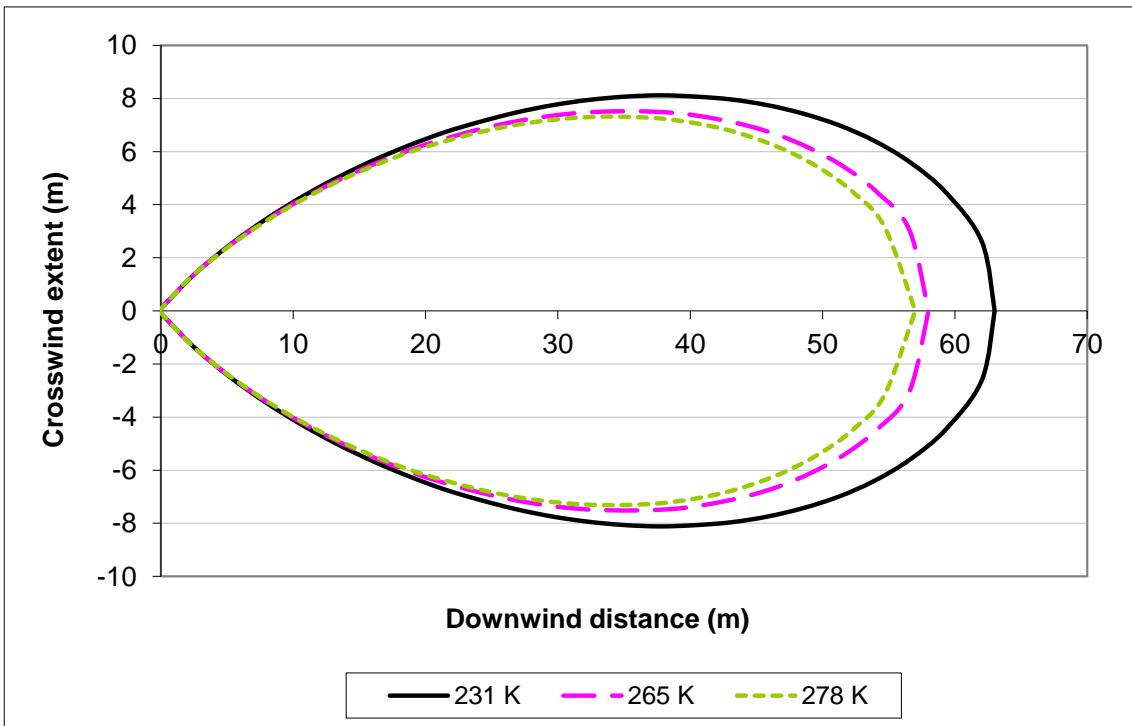


Figure 118 LFL isopleths for a release from a 100 mm hole in an LPG pipeline in F2 weather, varying the release temperature

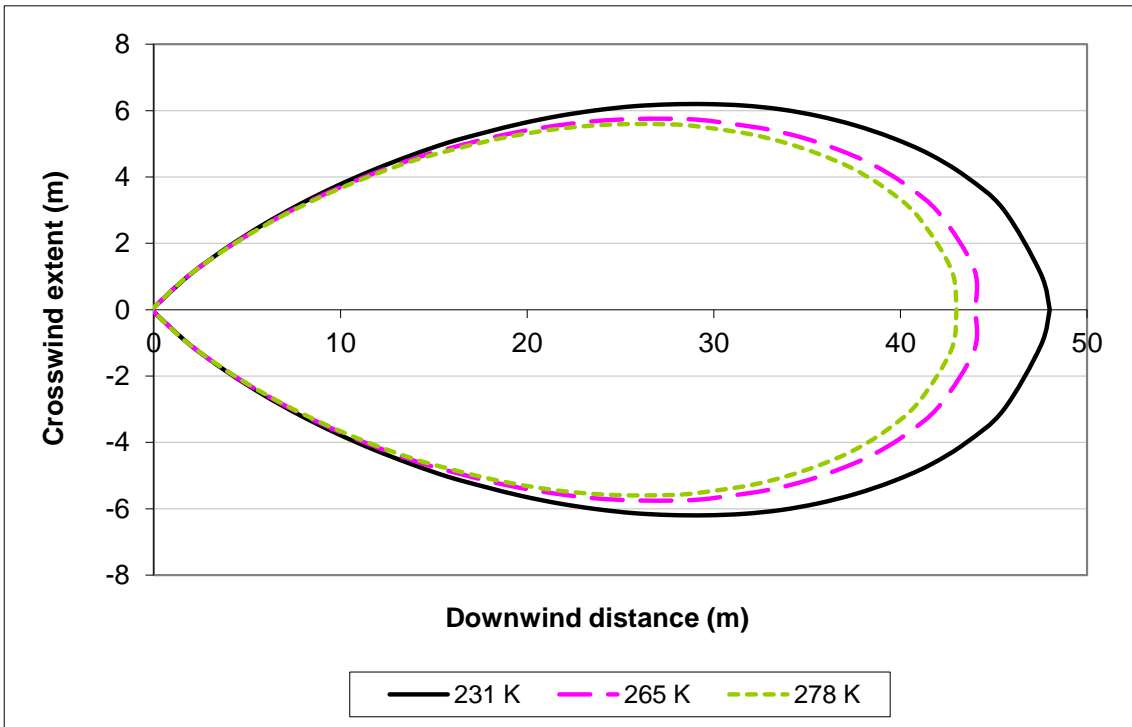


Figure 119 LFL isopleths for a release from a 75 mm hole in an LPG pipeline in F2 weather, varying the release temperature

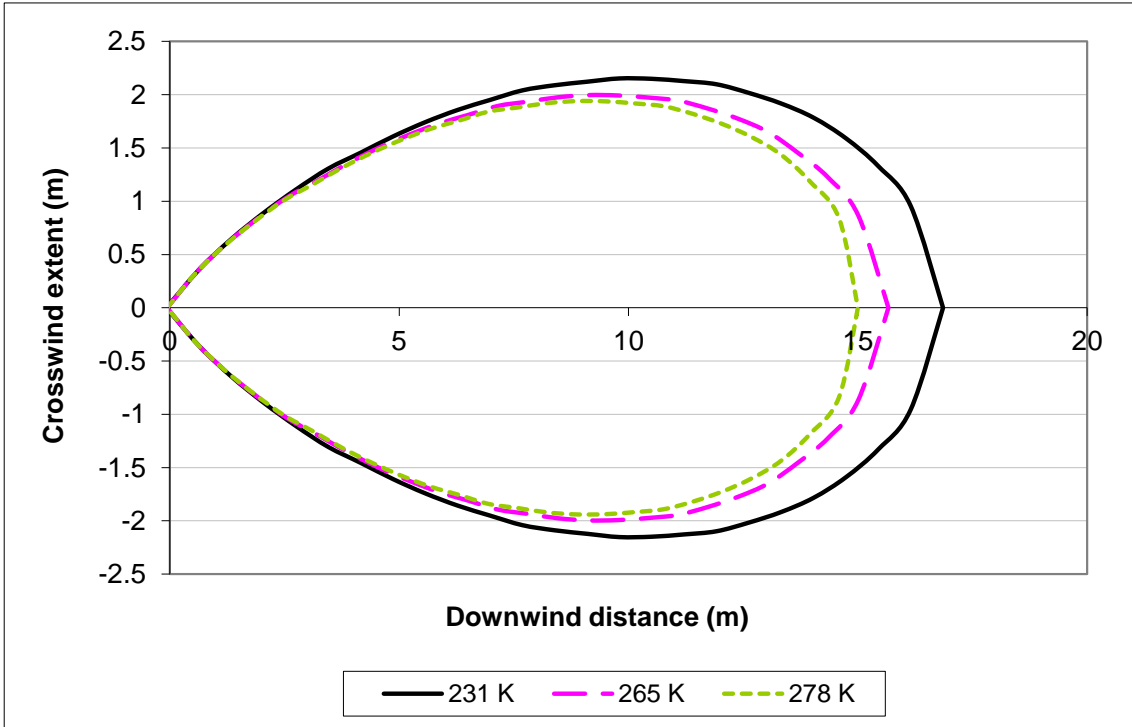


Figure 120 LFL isopleths for a release from a 25 mm hole in an LPG pipeline in F2 weather, varying the release temperature

Table 41 shows the maximum downwind distances to the LFL from an LPG pipeline at various release temperatures for both F2 and D5 weather. The largest difference in the maximum downwind extents output by DRIFT 3 is 8 m when modelling an initial temperature of 253 K compared to an initial temperature of 278 K. Increased temperature leads to increased flashing as the jet expands from the exit, which in turn leads to a reduction in the cloud density due to the higher proportion of vapour in the post-

flash release and a reduction in the cooling caused by vaporisation of the remaining liquid. Reducing the cloud density increases the dilution of the ground-based cloud since there is a reduction in the stabilising effect of mixing the dense underlying cloud with the overlying air.

Table 41 Maximum downwind distances to the LFL from an LPG release from a pipeline varying the release temperature

<i>Scenario</i>	<i>Maximum downwind distance to the LFL (m) at specified release temperature</i>			
	<i>231.1 K</i>	<i>253 K</i>	<i>265 K</i>	<i>278 K</i>
D5				
Rupture	N/A	122	119	117
100 mm hole	66	N/A	61	59
75 mm hole	50	N/A	46	45
25 mm hole	17	N/A	16	16
F2				
Rupture	N/A	136	132	128
100 mm hole	63	N/A	58	57
75 mm hole	48	N/A	44	43
25 mm hole	17	N/A	16	15

3.6.5 PipeTech version 54 outputs for pipeline holes

In the original assessment, PipeTech was used to derive the release rate and release temperature for the rupture release. LOSSESP was used to derive the release rates and temperatures for the three hole sizes, in line with HSE standard practice at the time the assessment was undertaken. LOSSESP is an in-house HSE model used to generate release rates for two-phase mixtures in pipelines. Since the time of the original assessment, HSE has moved to using PipeTech to obtain the source details for all release sizes from a pipeline failure. Sensitivity tests have been performed to assess the impact on the results of using PipeTech instead of the LOSSESP model to calculate the source details for the three hole sizes modelled. The release rates and temperatures output by PipeTech for the three hole sizes are given in Table 42, together with the liquid fraction and pressure output by PipeTech, all of which are used as inputs in DRIFT 3. The rupture scenarios have also been rerun as the original results were produced some years ago with an older version of PipeTech. PipeTech version 54 was used in this study.

PipeTech was unable to successfully run the 100 mm hole scenarios. As the 100 mm hole size is only slightly smaller than the diameter of the pipeline, the results from the rupture scenarios have been used in this case. PipeTech was also not able to successfully run the 75 mm hole in the 5.02 mm wall thickness pipeline. In the original assessment, the pipeline length was given as 3 km, which is shorter than the 16 km that is normally used for pipeline assessments. In this case, the pipeline appears to be approximately 3 km from end to end, in line with the input to the assessment. For the 75 mm hole in the 5.02 mm wall thickness pipeline, the pipeline length was increased to 4 km, which PipeTech was able to run. The results should not be significantly different from what would be obtained using a pipeline length of 3 km, and this can be confirmed by comparing the results from the 6.02 mm wall thickness pipeline with the 5.02 mm wall thickness pipeline. As expected, the flow rate from the thinner walled pipeline is slightly higher than that from the thicker walled pipeline.

Further investigation is being carried out on the most appropriate way to use PipeTech for LPG pipelines, particularly in cases where PipeTech fails to run.

Table 42 Outputs from PipeTech version 54 for LPG pipeline failures

Hole size	Release rate (kg/s)	Temperature (K)	Liquid fraction	Pressure at the release point (bara, Pa in brackets)
6.02 mm wall thickness				
Rupture	27.33	252.25	0.817	2.37 (237,000)
100 mm ¹	27.33	252.25	0.817	2.37 (237,000)
75 mm	14.13	270.21	1	4.33 (433,000)
25 mm	1.72	272.23	0	4.61 (461,000)
5.02 mm wall thickness				
Rupture	28.92	252.3	0.824	2.38 (238,000)
100 mm ¹	28.92	252.3	0.824	2.38 (238,000)
75 mm ²	14.34	270.43	1	4.36 (436,000)
25 mm	1.71	272.22	0	4.61 (461,000)

¹Pipetech version 54 could not run these scenarios, so the outputs have been set equal to those from the corresponding rupture scenarios

²The pipeline length was increased from 3 km to 4 km, to enable PipeTech version 54 to run for this scenario

The results for the 6.02 mm wall thickness pipeline in D5 weather are displayed in Figure 121 for the pipeline rupture scenario. The results are compared to those obtained using the earlier version of PipeTech. Figure 122 to Figure 124 display the LFL isopleths predicted by DRIFT 3 for the three hole sizes modelled. The results obtained using release rates calculated in PipeTech are compared with those obtained using release rates calculated in LOSSESP. The F2 weather and the 5.02 mm wall thickness pipeline results have not been displayed as they show the same trends. All of the results generated from these tests are given in Table 43.

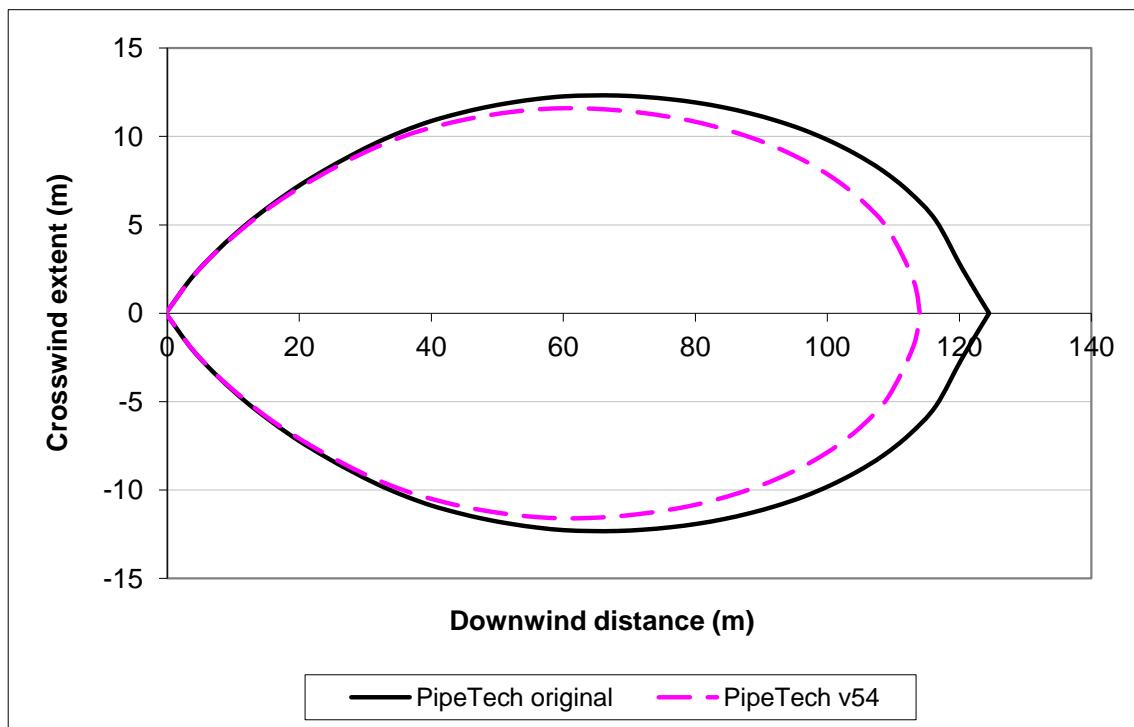


Figure 121 LFL isopleths for a rupture release from an LPG pipeline in D5 weather using release rates generated in two different versions of PipeTech

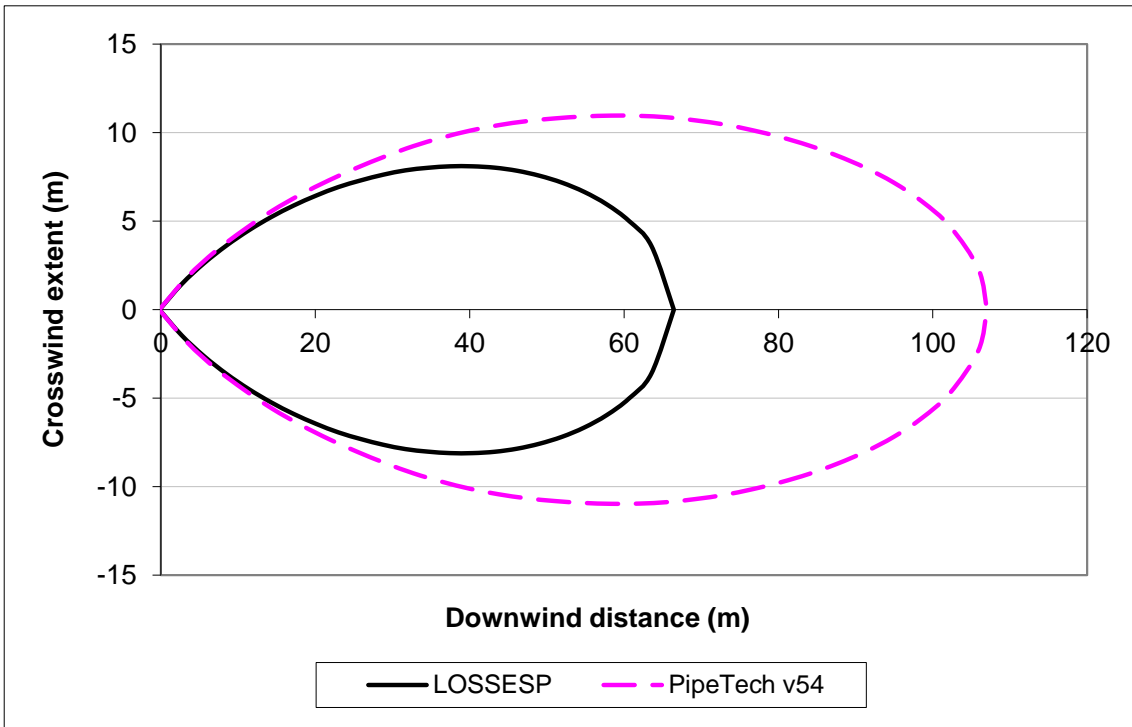


Figure 122 LFL isopleths for a release from a 100 mm hole in an LPG pipeline in D5 weather using two different release rate models

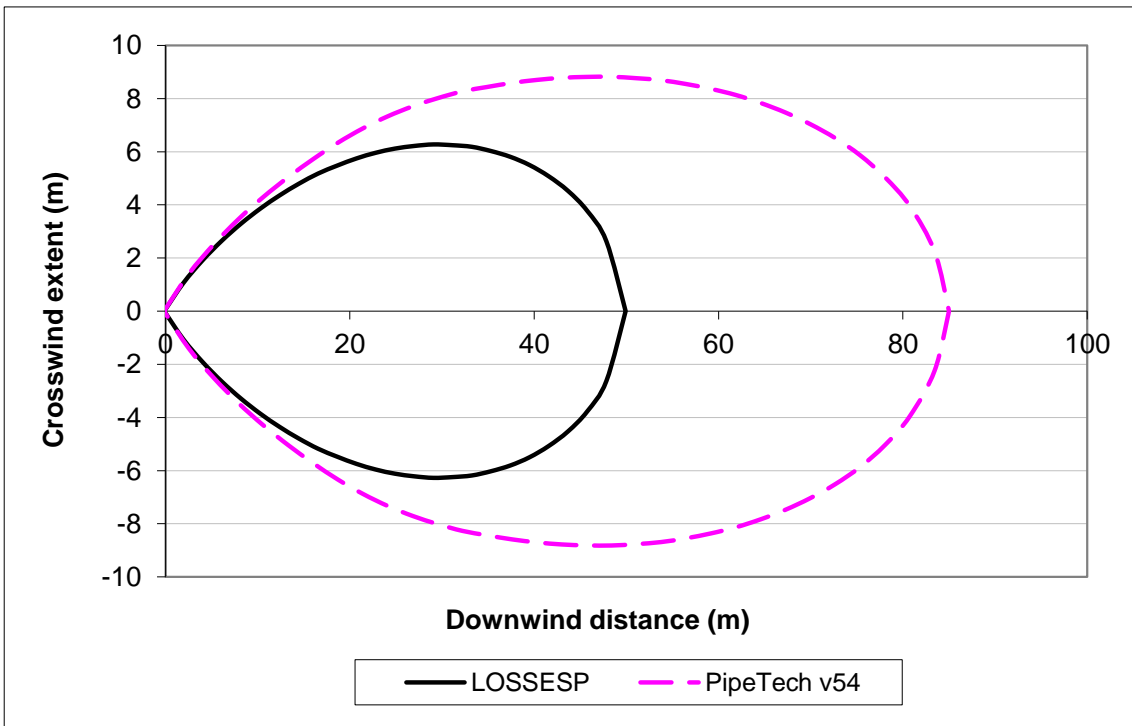


Figure 123 LFL isopleths for a release from a 75 mm hole in an LPG pipeline in D5 weather using two different release rate models

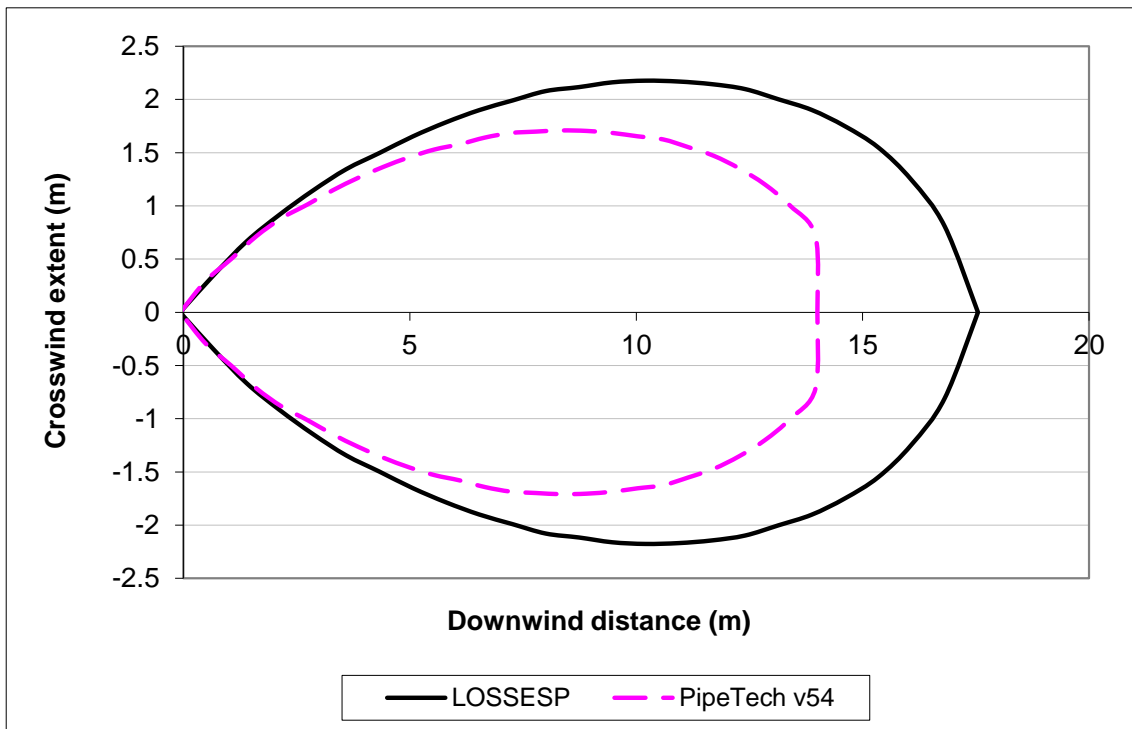


Figure 124 LFL isopleths for a release from a 25 mm hole in an LPG pipeline in D5 weather using two different release rate models

Table 43 shows the maximum downwind distances to the LFL predicted by DRIFT 3.6.14 for releases from an LPG pipeline, obtained using two different release rate models.

Table 43 Maximum downwind distances to the LFL predicted by DRIFT 3.6.14 for LPG releases from a pipeline, obtained using two different release rate models

Scenario	Maximum downwind distance to the LFL (m) for specified release rate model and wall thickness			
	PipeTech original (for ruptures) / LOSSESP (for holes)		PipeTech v54	
	6.02 mm	5.02 mm	6.02 mm	5.02 mm
D5 weather				
Rupture	122	129	114	118
100 mm hole	66	66	107	111
75 mm hole	50	50	85	85
25 mm hole	17	17	14	14
F2 weather				
Rupture	136	145	127	133
100 mm hole	63	63	112	116
75 mm hole	48	48	121	122
25 mm hole	17	17	14	14

The effect of using the latest version of PipeTech on the rupture results is to decrease the maximum downwind distance to the LFL by a small amount. Using PipeTech instead of LOSSESP for the 100 mm and 75 mm holes leads to a significant increase in the maximum downwind LFL distances, even though the release rates have been reduced. This is likely to be caused by differences in the values of the other DRIFT 3 inputs that are obtained from the Pipetech and LOSSESP outputs. LOSSESP predicts an outlet pressure that

is the same as atmospheric pressure, for example, whilst PipeTech gives an outlet pressure more than double atmospheric pressure for the 100 mm hole size scenario and an outlet pressure more than four times atmospheric pressure for the 75 mm hole size scenario (Table 42). LOSSESP also predicts a lower outlet temperature and a lower liquid fraction than PipeTech. The outlet pressure, in particular, has a significant impact on the final results generated by DRIFT 3. If all of the LOSSESP output values are used as inputs to DRIFT 3, but the outlet pressure is changed to that obtained from PipeTech, the maximum downwind distance to the LFL for a 100 mm hole in a 6.02 mm wall thickness pipeline in D5 weather is 105 m, which is similar to the value obtained (107 m) when all of the PipeTech outputs are used as inputs to DRIFT 3.

The maximum downwind distances to the LFL for the 25 mm hole scenarios decrease slightly when PipeTech is used compared to using LOSSESP. A decrease in the downwind distances is to be expected as the release rate calculated by PipeTech for this case is approximately eight times smaller than that calculated by LOSSESP.

The DRIFT 3 outputs have been input into MISHAP12 to determine the effect on the LUP zone sizes of using PipeTech rather than LOSSESP to model the release rates for all the hole sizes modelled. The results are shown in Table 44.

Table 44 Comparing risk based LUP zones (m) from MISHAP12 using PipeTech or LOSSESP to calculate the release rates from holes in an LPG pipeline of either 6.02 mm or 5.02 mm wall thickness

<i>Release rate model for holes</i>	<i>Land Use Planning Zone (m)</i>		
	<i>Inner Zone</i>	<i>Middle Zone</i>	<i>Outer Zone</i>
6.02 mm wall thickness			
LOSSESP	8	49	65
PipeTech	0	24	34
5.02 mm wall thickness			
LOSSESP	23	54	70
PipeTech	2	31	40

Table 44 shows that there is a significant reduction in all the LUP risk based zone sizes when PipeTech is used instead of LOSSESP. This is due to the effect that the reduction in the release rates has on the flash fire results, as well as the fireball and jet fire modelling, with the risks from all of these being reduced. MISHAP12 does not currently have the option of inputting liquid fractions, pressures and temperatures from the release rate model for all of the hole sizes, but instead uses only the values for the rupture scenario and applies them to all the holes.

3.7 GAS COMPRESSOR STATION SITING POLICY

This policy is used for the assessment of natural gas compressor stations, and considers the pipelines feeding into the station, as well as the station itself. HSE provides LUP advice for a large number of gas compressor stations. DRIFT 3.5 was used previously to develop the flash fire element of the policy. The aim of the reassessment using DRIFT 3.6.14 is to ensure that the results do not differ significantly from those obtained from the earlier version of DRIFT 3. Major differences between the two sets of results are not expected.

DRIFT 3.5 was used in the HSE assessment to calculate the thermal hazards from flash fires, and both holes and ruptures from the compressor and the pipeline were considered. In the development of the policy PFAF was used to model the release rates and the release duration was assumed to be 200,000 s. The

pressure was modelled as 951,325 Pa (85 barg). The location of the release was assumed to be at $x = y = 0$ and $z = 2$ m.

Criteria for both indoor and outdoor populations were derived in the siting policy. The LFL was used to determine the cloud extent that would affect an outdoor population and 1.6 times the LFL concentration (1.6 LFL) was used to determine the indoor population affected by the release. The value of 1.6 LFL for the indoor population was chosen based on ventilation assumptions, i.e. in order for the concentration to reach LFL inside, the concentration must be 1.6 LFL outside. Only the maximum downwind distances to the LFL were recorded from the DRIFT 3.5 scenarios run for this assessment.

In the reassessment, the finite duration model has been used in all cases. The same release duration as originally used, i.e. 200,000 s, has been used. Plots have not been produced as the DRIFT 3.5 isopleths are not available for comparison.

3.7.1 Maximum downwind extents for a release from the compressor

For the rupture scenario, a release rate of 9742 kg/s has been assumed, calculated from PFAF, and the equivalent compressor hole size is 1688 mm in diameter. For the release from a hole in the compressor, it is assumed that the release rate is 126 kg/s and the hole is 110 mm in diameter.

The maximum downwind distances to the LFL and 1.6 LFL predicted by DRIFT 3.6.14 are given in Table 45, together with those from DRIFT 3.5.

Table 45 Maximum downwind distances to the LFL and 1.6 LFL for a release from a methane gas compressor station

Scenario	Maximum downwind distance to the specified concentration (m)			
	DRIFT 3.6.14		DRIFT 3.5	
	LFL	1.6 LFL	LFL	1.6 LFL
Rupture – D5	448	290	451	291
Rupture – F2	480	283	470	285
110 mm hole – D5	66	44	66	44
110 mm hole – F2	63	42	64	43

Table 45 shows that there is little difference in the results from DRIFT 3.6.14 when compared to DRIFT 3.5. This is not surprising as only minor modifications have been made to the code since version 3.5.

3.7.2 Maximum downwind extents for a release from the above ground pipework

For the rupture scenario, a release rate of 6331 kg/s has been assumed, and the equivalent pipework hole size is 1194 mm in diameter. For the release from a hole, it is assumed that the release rate is 110 kg/s and the hole in the pipework is 110 mm in diameter.

The maximum downwind distances to the LFL are shown in Table 46, together with those from DRIFT 3.5.

Table 46 Maximum downwind distances to the LFL for a release from methane pipework

Scenario	Maximum downwind distance to the LFL (m)			
	DRIFT 3.6.14		DRIFT 3.5	
	LFL	1.6 LFL	LFL	1.6 LFL
Rupture – D5	370	240	371	240
Rupture – F2	370	231	366	232
110 mm hole – D5	62	42	63	42
110 mm hole – F2	60	40	60	40

Table 46 shows that there are only small differences in the results from DRIFT 3.6.14 when compared to those from DRIFT 3.5. As mentioned previously, this is not surprising due to the nature of the code changes to the finite duration model between the two versions of DRIFT.

3.8 SENSITIVITY ANALYSES FOR THE GAS COMPRESSOR STATION SITING POLICY

In the derivation of the original policy, a release duration of 200,000 s was used in the DRIFT scenarios. The HSE standard assumption for such cases is to use a release duration of 1800 s as it is anticipated that there will be some mitigating intervention undertaken by the operator or emergency services in this time period. Tests were performed to determine the effect of using 1800 s as the release duration rather than the 200,000 s used in the original policy. All the scenarios were rerun using the value of 1800 s for the release duration and it was found that there was no impact on the results. This implies that a steady state has been reached by 1800 s.

The effect of relative humidity on the results was ascertained through a set of tests using 80% relative humidity, rather than the 60% relative humidity used in the original calculations. HSE uses a standard value of 60% relative humidity in Hazardous Substances Consent (HSC)/PSR assessments. The impact on the results was negligible with a maximum difference of 1 m seen in the maximum downwind distance to the LFL.

The effect of the location height on the results was examined by moving from a height of $z = 2$ m in the original assessment to $z = 0$ m in the sensitivity tests. It was found that the location height had little impact with a maximum difference of 3 m in the maximum downwind distance to the LFL being observed.

3.9 DISCUSSION AND CONCLUSIONS FOR CONTINUOUS FLASHING RELEASES

For the ethylene pipeline PSR risk assessment considered, the LFL isopleths predicted by DRIFT 3.6.14 are, in general, shorter and narrower than those predicted by DRIFT 2.31. In the original assessment, the CREATE model was used to generate the source terms from the jet for DRIFT 2. CREATE is a relatively simple model with a number of approximations. DRIFT 3 contains a more sophisticated jet model that has improved modelling of air entrainment and droplet evaporation. Most of the differences in the maximum downwind LFL distances generated by the two versions of DRIFT are due to the difference in the source term model i.e. use of the jet model within DRIFT as opposed to CREATE.

An LPG pipeline for which CRUNCH was previously used for the flash fire element has been reassessed using DRIFT 3.6.14. In general, the downwind distances produced by DRIFT 3 are significantly shorter than those predicted by CRUNCH. This is also the case for the ethylene pipeline. This has an impact on the risk based LUP zones around the pipeline, with reductions seen in the inner, middle and outer zone sizes.

The effect of using the steady continuous model instead of the finite duration model has been assessed using the two pipeline cases. It was found to have no impact on the results. This is as could be expected as the two models contain the same basic equations with differences only occurring at the post-processing

stage. If the cloud travel time is much less than the release duration, which is the case in both of the pipeline scenarios (i.e. they have long release durations), then the results from the finite duration model tend towards those from the steady continuous model.

For the ethylene pipeline assessment, the rupture scenario was modelled using a coefficient of discharge of 0.8 (for consistency with the original assessment) and a coefficient of discharge of 0.95 (in line with standard HSE practice for pipelines). This was shown to have a negligible impact on the results. In addition, the effect of moving the release height from 0 m to 2 m was also assessed. Modelling the release at a 2 m release height rather than 0 m reduced both the downwind distance and crosswind extent of the LFL isopleths. Similar tests performed on the LPG pipeline showed the same effects. A release height of 0 m is recommended as a cautious approach. It is equivalent to approximating the jet release as issuing out of the crater and travelling along the ground.

The effects of varying the release angle on the ethylene pipeline case have been considered. An angle of 90°, corresponding to a vertical release, would not run in DRIFT 3, but an angle of 45° has been tested. The results indicate that the contours and maximum downwind distances to the LFL are reduced when an angle greater than 0° is used, which is to be expected given that there is now a vertical component to the momentum of the jet and there is additional mixing due to the effect of the ambient cross-flow.

The effect of the release temperature on the results generated by DRIFT 3 has been considered. As the release temperature increases, the maximum downwind distances to the LFL output by DRIFT 3 decrease. This is a result of increased mixing of the cloud with the surrounding atmosphere as the temperature increases and the cloud density decreases. If the liquid fraction at the exit point is used, then, for consistency with energy conservation, the temperature at the exit should be used. Using a higher temperature leads to results that are overly optimistic. It is therefore recommended that the temperature from the release rate model is used.

In the original assessment by HSE, ethylene was treated as a gas when modelling the pipeline rupture releases. Since the original assessment, HSE has started using the outputs from the release rate model PipeTech. The outputs generated by PipeTech for the ethylene pipeline suggest that the rupture should be modelled as a two-phase release rather than a gaseous release. A sensitivity test has been performed to assess the effect of assuming two-phase flow for rupture releases from ethylene pipelines on the maximum distances to the LFL produced within DRIFT 3, and on the risk based LUP zones from MISHAP. The results indicate that the LFL distances are increased significantly by assuming two-phase flow, and this has the effect of increasing the LUP zone sizes. The presence of aerosol in the two-phase flow increases cloud density and suppresses mixing, leading to larger distances to the LFL, even for the same flow rate.

For the compressor station siting policy, DRIFT 3.5 was used in the original calculations. The maximum downwind LFL distances indicate that there is very little difference between the outputs of DRIFT 3.5 and DRIFT 3.6.14 for the scenarios modelled. Few modifications have been made to the finite duration model between these two versions that are likely to have a significant impact on results.

It should be noted that the pipework connected to the compressor station is above ground, in contrast to the other pipelines that have been considered in this section.

In the original calculation of the compressor station siting policy, a duration of 200,000 s was used, as opposed to the 1800 s normally used by HSE for assessments. Reducing the duration to 1800 s had no impact on the results.

For the pipeline and compressor siting assessments, sensitivity tests were performed to determine whether there was any dependency on the relative humidity. It was found that the results were unaffected by modifying the relative humidity from 60% to 80%.

4 MODELLING INSTANTANEOUS FLASHING RELEASES OF FLAMMABLE SUBSTANCES FROM CATASTROPHIC VESSEL FAILURE

4.1 INTRODUCTION

The hazards posed by a catastrophic failure of a vessel storing a pressure-liquefied flammable substance and the subsequent dispersion of the flammable substance have previously been assessed by HSE using a source term model such as IRATE and by modelling the release as instantaneous in DRIFT 2.31.

Three consent applications for which this methodology was used have been reassessed using the ACE source term model and DRIFT 3.6.14. The hazard ranges to the Lower Flammable Limit (LFL) obtained in the original assessments and the reassessments have been compared to assess the impact of adopting DRIFT 3.6.14 on HSE's land-use-planning advice. Possible reasons for the differences between the predicted hazard ranges, such as the use of different mathematical models, release types and modelling assumptions, are discussed.

ACE [28, 29] is a source term model that can model the initial stages of a flashing instantaneous release from a catastrophic failure of a vessel storing a pressure liquefied gas. ACE predicts both the properties of the airborne cloud that is generated and the amount of released material that will form a pool. ACE was originally written for HSE by WS Atkins in 1999. It has since been reviewed by an independent expert [30] and written as a new piece of software based upon the science in the original WS Atkins papers [28, 29], the recommendations from the review and further validation work on the model [36]. The reauthoring of the code is to allow HSE to implement further changes to the model to allow it to be more easily integrated into HSE's hazard and risk assessment processes. It also allows modification to ensure the calculations within the model are consistent with similar calculations in other models used by HSE.

Some modifications have been made to the underlying assumptions within the ACE model. The most significant of these concerns the experimental correlations used within the model to determine the proportion of the release that becomes airborne. There are two correlations that relate the airborne fraction to the flash fraction, referred to as the 'upper' and 'lower' curve correlations. In the original ACE implementation [29], the 'upper' correlation was associated with a spherical release where the substance is assumed to be released in all directions forming a spherical cloud. The 'lower' correlation was associated with a hemispherical release where the release is assumed to be downwards, forming a hemispherical ground-based cloud. The 'upper' curve assumes that a greater proportion of the release becomes airborne than is the case with the 'lower' correlation. Further investigation and validation suggested that the 'upper' correlation was the most appropriate to be used for either a spherical or hemispherical release. The 'upper' curve correlation is associated with both types of release in the new version of ACE.

When comparing plots of DRIFT 2.31 results to DRIFT 3.6.14 results, it should be noted that, for DRIFT 2.31, the maximum downwind and crosswind extents are used to form an isopleth of two half ellipses, which are joined along their major axes. The DRIFT 3.6.14 plots, in contrast, display the calculated crosswind extents at each downwind distance and represent the actual shape of the cloud as opposed to an idealised shape.

4.2 METHODOLOGY

A consent application for isobutane and an application for propane have been reassessed. The original assessments used IRATE and DRIFT 2 to generate the LFL hazard distances. The sites have been reassessed using ACE 3.11 and DRIFT 3.6.14.

A consent application for *o*-cresol has also been reassessed. The original assessment used IRATE and DRIFT 3.6.4 to generate toxic isopleths. *o*-Cresol is also flammable and so the original results have been

examined to obtain information about the flammable hazards. The site has been reassessed using ACE 3.11 and DRIFT 3.6.14.

The substances and sites investigated in this study and described in this section are typical of those investigated by HSE as part of the Hazardous Substance Consent (HSC) assessment process.

A review of IRATE [14] confirmed that this is a simple model that assumes the entire inventory becomes airborne and neglects the potential for rainout and pool formation. ACE is considered to be a model that better represents reality and has now been adopted for use in assessments by HSE, replacing the use of the IRATE model.

Each scenario was initially reassessed in DRIFT 3.6.14 using input values chosen to replicate the assumptions used in DRIFT 2.31 or DRIFT 3.6.4 as closely as possible. An instantaneous release was modelled in DRIFT 3 for all cases. ACE generates information about the quantity of released material that may form a pool from the release. In addition to the initial airborne puff being modelled as an instantaneous release in DRIFT 3.6.14, any pool formed has also been modelled using the GASP pool spreading and evaporating model and the finite duration model in DRIFT 3.6.14. The pool and airborne components from a release cannot be currently combined in DRIFT 3.6.14 and must be considered separately. The scenario that leads to the larger isopleths is the one that is used in the HSC assessments. However, in cases where the pool component is significant, the instantaneous airborne source term is adjusted accordingly. Details of the process are given by McGillivray and Cruse [23].

The HSE recommended input values for a flashing release of a flammable substance from a catastrophic vessel failure are given in Table 47.

Table 47 Recommended input values for use in DRIFT 3 for a flashing release of a flammable substance from a catastrophic vessel failure

Input	Recommended value in DRIFT 3
Release type	Instantaneous
Phase	Dependent on the substance
Substance, temperature, liquid fraction, rainout fraction, contaminant fraction and contaminant mass	Output from ACE
Location	(0,0,0) (z = 0 m corresponds to ground level) unless specified otherwise
Initial cloud radius	Output from ACE
Weather scheme	Pasquill
Input inversion height	No (the model determines this from a look-up table when the Pasquill weather scheme is selected)
Temperature	288.15 K (D); 278.15 K (F)
Relative humidity	60%
Reference height	10 m
Roughness length	0.1 m (rural); 0.3 m (urban)
Wind angle from North ¹	270° (towards the positive x direction)
Pasquill stability	D (day) or F (night)
Wind speed	F2.4, D2.4, D4.3 and D6.7
User input flammability limits	No, as these should be read in automatically from the SPI file
Levels of interest	Lower Flammable Limit (LFL)

¹In DRIFT 3, the wind direction is defined as the direction from which the wind is blowing. This is the convention used by the Met Office. In EJECT (the jet model used in conjunction with DRIFT 2.31), the wind direction is defined as the direction towards which the wind is blowing. DRIFT 3 automatically corrects for this when opening a legacy DIN file.

A full list of the DRIFT input values used in the original assessments and the reassessments is provided in Section 6.3 of the Appendices. The values of the LFL for each substance are given in Section 6.4 of the Appendices.

4.3 ISOBUTANE ASSESSMENT

The site contains a 1760 m³ sphere containing a liquefied flammable gas at 651,325 Pa (5.5 barg) and ambient temperature. For the original assessment IRATE was used to generate the inputs to DRIFT 2, assuming a release of 1056 tonnes of isobutane as the exemplar substance. Exemplar substances are used by HSE when a hazard substances consent application gives only the generic substance class (non-named substance) or when insufficient substance property data are available to model a named substance. For non-named substances, the exemplar represents the entire substance class and aims to provide a representation of the hazard of interest, typically for the most hazardous substance in that class.

The outputs from IRATE that were used in the original assessment and in the reassessment are shown in Table 48. The outputs from ACE that were used in the reassessment are also shown.

Table 48 Outputs from IRATE and ACE for modelling a catastrophic failure of a sphere storing isobutane for the specified weather conditions

<i>Property</i>	<i>D5</i>	<i>F2</i>
IRATE		
Mass of air entrained (te)	1440	1000
Mass of vapour (te)	665	484
ACE – Sphere		
Contaminant mass fraction	0.143	0.154
Contaminant mass (kg)	762238	523001
Cloud radius (m)	96.59	81.90
Liquid fraction	0.762	0.789
ACE – hemisphere		
Contaminant mass fraction	0.253	0.270
Contaminant mass (kg)	762238	523001
Cloud radius (m)	96.58	81.90
Liquid fraction	0.762	0.789

In the reassessment, both IRATE and ACE 3.11 were used to derive the inputs for an instantaneous release modelled in DRIFT 3.6.14. The release was modelled as both a spherical release and a hemispherical release in ACE. For the spherical release in F2 weather, the atmospheric inversion height in DRIFT had to be increased from 100 m to 150 m in order for the model to run. This is due to the cloud depth being similar to the inversion height. The LFL isopleths predicted by DRIFT 3.6.14 for both the spherical and hemispherical releases in D5 weather are shown in Figure 125, together with the results generated by DRIFT 3.6.14 when IRATE was used to provide the source term inputs. The equivalent results for F2 weather are shown in Figure 126.

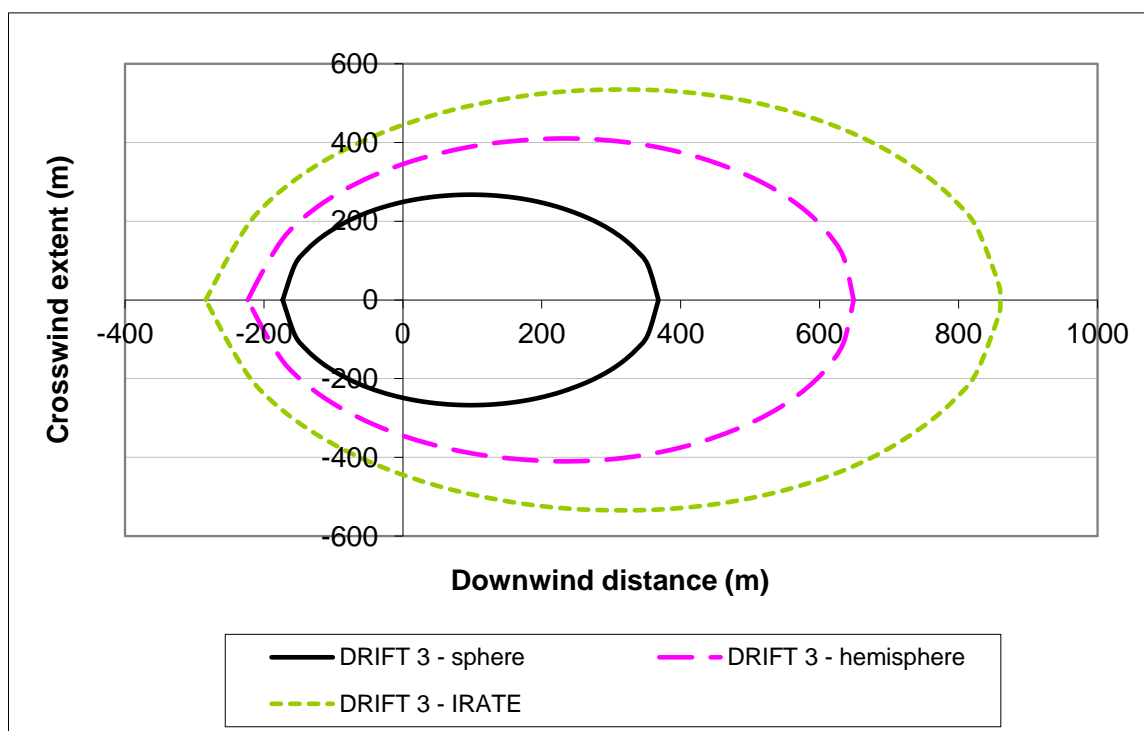


Figure 125 LFL isopleths for an instantaneous release following a catastrophic failure of a sphere storing isobutane in D5 weather

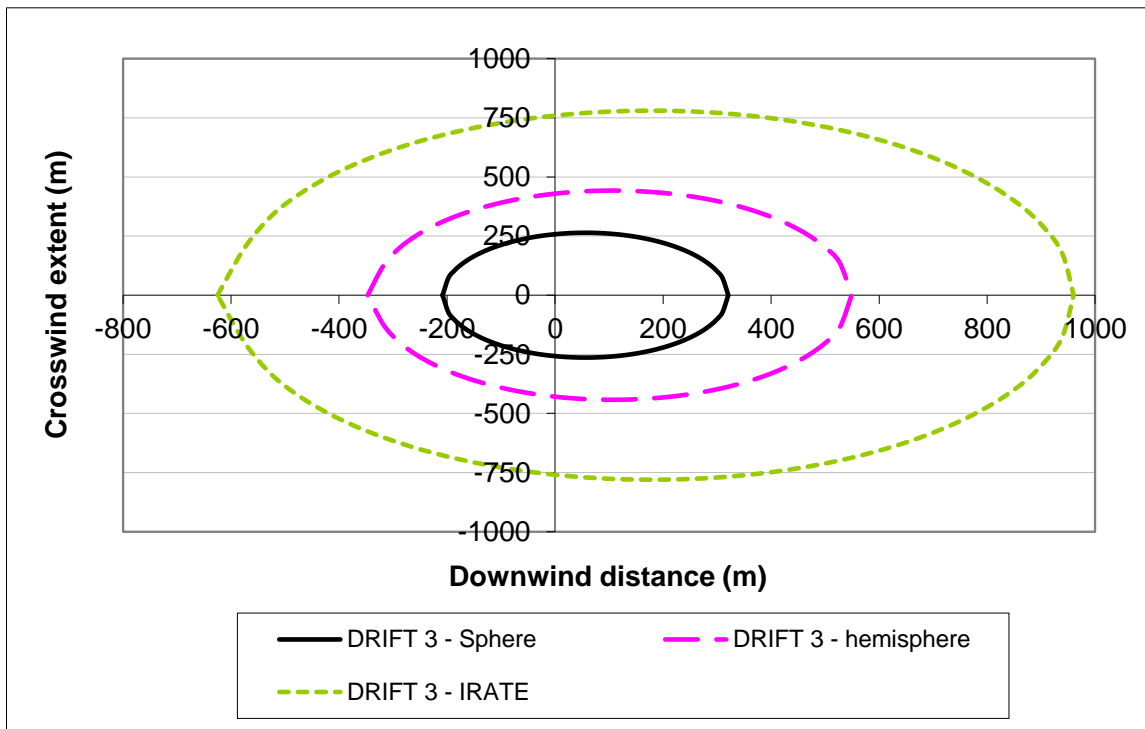


Figure 126 LFL isopleths for an instantaneous release following a catastrophic failure of a sphere storing isobutane in F2 weather

The maximum downwind distances to the LFL for an instantaneous isobutane release are shown in Table 49. From the table and the figures it can be seen that DRIFT 3.6.14 is predicting shorter maximum downwind distances to the LFL in F2 weather than in D5 weather when the release is modelled as either a spherical or hemispherical release in ACE. DRIFT 2 also produced shorter distances in F2 weather. The results are not shown in the figures as they were not available for plotting. Only the downwind distances have been reported and these are given in Table 49. In F2 weather the gravity driven radial spreading exceeds the downwind advection (driven by the wind) for longer. In some circumstances, this effect (which includes “edge” entrainment driven by the gravity spreading front) dominates over the reduced “top” entrainment in F2 conditions. This has the effect of shortening the downwind extent but increasing the upwind and crosswind extents. This is observed when Figure 126 is compared to Figure 125.

Table 49 Maximum downwind distances to the LFL for an instantaneous release following a catastrophic failure of a sphere storing isobutane in D5 and F2 weather

Scenario	Maximum downwind distance to the LFL (m)	
	D5	F2
DRIFT 2 + IRATE	514	434
DRIFT 3 + IRATE	860	960
DRIFT 3 + ACE – sphere	368	320
DRIFT 3 + ACE – hemisphere	649	549

Using IRATE to generate the source terms for DRIFT 3.6.14 produces significantly larger contours than when ACE is used. The results using DRIFT 2 indicate that, in general, the maximum downwind distances to the LFL are shorter than those obtained when using DRIFT 3. As the original files are unavailable, however, it is not certain that exactly the same inputs have been used and the same assumptions made. The DRIFT 2 results are shown for indicative purposes only.

The maximum downwind distances to the LFL obtained when modelling a hemispherical release in ACE are larger than those obtained when modelling a spherical release. The hemispherical cloud is assumed to have

half the volume of the spherical cloud, but the mass of isobutane within the cloud is identical, so the hemispherical release is a smaller, more concentrated source. In addition, the hemispherical cloud has a lower surface area in contact with/interacting with the surrounding atmosphere than the spherical cloud, meaning that less mixing can occur at any given time. This leads to longer dispersion times and longer overall distances to the criterion concentration when a hemispherical release is modelled.

4.3.1 Modelling the pool component

Following a catastrophic failure of a vessel storing isobutane, a cloud will form that disperses as a dense gas, but some of the isobutane will rain out to form a pool. For a full analysis of the release, it is important to assess the risk posed by both the initial airborne component and the component that rains out. The contributions from the two components cannot currently be combined in DRIFT and therefore the two components are modelled separately to determine which gives the greatest hazard. ACE outputs the mass of contaminant in the pool and the pool diameter, which can be used as inputs in GASP. The pool scenario arising from a catastrophic failure of an isobutane vessel has been modelled using GASP and DRIFT 3.6.14, assuming a hemispherical release in ACE. The inputs to GASP are shown in Table 50.

Table 50 Inputs to GASP for modelling the pool formed following a catastrophic failure of a sphere storing isobutane, using the results from the hemispherical option in ACE

<i>Scenario</i>	<i>Puddle depth (m)</i>	<i>Pool roughness length (m)</i>	<i>Pool mass (kg)</i>	<i>Pool radius (m)</i>	<i>Temperature (K)¹</i>
D5	0.0254	0.00023	294000	48.295	284.89 ²
F2	0.0309	0.00023	533000	40.955	276.19 ²

¹ This is the cloud temperature from ACE

² Temperature is reset to 260.424 K in GASP, i.e. just below the boiling point. This is a general assumption for all rainout.

The results are shown in Figure 127 for D5 weather and in Figure 128 for F2 weather. The release meets the HSE 'peaky' criteria and so the 'peaky' methodology has been used (this methodology is described in Section 2.2). The standard HSE 'non-peaky' method and the DRIFT 3 time varying model have also been used to compare against the results obtained using the 'peaky' methodology. The time varying model did not run successfully for D5 weather. The DRIFT 3 results are reported at a height just above the surface of the pool. The maximum downwind distances to the LFL are shown in Table 51.

In Figure 127 the 'non-peaky' contour appears to be approximately a circle that has been stretched downstream. In this case DRIFT 3 predicts an upwind element to the cloud that is approximately the radius of the pool. It appears that the pool evaporation generates a cloud above the pool, which moves downstream with the wind for a short distance before diluting below the LFL.

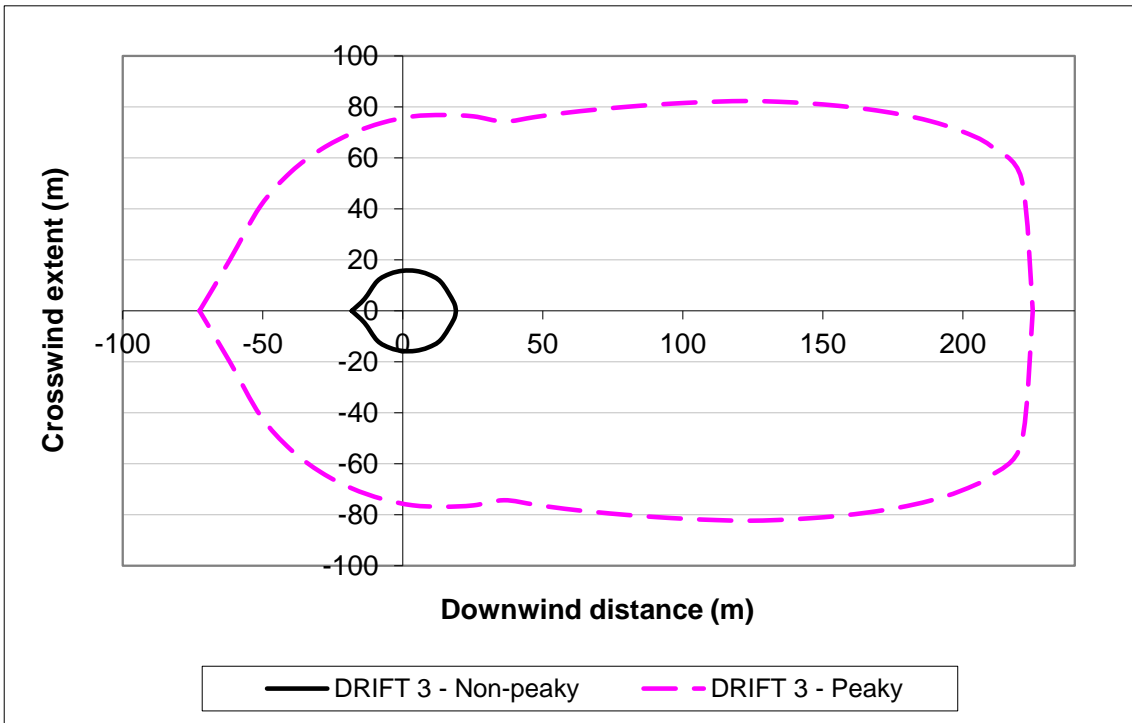


Figure 127 LFL isopleths for the pool formed by an instantaneous, hemispherical release of isobutane following a catastrophic failure of a vessel in D5 weather

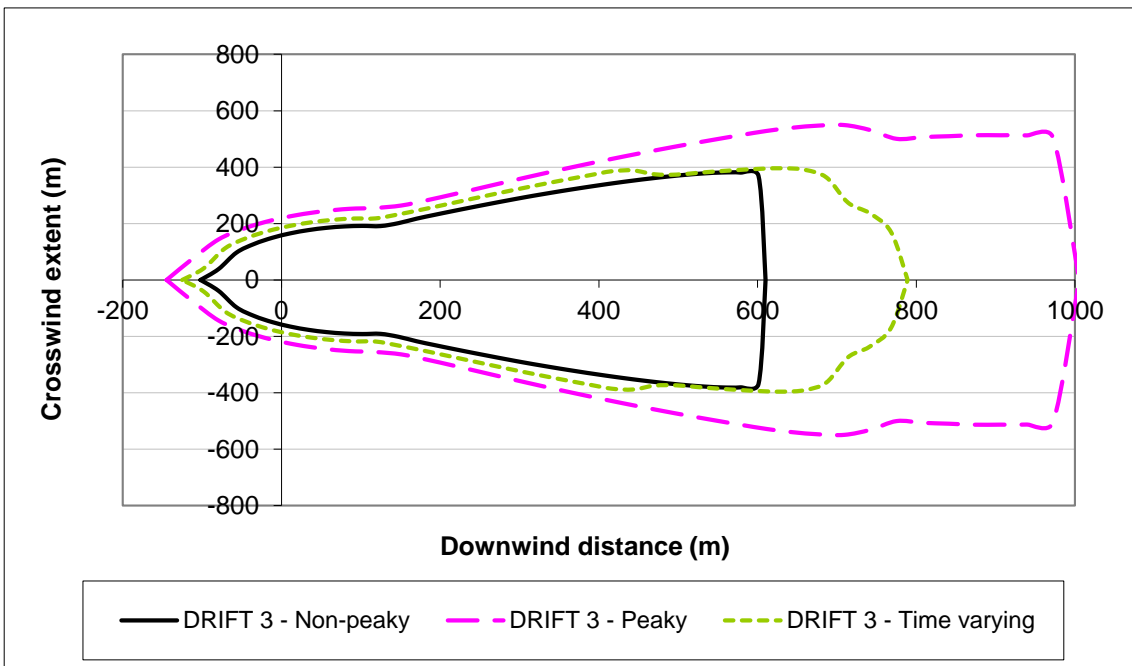


Figure 128 LFL isopleths for the pool formed by an instantaneous, hemispherical release of isobutane following a catastrophic failure of a vessel in F2 weather

Table 51 Maximum downwind distances to the LFL for a pool formed by an instantaneous hemispherical isobutane release following a catastrophic failure of a vessel in D5 and F2 weather

Scenario	Maximum downwind distance to the LFL (m)	
	D5	F2
DRIFT 3 – ‘Non-peaky’	19	610
DRIFT 3 – ‘Peaky’	225	980
DRIFT 3 – Time varying	NR	789

NR indicates no result obtained

Table 51 shows that the time varying method produces a maximum distance to the LFL that lies between those generated using the ‘peaky’ method and the ‘non-peaky’ method, when modelling F2 weather. In D5 weather, the ‘peaky’ methodology produces contours that are significantly larger than those generated using the ‘non-peaky’ method.

If the results in Table 51 are compared with those in Table 49, it can be seen that in F2 weather the maximum downwind LFL distances from the pool are of a similar magnitude to those from the initial cloud formed upon catastrophic vessel failure. If Figure 128 is compared to Figure 126, it can also be seen that in F2 weather, the crosswind extent from the pool is of a similar magnitude to that predicted for the initial cloud. It is therefore important to consider both scenarios when carrying out an assessment.

4.4 PROPANE ASSESSMENT

The site contains three 940 m³ spheres with a design temperature of 323 K and pressure of 480,000 Pa (4.8 bara). Propane was used as the exemplar substance, and the temperature was reduced to 274 K so that the vessel pressure rating was not exceeded (the saturated vapour pressure of propane at 274 K is approximately 4.8 bara). In the original assessment, IRATE was used to provide the inputs to DRIFT 2 and these are shown in Table 52.

Table 52 Inputs and outputs from IRATE for modelling a catastrophic failure of a vessel storing propane

IRATE inputs			IRATE outputs used as inputs to DRIFT 3					
Air Temp (K)	Quantity (kg)	Temp (K)	Initial Flash Fraction	Mass of Air (kg)	Contaminant Mass Fraction ^{1,2}	Equilibrium Temp (K) ²	Cloud Radius (m) ²	Cloud Quality (Liquid Fraction) ²
					DRIFT 2 Inputs			
288.15	548400	274.15	0.2069	1.285×10 ⁶	0.2992	200.4	65.95	0.1214
278.15	548400	274.15	0.2069	1.285×10 ⁶	0.2992	199.6	65.62	0.1718

¹Contaminant mass fraction, $CMF = M_c / [M_c + M_a]$, M_a = mass of air, M_c = mass of contaminant

²These are the outputs required as inputs to DRIFT

In the reassessment, both IRATE, using the values in Table 52, and ACE 3.11 have been used to derive the inputs for DRIFT 3.6.14. ACE has been run using both the hemispherical and spherical options. The release has been modelled as instantaneous in DRIFT 3.6.14.

The results for D5 weather are shown in Figure 129 and for F2 weather in Figure 130. Using IRATE with either DRIFT 2 or DRIFT 3 produces larger LFL isopleths, both in the downwind and the crosswind direction, than using ACE to provide the source terms. Assuming a hemispherical release in ACE produces significantly larger downwind LFL extents than when a spherical release is assumed. DRIFT 2 appears to produce larger downwind LFL distances than DRIFT 3 but it should be noted that there is an upwind component in DRIFT 3. In DRIFT 2, the maximum width and downwind distance have been used to form an ellipse, and the upwind

component has not been considered. This will account for some of the differences in the outputs generated by the two versions of DRIFT used in this assessment.

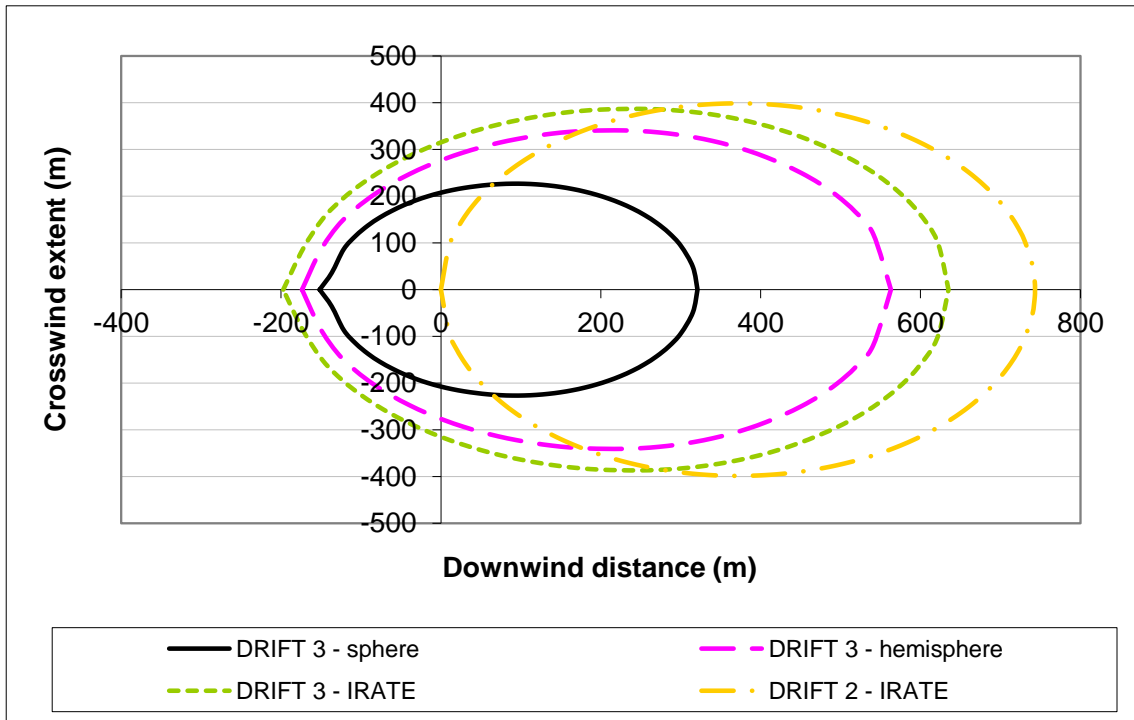


Figure 129 LFL isopleths for an instantaneous release following a catastrophic failure of a vessel storing propane in D5 weather

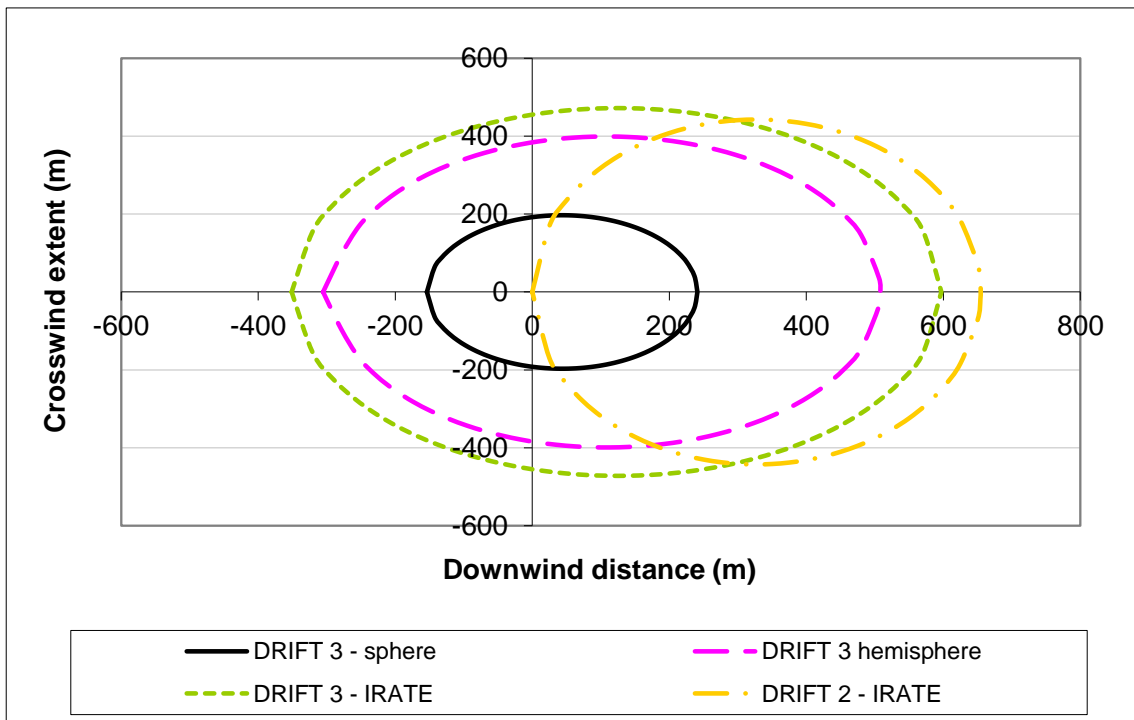


Figure 130 LFL isopleths for an instantaneous release following a catastrophic failure of a vessel storing propane in F2 weather

The maximum downwind distances to the LFL for a release from an instantaneous release of propane are shown in Table 53. The results indicate that the maximum downwind distances to the LFL are shorter in F2 weather than in D5 weather. This has been explained in Section 4.3.

Table 53 Maximum downwind distances to the LFL for an instantaneous release following a catastrophic failure of a vessel storing propane in D5 and F2 weather

<i>Scenario</i>	<i>Maximum downwind distance to the LFL (m)</i>	
	<i>D5</i>	<i>F2</i>
DRIFT 2 + IRATE	743	654
DRIFT 3 + IRATE	635	597
DRIFT 3 + ACE – sphere	321	241
DRIFT 3 + ACE – hemisphere	563	508

4.4.1 Modelling the pool component

Following a catastrophic failure of a vessel storing propane, some of the released substance will form a cloud which will disperse as a dense gas, and some of the substance will rain out to form a pool. DRIFT 3 does not currently have the capability to combine the effects from the pool and the airborne component and therefore these two outputs are considered separately. ACE outputs information about the pool formation, which can be used as inputs in GASP. The pool scenario arising from a catastrophic failure of a propane vessel has been modelled using GASP and DRIFT 3, assuming a hemispherical release in ACE. The inputs to GASP are shown in Table 54. The pool component was also modelled using the outputs obtained from the spherical option in ACE. However, the pool properties predicted by ACE were insensitive to whether the release was modelled as hemispherical or spherical, leading to no change in the GASP outputs.

Table 54 Inputs to GASP for modelling the pool formed following a catastrophic failure of a vessel storing propane, using the results from the hemispherical option in ACE

<i>Scenario</i>	<i>Puddle depth (m)</i>	<i>Pool roughness length (m)</i>	<i>Pool mass (kg)</i>	<i>Pool radius (m)</i>	<i>Temperature (K)¹</i>
D5	0.0149	0.00023	55600	46.375	282.59 ²
F2	0.0148	0.00023	55600	46.375	273.65 ²

¹ This is the cloud temperature from ACE

² Temperature is reset to 230.65 K in GASP i.e. just below the boiling point. This is a general assumption for all rainout.

The results are shown in Figure 131 for D5 weather and in Figure 132 for F2 weather. The release meets the HSE ‘peaky’ criteria and so the ‘peaky’ methodology has been used. The standard HSE ‘non-peaky’ method and the DRIFT 3 time varying model have also been used to compare against the results obtained using the ‘peaky’ methodology. The time varying model did not run successfully for either of the weather conditions modelled. The outputs from DRIFT are reported at a height fractionally above the surface of the pool. Table 55 reports the maximum downwind distances to the LFL.

The ‘peaky’ isopleth in Figure 132 appears to be less smooth than the other isopleths. The plots have been generated using the default parameters in DRIFT 3. Smoother plots can be obtained by adjusting the “Finite Duration Model Time Series Precision” parameter and increasing the “Finite Duration Time Series Extent” parameter in the model. This can lead to a small, approximately 5%, increase in the predicted LFL extent. In the interests of cleaner sensitivity comparisons between all runs, these parameters have not been adjusted.

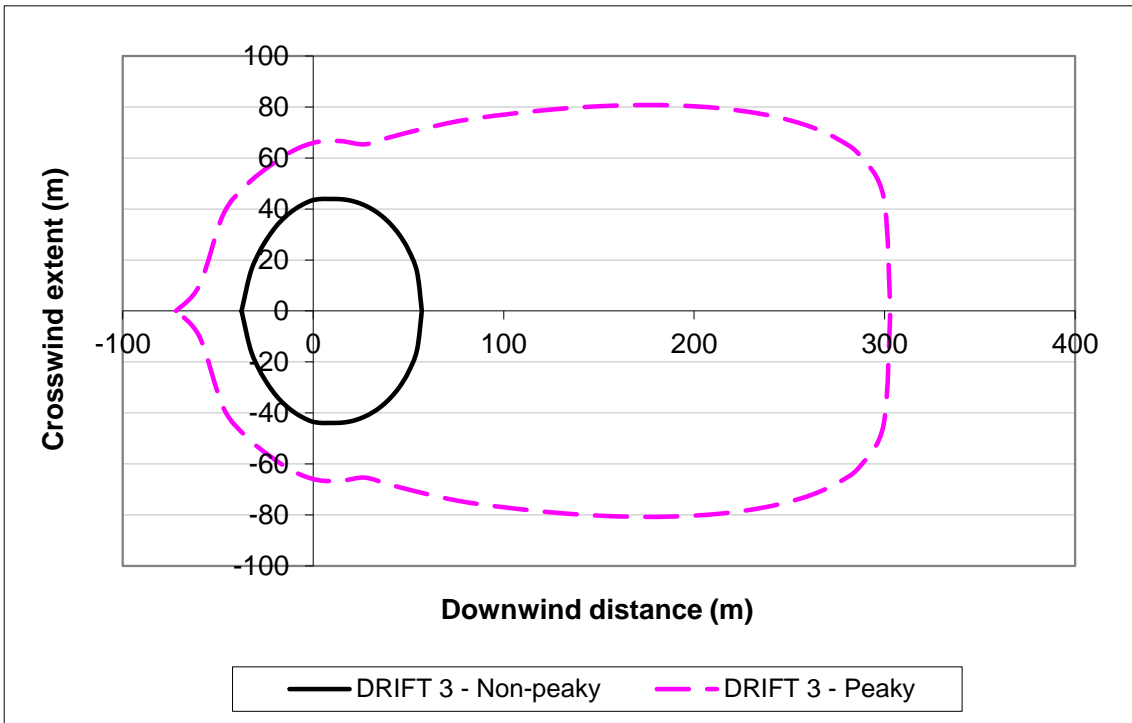


Figure 131 LFL isopleths for the pool formed by an instantaneous, hemispherical release of propane following a catastrophic failure of a vessel in D5 weather

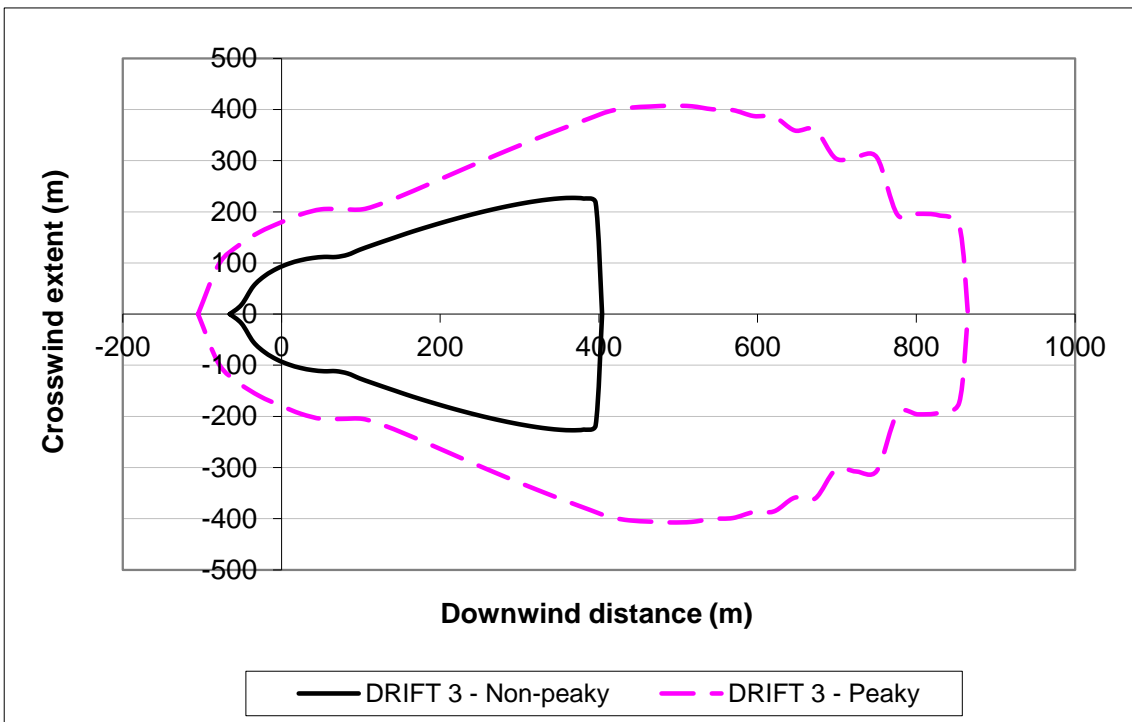


Figure 132 LFL isopleths for the pool formed by an instantaneous, hemispherical release of propane following a catastrophic failure of a vessel in F2 weather

The maximum downwind distances to the LFL for a propane pool are shown Table 55.

Table 55 Maximum downwind distances to the LFL for a pool formed by an instantaneous hemispherical propane release following a catastrophic failure of a vessel in D5 and F2 weather

Scenario	Maximum downwind distance to the LFL (m)	
	D5	F2
DRIFT 3 – ‘Non-peaky’	57	404
DRIFT 3 – ‘Peaky’	303	865
DRIFT 3 – Time varying	NR	NR

NR indicates no result obtained

The ‘peaky’ methodology produces larger LFL isopleths than those generated using the ‘non-peaky’ method. This is particularly noticeable in the D5 weather case, where the maximum downwind LFL distance predicted by the ‘peaky’ methodology is over five times the distance generated when the ‘non-peaky’ methodology is used.

If the results in Table 55 are compared with those in Table 53, it can be seen that the maximum downwind LFL distances from the pool (when modelled using the ‘peaky’ methodology) are of similar magnitude to those from the initial cloud. It is therefore important to consider both scenarios when carrying out an assessment.

4.5 O-CRESOL ASSESSMENT

The site contains a xylene column reboiler and a xylene column, with a combined maximum inventory of 4 tonnes at 220 °C (493.15 K) and 140,000 Pa (1.4 bara). *o*-Cresol was used in the original assessment as the exemplar substance for xylene, as there was insufficient information available to model xylene directly. Exemplar substances are chosen to have similar physical properties to the substance named on the consent application, with care taken to most carefully match the substance properties that have the greatest impact on the predicted hazard distances. The combined catastrophic event, i.e. a release of 4000 kg, was considered in the assessment. IRATE was used to generate the inputs to DRIFT 3.6.4, assuming an initial temperature of 493.15 K. The outputs from IRATE that were used as inputs to DRIFT 3.6.4 are given in Table 56.

Table 56 Inputs and outputs from IRATE for modelling a catastrophic failure of a vessel storing *o*-cresol

IRATE inputs			IRATE outputs used as inputs to DRIFT 3					
Air Temp (K)	Quantity (kg)	Temp (K)	Initial Flash Fraction	Mass of Air (kg)	Contaminant Mass Fraction ¹	Equilibrium Temp (K)	Cloud Radius (m)	Cloud Quality (Liquid Fraction)
288.15	4000	493.15	0.2136	41680	0.0876	329.6	23.17	0.8435 ²
278.15	4000	493.15	0.2136	41680	0.0876	323.5	23.01	0.8951 ²

¹Contaminant mass fraction, $CMF = M_c / [M_c + M_a]$, M_a = mass of air, M_c = mass of contaminant

²This was reset to 1 – see following paragraph

In the reassessment, the outputs from IRATE have been used as inputs to DRIFT 3.6.14 to replicate the scenarios modelled in DRIFT 3.6.4 as closely as possible. In the original assessment, the liquid fraction calculated by IRATE was not used and a value of 1 was input instead. A liquid fraction of 1 has also been used in the DRIFT 3.6.14 runs to ensure that the same inputs are being modelled in the reassessment. ACE 3.11 has also been used to generate source terms to input into DRIFT 3.6.14 for these scenarios to allow a comparison with the use of IRATE as the source term model. Since the original assessment was undertaken, the IRATE model has been replaced by ACE in HSE assessments.

The results from DRIFT 3.6.4 in D5 weather are displayed in Figure 133 together with the outputs from DRIFT 3.6.14, where IRATE has been used in both cases to model the source terms. As ACE can model the release as either spherical or hemispherical, the results from DRIFT 3.6.14 are shown in the figure for both release options when ACE is used to generate the source terms. Identical outputs are obtained from DRIFT 3.6.14 and DRIFT 3.6.4 when the IRATE source term is used, so these isopleths are overlaid in the figure.

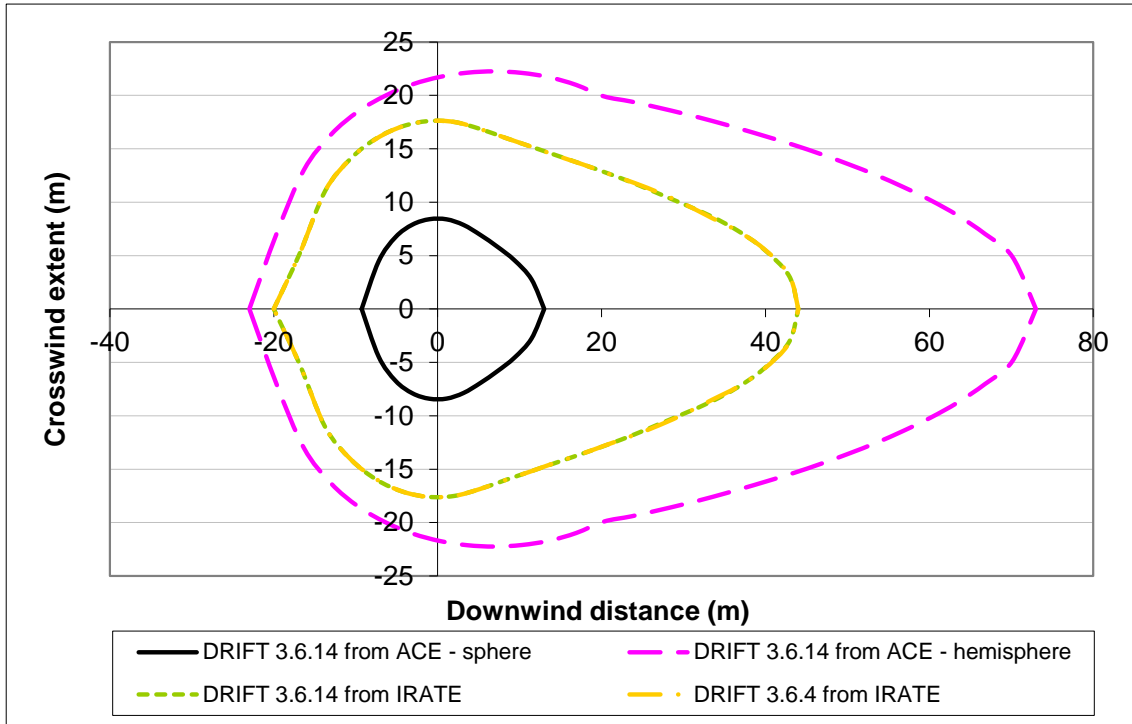


Figure 133 LFL isopleths for an instantaneous release following a catastrophic failure of a vessel storing *o*-cresol in D5 weather

The equivalent plot for F2 weather is shown in Figure 134. The release is slightly buoyant in F2 weather and the downstream distance to the LFL at the centreline height is reported in the figure. The downstream distance is the distance along the centreline of the plume (as opposed to the distance along the ground). For a grounded cloud, the downstream distance is identical to the downwind distance, but for a buoyant cloud, the downstream distance will be greater than the downwind distance.

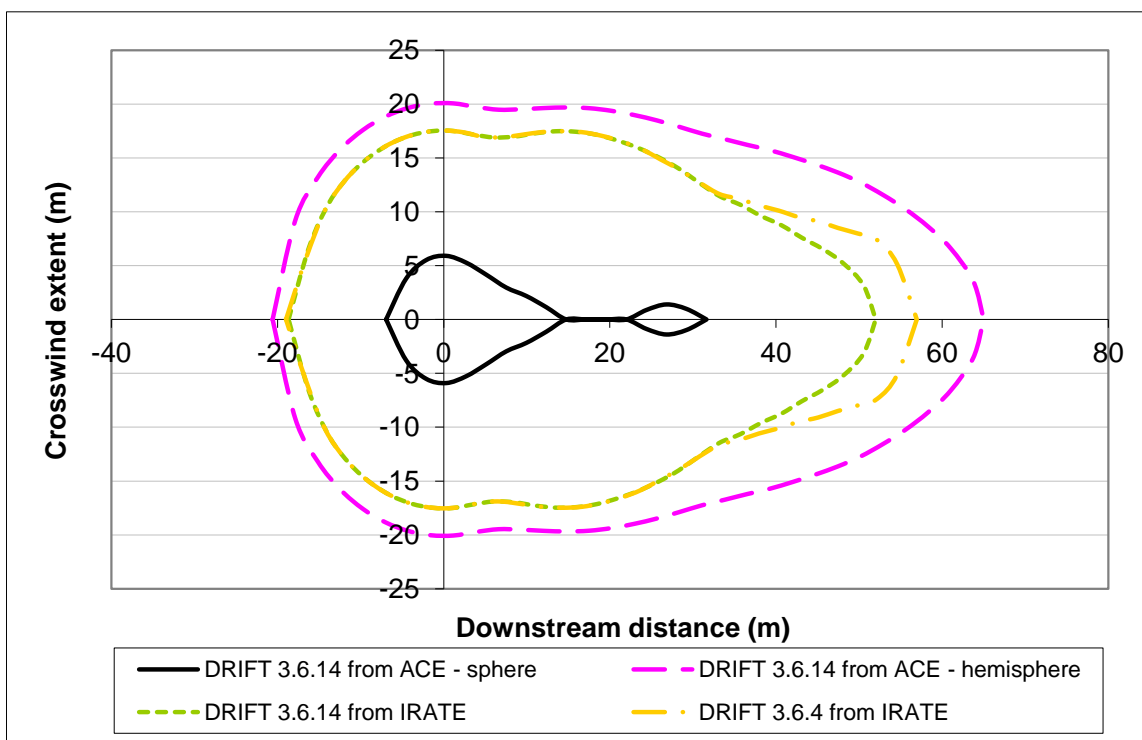


Figure 134 LFL isopleths for an instantaneous release following a catastrophic failure of a vessel storing *o*-cresol in F2 weather

The maximum downstream distances to the LFL at the cloud centreline height are shown in Table 57 for an instantaneous release of *o*-cresol.

Table 57 Maximum downstream distances to the LFL at the cloud centreline height for an instantaneous *o*-cresol release following a catastrophic failure of a vessel in D5 and F2 weather

<i>Scenario</i>	<i>Maximum centreline distance to the LFL (m)</i>	
	<i>D5</i>	<i>F2</i>
DRIFT 3.6.4 + IRATE	44	57
DRIFT 3.6.14 + IRATE	44	52
DRIFT 3.6.14 + ACE – sphere	13	13
DRIFT 3.6.14 + ACE – hemisphere	73	65

Modelling the release in DRIFT 3.6.14 using outputs of the ACE spherical release model reduces the size of the LFL isopleths when compared to the original assessment using DRIFT 3.6.4 and IRATE. If the release is modelled as hemispherical in ACE, the isopleths increase in size and are larger than when IRATE is used with either version of DRIFT. When DRIFT 3.6.14 is used with IRATE, the isopleths produced are similar to those output by DRIFT 3.6.4.

The similarity between the results when IRATE is used with DRIFT 3.6.4 and DRIFT 3.6.14 is due to the scenario modelled being largely unaffected by the changes made to the instantaneous model since version 3.6.4 was released.

The maximum downstream distances to the LFL obtained when the release is modelled as hemispherical in ACE are considerably larger than those obtained when the release is modelled as spherical. The hemispherical cloud is assumed to have half the volume of the spherical cloud, but the mass of *o*-cresol within the cloud is identical, so the hemispherical release is a smaller, more concentrated source. In addition, the hemispherical cloud has a lower surface area in contact with/interacting with the surrounding atmosphere than the spherical cloud, meaning that less mixing can occur at any given time. This leads to

longer dispersion times and longer overall distances to the criterion concentration when a hemispherical release is modelled.

When the release is modelled as hemispherical in ACE, the downstream distance to the LFL in F2 weather is shorter than that predicted in D5 weather. This is in contrast to the results obtained when modelling the release as spherical or when IRATE is used instead of ACE. This observation could be a result of the gravity driven radial spreading, which exceeds the downwind advection (driven by the wind) for longer in F2 weather. In some circumstances, this can shorten the downwind extent.

Figure 134 shows that the LFL isopleth for the scenario modelled in DRIFT 3.6.14 using the spherical release option in ACE appears unusual in that it decreases to zero at a distance of 13 m downstream, but then there is a second isopleth hazard region between 20 m and 30 m downstream. This is likely to be a limitation of the output steps and contouring method used in the model. DRIFT 3 initially models the area around the source of the release, and then advects the cloud downwind. These two processes should result in a continuous contour but, in some cases, it appears that the output steps are such that the results from each section can become disconnected, leading to the situation seen in Figure 134. The actual downstream distance should therefore be approximately 30 m, not the 13 m that DRIFT 3 reports, and the isopleth should have a non-zero crosswind extent between 13 m and 22 m. This has been corrected in DRIFT 3.7, which will replace DRIFT 3.6.14 once it has undergone full evaluation and assessment.

In F2 weather, the *o*-cresol release is buoyant. The maximum downstream distance to the LFL at various receiver heights has been recorded for the scenarios modelled in DRIFT 3.6.14. When a hemispherical release is modelled in ACE, the maximum downstream LFL distance is 38 m at a receiver height of 0 m, 41 m at a receiver height of 5 m, and 42 m at a receiver height of 10 m. The cloud reaches a maximum height of about 37 m. When the scenario is modelled in DRIFT 3.6.14 using a source term generated by IRATE, the maximum downstream LFL distance is 33 m at a receiver height of 0 m, and 34 m at receiver heights of 2 m, 5 m and 10 m. The cloud reaches a maximum height of about 42 m.

In the original assessment, further tests were performed using a stagnation temperature of 480.15 K as an input to IRATE rather than the 493.15 K temperature used to set the LUP zone sizes. This was due to the predicted saturation vapour pressure (SVP) at 493.15 K being higher than the 140,000 Pa (1.4 bara) normal operating pressure. The additional inputs and outputs from IRATE are given in Table 58. Figure 135 and Figure 136 display the LFL isopleths predicted by DRIFT 3 in D5 weather and F2 weather, respectively, when the lower stagnation temperature is used as an input for IRATE and ACE.

Table 58 Inputs and outputs from IRATE for modelling a catastrophic failure of a vessel storing *o*-cresol using a lower input temperature

IRATE inputs			IRATE outputs used as inputs to DRIFT 3					
Air Temp (K)	Quantity (kg)	Temp (K)	Initial Flash Fraction	Mass of Air (kg)	Contaminant Mass Fraction ¹	Equilibrium Temp (K)	Cloud Radius (m)	Cloud Quality (Liquid Fraction)
288.15	4000	480.15	0.1208	27240	0.1281	340.5	20.35	0.8026 ²
278.15	4000	480.15	0.1208	27240	0.1281	335.7	20.24	0.8516 ²

¹Contaminant mass fraction, $CMF = M_c / [M_c + M_a]$, M_a = mass of air, M_c = mass of contaminant

²This is reset to 1 – see following paragraph

In the reassessment, the outputs from IRATE have been used as inputs to DRIFT 3.6.14 to replicate the scenarios modelled in DRIFT 3.6.4 as closely as possible. In the original assessment, the liquid fraction calculated by IRATE was not used and a value of 1 was input instead. A liquid fraction of 1 has also been used in the DRIFT 3.6.14 runs to ensure that the same inputs are being modelled in the reassessment.

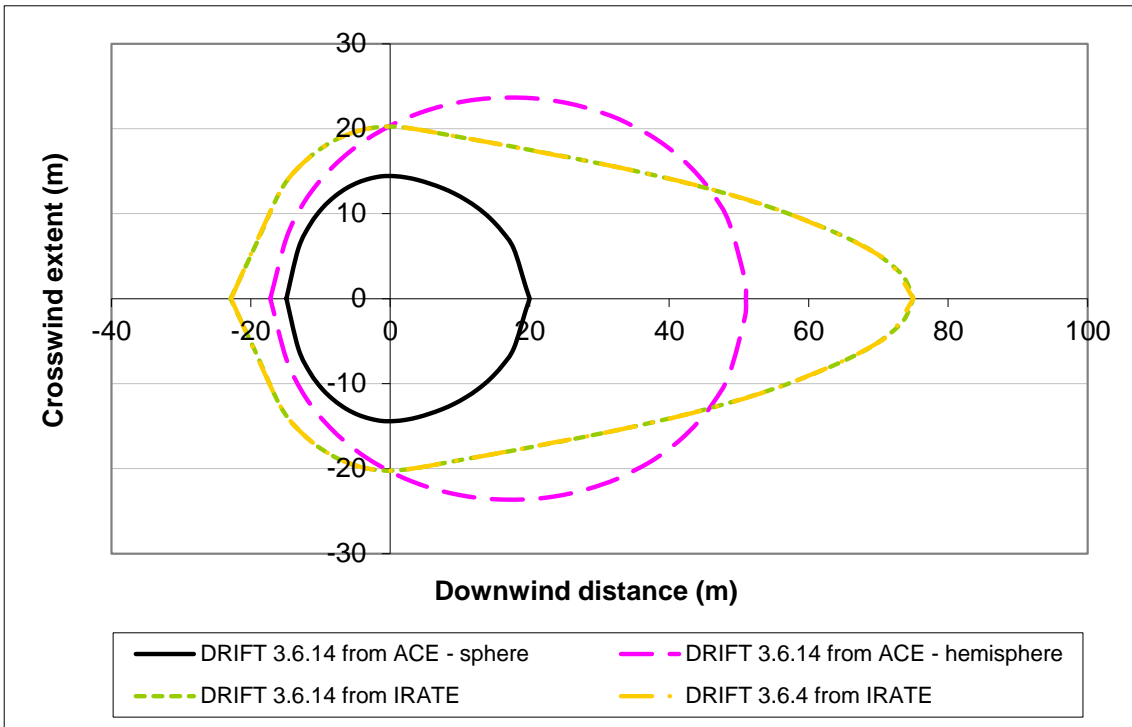


Figure 135 LFL isopleths for an instantaneous release following a catastrophic failure of a vessel storing *o*-cresol in D5 weather at a lower temperature of 480.15 K

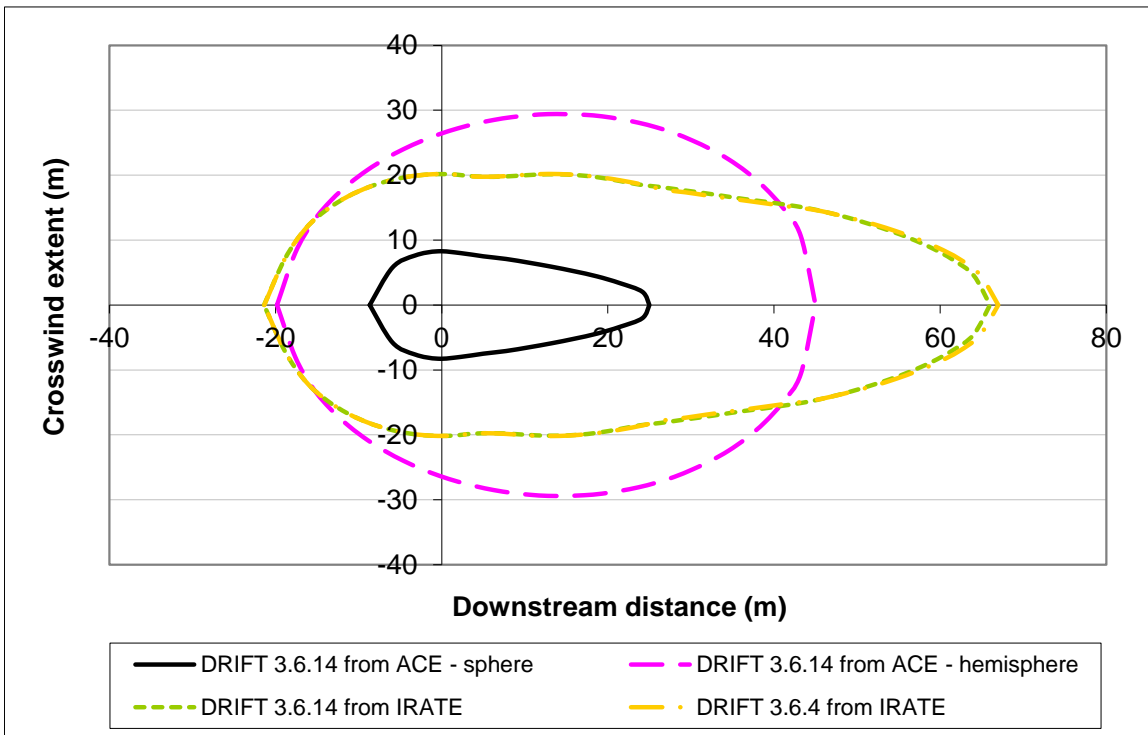


Figure 136 LFL isopleths for an instantaneous release following a catastrophic failure of a vessel storing *o*-cresol in F2 weather at a lower temperature of 480.15 K

The maximum downstream distances to the LFL at the cloud centreline height are shown in Table 59 for an instantaneous release of *o*-cresol at a lower temperature of 480.15 K.

Table 59 Maximum downstream distances to the LFL at the cloud centreline height for an instantaneous *o*-cresol release following a catastrophic failure of a vessel in D5 and F2 weather at a lower temperature of 480.15 K

<i>Scenario</i>	<i>Maximum centreline distance to the LFL (m)</i>	
	<i>D5</i>	<i>F2</i>
DRIFT 3.6.4 + IRATE	75	67
DRIFT 3.6.14 + IRATE	75	66
DRIFT 3.6.14 + ACE – sphere	20	25
DRIFT 3.6.14 + ACE – hemisphere	51	45

When IRATE is used to generate the source terms, the maximum downstream distances to the LFL are larger than those obtained at a stagnation temperature of 493.15 K. At a stagnation temperature of 480.15 K, the maximum downstream distances to the LFL are predicted to be larger in D5 weather than in F2 weather, in contrast to the results obtained at 493.15 K. There is a negligible difference between the results obtained from DRIFT 3.6.4 and the results from DRIFT 3.6.14 when IRATE is used to generate the source terms for the dispersion model.

At a stagnation temperature of 493.15 K, the largest maximum downstream distances to the LFL were obtained when modelling the source term using the hemispherical option in ACE. In contrast, when ACE is used to generate the source terms at a temperature of 480.15 K, the maximum downstream distances to the LFL obtained using both the spherical and hemispherical options are smaller than those obtained using IRATE. Larger maximum downstream LFL distances and crosswind LFL extents are obtained when the release is approximated as hemispherical rather than spherical. The reason for this difference is explained in Section 4.3.

The cloud is buoyant in F2 weather, except when the release is modelled as hemispherical in ACE. When modelling a spherical release in ACE, the maximum downstream distance to the LFL is 15 m at a receiver height of 0 m. This is compared to a downstream distance of 25 m when the centreline height of the cloud is used, as reported in Table 59. The maximum LFL distance for this case is obtained at a receiver height of around 6 m. When using IRATE to generate the source terms, the maximum downstream LFL distance is 35 m at a receiver height of 0 m and then increases as higher receiver heights are modelled. At a receiver height of 10 m, the maximum downstream distance to the LFL is 38 m when using IRATE with DRIFT 3. The maximum height of the top edge of the cloud is approximately 50 m.

4.5.1 Modelling the pool component

Following a catastrophic failure of a vessel storing *o*-cresol, some of the released substance will form a cloud that disperses as a dense gas, but potentially some of the substance will rainout and form an evaporating pool. The ACE model calculates the quantity and size of the pool formed from an instantaneous release, but only has a simple pool evaporation model that assumes that the entire contents of the pool vaporise. GASP is HSE's preferred model for modelling the spreading and vaporisation of a pool of a hazardous substance. The ACE model outputs can be used as inputs to GASP. The freezing point of *o*-cresol, however, is higher than the cloud temperature predicted by ACE, and is also higher than the ground temperature (in normal conditions). Any *o*-cresol that is rained out of the cloud is likely to be at a low enough temperature to be solid, or will form a solid on contact with the ground. Formation of a liquid evaporating pool is considered unlikely in these circumstances and has not been considered further.

4.6 DISCUSSION AND CONCLUSIONS FOR INSTANTANEOUS FLASHING RELEASES

Isobutane and propane releases were investigated and the results of the testing are shown earlier in this section. For such substances, a catastrophic vessel failure will generally lead to some of the contaminant

raining out and forming a pool on the ground, as well as the formation of an instantaneous puff that disperses as a dense gas with the wind. In such circumstances, the pool and the initial airborne release should be modelled separately and the results compared to determine which release mechanism generates the greater hazard. This is because the testing shows that the maximum downwind distances and crosswind extents to the LFL from the pool may be similar to or, in some circumstances, greater than those from the initial cloud. DRIFT 3.6.14 cannot currently combine the pool and cloud results, although this is being investigated as a possible future enhancement to the model. Currently, HSE uses the scenario that produces the largest LFL distances to generate its LUP advice.

A flashing release of *o*-cresol at elevated temperature and pressure was also considered. In F2 weather, DRIFT 3 predicted that the cloud would be buoyant. In such circumstances, consideration needs to be given as to whether the LFL isopleths calculated at the centreline height should be used or whether the distance at a specified receiver height should be considered instead. Using a specific receiver height will generally result in shorter distances to the LFL, whilst using the centreline height distance will generally be the most cautious approach.

When modelling the pool formed from a catastrophic vessel failure, the outputs generated by GASP met HSE's 'peaky' criteria for all of the isobutane and propane scenarios. Three different methodologies were used to model the release in these cases, the 'peaky' methodology, the 'non-peaky' method, and the time varying model within DRIFT 3. It was found that the time varying model only ran successfully for one of the scenarios considered. This issue will be addressed in future versions of DRIFT. The 'non-peaky' method produces significantly shorter maximum downwind LFL extents than those generated using the 'peaky' method. The 'peaky' methodology models a large initial vaporisation rate that quickly degrades with time; the 'non-peaky' methodology uses an average vaporisation rate for the entire duration of the release and does not consider the initial peak vaporisation rate. This can lead to the 'non-peaky' methodology underestimating the maximum downwind distances to the LFL.

The ACE model treats instantaneous releases as either spherical or hemispherical in shape. The default option used by HSE is to assume a hemispherical release, as this is a more appropriate geometry for a large expanding release near the ground. From the tests using isobutane, propane and *o*-cresol, it was found that the choice of release configuration within ACE had a significant effect on the results produced by DRIFT 3. In ACE, the hemispherical cloud is assumed to have half the volume of the spherical cloud, but the mass of contaminant within the cloud is identical, so the hemispherical release produces a smaller, more concentrated source. In addition, the hemispherical cloud has a lower surface area in contact with the surrounding atmosphere than the spherical cloud, meaning that less mixing can occur at any given time. This leads to longer dispersion times and longer overall distances to the criterion LFL concentration when a hemispherical release is modelled in DRIFT 3.

5 CONCLUSIONS

The DRIFT dispersion model was developed for HSE by ESR Technology. ESR Technology has recently released a new version of the model, DRIFT version 3 (DRIFT 3). DRIFT 3 includes a significant number of modelling enhancements over the version of DRIFT previously used by HSE (DRIFT 2.31 [1, 2]). These include the extension of the model to consider buoyant lift off and buoyant rise, and the option to calculate initial dilution over the source and upwind spreading. New modelling options such as finite duration and time varying releases can be modelled in DRIFT 3, in addition to the instantaneous and steady continuous releases that are available in DRIFT 2.31. The mathematical and scientific basis for the finite duration and time varying models has been subject to expert peer review and found to be appropriate [18, 20]. DRIFT 3 also has an improved user interface, and is simpler and more intuitive to use than its predecessor, DRIFT 2.31. It is compatible with HSE's Substance Property Information (SPI) data files.

DRIFT 3 must undergo thorough testing before being adopted for use by HSE. This report describes the testing of the performance of DRIFT 3 when modelling the dispersion of flammable substances. The dispersion of such releases was previously modelled using DRIFT 2.31 or CRUNCH [9].

The proposed methodology for modelling the dispersion of flammable substances using DRIFT 3 has been described for each of three release types: evaporating pools, flashing continuous releases from vessel, pipework and pipeline holes, and instantaneous flashing releases from catastrophic vessel failure. The LFL (lower flammable limit) isopleths predicted by DRIFT 3 have been compared to those predicted by the models previously used by HSE. In the case of pipeline holes, the final LUP (land-use planning) zones have also been considered. The LUP zones refer to areas around pipelines where development is regulated due to the risks posed to people in the vicinity of the pipeline should a failure occur.

The modelling recommendations were made in consultation with the developers of the model and specialist inspectors and researchers within HSE. In most cases, differences between the modelling methodologies used in DRIFT 2.31 and DRIFT 3 only arise because the enhanced modelling capability of DRIFT 3 is being exploited to address particular physical effects, or because the source term models that provide the inputs to DRIFT have been updated. The version of DRIFT used in this study was DRIFT 3.6.14.

5.1 COMPARISON OF THE OUTPUTS OF DRIFT 3.6.14 AND PREVIOUS MODELS

5.1.1 Evaporating pools

Hazardous Substance Consent applications for liquefied hydrogen and LNG (liquefied natural gas) that were originally assessed using GASP and DRIFT 2.31 have been reassessed using GASP and DRIFT 3.6.14. The LFL isopleths obtained in the original assessments and the reassessments have been compared.

The LFL isopleths predicted by DRIFT 3.6.14 are generally shorter and narrower than those predicted by DRIFT 2.31. The LFL isopleths predicted by DRIFT 3.6.14 extend upwind whereas those predicted by DRIFT 2.31 do not.

It is possible that the difference between the LFL isopleths predicted by the two versions of DRIFT is partly caused by the fact that DRIFT 2.31 is unable to model area sources. DRIFT 2.31 treats the GASP output as a line source along the crosswind axis, of length equal to the mean pool diameter predicted by GASP. The area source modelled by DRIFT 3.6.14 is necessarily more dilute than the line source modelled in DRIFT 2.31. Furthermore, when an area source is modelled, some of the flammable material will start to disperse from positions upwind of the origin and may spread further upwind and dilute due to gravity spreading. These factors may help to explain why DRIFT 3.6.14 predicts generally smaller downwind dispersion distances than those obtained in DRIFT 2.31.

For some scenarios, DRIFT 2.31 cannot run using the cloud properties predicted by GASP. In such cases, it is possible to manually modify the plume velocity and roughness length output by GASP to allow DRIFT 2.31 to be run successfully for the source dimensions and vaporisation rate generated by GASP. However, using the edited source term may not give a good representation of the dispersion from the pool. DRIFT 3 contains an improved sub-model for low momentum area sources, which includes the effects of upwind spreading. As a result, scenarios that would not run in DRIFT 2.31 usually run in DRIFT 3 without difficulty, providing more justifiable hazard ranges from the dispersion modelling.

5.1.2 Flashing continuous releases from vessel, pipework and pipeline holes

Two Pipeline Safety Regulations (PSR) assessments for ethylene and LPG (liquefied petroleum gas) that used CRUNCH for the dispersion modelling have been reassessed using DRIFT 3.6.14. The LFL isopleths obtained in the original assessments and the reassessments have been compared, to assess the impact of adopting DRIFT 3 on HSE's land-use-planning advice. The results have also been incorporated into HSE's pipeline risk assessment tool, MISHAP12, to assess the impact on the LUP zones.

In addition, a gas compressor station siting policy that originally used PFAF to generate the release rates and DRIFT 3.5 to model the dispersion has been reassessed using PFAF and DRIFT 3.6.14.

For the gas compressor station siting policy, little difference is seen by moving from DRIFT 3.5 to DRIFT 3.6.14. For the pipelines, the downwind LFL distances generated by DRIFT 3.6.14 are considerably shorter than those from CRUNCH, particularly in F2 weather conditions. This is likely to be due to the fact that CRUNCH does not contain a jet model, so was used in conjunction with a simple in-house jet model. CRUNCH has also been identified as being more appropriate for modelling dispersion at higher wind speeds [9]. The large reductions in the predicted sizes of the LFL isopleths that are observed when DRIFT 3 is used instead of CRUNCH lead to a significant reduction in the risk based LUP zones generated by MISHAP12.

The effect of varying the release temperature on the maximum downwind distance to the LFL calculated by DRIFT 3 has been investigated for the pipeline scenarios. It was found that, as the release temperature is increased, the maximum downwind distance to the LFL output by the DRIFT 3 model decreases. This is due to the increased amount of energy in the cloud as the temperature increases, which increases the amount of mixing with the surrounding atmosphere, causing more rapid dilution of the cloud. For flashing releases, increasing the release temperature decreases the liquid fraction which leads to lower cloud density and less suppression of mixing.

5.1.3 Instantaneous flashing releases from catastrophic vessel failure

Consent assessments for isobutane, propane and *o*-cresol that used IRATE and either DRIFT 3.6.4 (for the toxic harm in the case of *o*-cresol) or DRIFT 2.31 to model the dispersion have been reassessed using ACE 3.11 and DRIFT 3.6.14.

In the isobutane case, DRIFT 3 produces longer maximum downwind distances to the LFL than DRIFT 2.31, when using IRATE to generate the source terms. When ACE is used to generate source terms for DRIFT 3, the predicted LFL isopleths are significantly smaller than those obtained using IRATE (for both spherical and hemispherical releases).

For the propane assessment, the predicted downwind distances to the LFL are reduced when DRIFT 3 is used instead of DRIFT 2.31. The maximum LFL distances are further reduced when ACE is used to generate the source terms for DRIFT 3 rather than IRATE.

For the *o*-cresol scenarios modelled, the LFL isopleths obtained using IRATE and DRIFT 3.6.14 are similar to those generated using IRATE and DRIFT 3.6.4. It appears that the modifications that were made to the DRIFT 3 instantaneous model between DRIFT 3.6.4 and DRIFT 3.6.14 have not had a significant effect on

these particular scenarios. When the releases are modelled using the spherical option in ACE, the predicted LFL isopleths are significantly smaller than those predicted when using IRATE. In contrast, if the releases are modelled as hemispherical in ACE, then the predicted LFL isopleths are larger than those obtained if IRATE is used to generate the source terms for DRIFT 3.

In the isobutane and propane scenarios modelled, any pool resulting from rainout from the initial release should also be modelled as the distances to the LFL associated with this release mechanism may be as large, or larger, than those generated from the initial cloud dispersion. The output from ACE should be used as input to GASP for this part of the modelling process.

5.2 OUTCOMES

As a result of this work, DRIFT 3.6.14 has now been adopted by HSE to model:

- The dispersion of vapour evolved from pools of flammable substances;
- The dispersion of vapour from flashing releases of flammable substances from holes; and
- The dispersion of vapour from flashing releases of flammable substances from catastrophic vessel failure.

DRIFT 3.6.14 has therefore replaced DRIFT 2.31 for use in Hazardous Substances Consent assessments. It has also replaced CRUNCH for use with pipelines that fall under the Pipeline Safety Regulations.

Specific details of the modelling for each type of release are given subsequently.

5.2.1 Evaporating pools

The *finite duration* model in DRIFT 3 is the most appropriate option for modelling the dispersion of vapour evolved from pools of flammable liquids. A relative humidity of 60% is assumed.

The centreline height output option in DRIFT 3 is used to determine the hazard range in all cases, including when the cloud becomes buoyant. It is possible that an observer on the ground will be beneath a flammable cloud. If the cloud ignites, the observer could be harmed by the resultant fire. The option of using the centreline height provides a more cautious approach than using a specific receiver height and captures this scenario.

For an evaporating pool release where the GASP results do not vary significantly over time then a mean vaporisation rate for the duration of the release can be used as input to DRIFT 3 to model the release scenario.

For an evaporating pool release where the GASP results indicate that the vaporisation rate varies significantly over time then the methodology developed by HSE for generating the source term is used. This method takes into consideration a potentially large initial vaporisation rate that then quickly reduces over a short duration to a steadier vaporisation rate for the remainder of the pool duration. The mean vaporisation rate should not be used in such cases as it will not account for any initial peak in the vaporisation rate.

5.2.2 Flashing releases from holes from vessels, pipework and pipelines

For all cases of flashing releases from vessel, pipework or pipeline holes, the *finite duration* option in DRIFT 3.6.14 is the most appropriate, with a relative humidity of 60%.

DRIFT 3.6.14 has replaced CRUNCH for the modelling of the dispersion of releases from pipelines.

For buried pipelines, a release height of 0 m is assumed, given that DRIFT cannot model releases below ground, nor the crater that is subsequently formed. This represents the closest approximation to a release that is deflected by the crater and then runs along the ground. The release is assumed to be horizontal as this produces the most cautious distances. In reality, the release could be in any orientation.

5.2.3 Flashing releases from catastrophic vessel failure

The *instantaneous* model is the most appropriate option in DRIFT 3.6.14 when modelling near-instantaneous flashing releases following a catastrophic failure of a vessel.

For these scenarios, any pool that is formed by rainout of the substance from the cloud is considered in conjunction with the initial cloud. The methodology followed for this element of the release is that recommended for evaporating pools.

The release is modelled as a hemisphere in the ACE source term model.

6 APPENDICES

6.1 INPUT VALUES USED FOR EVAPORATING POOLS ASSESSMENTS

Tables 60 and 61 summarise the input values used in GASP, when carrying out the evaporating pool consent assessments described in Section 2.

Table 60 General GASP input values used for the consent assessments described in Section 2

<i>Input</i>	<i>Liquefied hydrogen</i>	<i>LNG</i>
Surface type	Land	Land
Substrate	Concrete	Dry soil or wet soil
Heat transfer mode	Perfect thermal contact, temperature varying substrate	Perfect thermal contact, temperature varying substrate
Pool roughness length ¹	0 m	0 m
Air temperature	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)
Wind speed (at 10 m)	15 m/s, 10 m/s, 5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)
Pasquill stability class	D (day) or F (night)	D (day) or F (night)
Relative humidity ²	70%	70%
Surface roughness length	0.1 m	0.1 m
Additional heat flux	270 W/m ² (day) or 0 W/m ² (night)	270 W/m ² (day) or 0 W/m ² (night)
Termination criteria	Pool age is greater than 1800 s or 1% of the pool remains	Pool age is greater than 1800 s or 1% of the pool remains
Evaporation mode	Calculated (default)	Calculated (default)

¹The currently recommended HSE value for the pool roughness length is 0.00023 m [33]

²The currently recommended HSE value for the relative humidity is 60%

The default values were used for all the thermodynamic options and numerical control inputs in GASP.

Table 61 Scenario-specific GASP input values used for the consent assessments described in Section 2

<i>Input</i>	<i>Instantaneous release of liquid hydrogen</i>	<i>Continuous release of liquid hydrogen</i>	<i>Instantaneous release of LNG with bund failure</i>	<i>Major release of LNG with bund failure</i>	<i>Minor release of LNG with bund failure</i>	<i>Instantaneous release of LNG without bund failure</i>	<i>Failure of LNG pipework</i>
Bund radius	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Puddle depth ¹	0.00404 m	0.00404 m	0.12 m	0.083 m	0.037 m	0.053 m	0.02 m
Release type	Instantaneous	Continuous	Instantaneous	Continuous	Continuous	Instantaneous	Continuous
Mass release rate	N/A	14.3 kg/s	N/A	3970 kg/s	357 kg/s	N/A	61 kg/s
Aperture diameter	N/A	0.05 m	N/A	1 m	0.3 m	N/A	0.2 m
Release constraints	N/A	Time limited: 245 s	N/A	Time limited: 1800 s	Time limited: 245 s	N/A	Time limited: 1800 s
Pool mass	3500 kg	N/A	21,000,000 kg	N/A	N/A	1,888,000 kg	N/A
Pool radius	4 m	N/A	23 m	N/A	N/A	23 m	N/A
Spreading velocity	0 m/s	N/A	0 m/s	N/A	N/A	0 m/s	N/A
Release temperature ²	19.4175 K	19.4175 K	110.749 K	110.749 K	110.749 K	110.749 K	110.749 K

¹The puddle depths were reported in the original assessments

²The release temperatures were reported in the original assessments

Table 62 summarises the input values used in DRIFT 2.31 and the final recommended inputs used in DRIFT 3.6.14, when carrying out the hydrogen and LNG consent reassessments described in Section 2. Where the same input has different names in DRIFT 2.31 and DRIFT 3.6.14, the DRIFT 2.31 name is given in brackets.

Table 62 DRIFT input values used for the hydrogen and LNG consent assessments described in Section 2

<i>Input</i>	<i>Hydrogen (DRIFT 2.31)</i>	<i>Hydrogen (DRIFT 3.6.14 with new assumptions)</i>	<i>LNG (DRIFT 2.31)</i>	<i>LNG (DRIFT 3.6.14 with new assumptions)</i>
Release type	Continuous	Finite duration	Continuous	Finite duration
Phase (cloud state) ¹	Immiscible aerosol and water (imported from DIN file ²)	Gaseous (imported from DIN file ²)	Immiscible aerosol and water (imported from DIN file ²)	Gaseous (imported from DIN file ²)
Substance; temperature (cloud temperature); contaminant fraction (contaminant mass fraction); release rate (mass flux) and release duration	As imported from DIN file ²	As imported from DIN file ² or GASP file	As imported from DIN file ²	As imported from DIN file ² or GASP file
Cloud quality; plume velocity ³	As imported from DIN file ²	As imported from DIN file ² or GASP file	As imported from DIN file ²	As imported from DIN file ² or GASP file
Location (initial displacement)	0 m	(0,0,0)	0 m	(0,0,0)
Source type	N/A	Low momentum area source	N/A	Low momentum area source
Source diameter (plume half-width) ⁴	As imported from DIN file ²	As imported from DIN file ² or GASP file	As imported from DIN file ² or GASP file	As imported from DIN file ² or GASP file
Include dilution over source	N/A (DRIFT 2.31 does not have this functionality)	Yes	N/A (DRIFT 2.31 does not have this functionality)	Yes
Weather scheme	Pasquill	Pasquill	Pasquill	Pasquill
Input inversion height	N/A	No	N/A	No
Temperature	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)
Relative humidity	70%	60%	70%	60%
Reference height	10 m	10 m	10 m	10 m

<i>Input</i>	<i>Hydrogen (DRIFT 2.31)</i>	<i>Hydrogen (DRIFT 3.6.14 with new assumptions)</i>	<i>LNG (DRIFT 2.31)</i>	<i>LNG (DRIFT 3.6.14 with new assumptions)</i>
Roughness length	0.1 m	0.1 m	0.1 m	0.1 m
Wind angle from North	N/A	270°	N/A	270°
Pasquill stability	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)
Wind speed	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)
Receiver height	0 m	Use centreline height	0 m	Use centreline height

¹DRIFT 3 has different phase categories to DRIFT 2.31. If the phase in the DIN file is 'immiscible aerosol and water', this will be converted to 'gaseous' when the file is opened in DRIFT 3.6.14.

²A DIN file is a DRIFT input text file

³For some release scenarios, the plume velocity had to be increased to enable DRIFT 2.31 to run

⁴The source diameter and the plume half-width are not equivalent but are derived from the same information in the DIN file

6.2 INPUT VALUES USED FOR CONTINUOUS FLASHING RELEASE ASSESSMENTS

Table 63 summarises the input values used in DRIFT 2.31, DRIFT 3.5 or CRUNCH and the final recommended inputs used in DRIFT 3.6.14, when carrying out the ethylene, LPG and methane assessments described in Section 3. Where the same input has different names in DRIFT 2.31 and DRIFT 3.6.14, the DRIFT 2.31 name is given in brackets.

Table 63 DRIFT input values used for the ethylene and LPG PSR assessments and the methane gas compressor siting policy described in Section 3

<i>Input</i>	<i>Ethylene (DRIFT 2.31)</i>	<i>Ethylene (DRIFT 3.6.14 with new assumptions)</i>	<i>LPG (CRUNCH)</i>	<i>LPG (DRIFT 3.6.14 with new assumptions)</i>	<i>Methane (DRIFT 3.5)</i>	<i>Methane (DRIFT 3.6.14 with new assumptions)</i>
Release type	Continuous	Finite duration	N/A	Finite duration	Finite duration	Finite duration
Phase (cloud state)	Contaminant gas only	As indicated by PipeTech (two-phase for ruptures, gaseous for holes)	N/A	Two-phase	Gaseous	Gaseous
Substance	Ethylene	Ethylene	Propane	Propane	Methane	Methane
Temperature	256.5 K	From PipeTech	Boiling point (231.11 K)	From release rate model	278 K	278 K
Pressure	N/A	From PipeTech	N/A	From release rate model	N/A	N/A
Liquid fraction	N/A	From PipeTech	0.828 (called aerosol fraction)	From release rate model	N/A	N/A
Rainout fraction	N/A	0	N/A	0	N/A	N/A
Contaminant fraction	0.0715	1	N/A	1	1	1
Release rate	As specified for each release size	As specified for each release size	As specified for each release size	As specified for each release size	As specified for each release size	As specified for each release size

Input	Ethylene (DRIFT 2.31)	Ethylene (DRIFT 3.6.14 with new assumptions)	LPG (CRUNCH)	LPG (DRIFT 3.6.14 with new assumptions)	Methane (DRIFT 3.5)	Methane (DRIFT 3.6.14 with new assumptions)
Release duration	120 s	Release duration or 1800 s	N/A	Release duration or 1800 s	200,000 s	1800 s
Orifice diameter	As specified for the release size	As specified for the release size	N/A	As specified for the release size	As specified for the release size	As specified for the release size
Discharge coefficient	N/A	0.95 (rupture) or 0.8 (holes for gas releases) or 0.61 (holes for two- phase releases)	N/A	0.95 (rupture) or 0.61 (holes)	0.95 (rupture) or 0.8 (holes)	0.95 (rupture) or 0.8 (holes)
Angle from horizontal	N/A	0°	N/A	0°	0°	0°
Angle from north	N/A	90°	N/A	90°	90°	90°
Location (initial displacement)	0 m	(0,0,0)	N/A	(0,0,0)	(0,0,2)	(0,0,2)
Source type	Momentum jet	Momentum jet	N/A	Momentum jet	Momentum jet	Momentum jet
Weather scheme	Pasquill	Pasquill	Pasquill	Pasquill	Pasquill	Pasquill
Input inversion height	N/A	No	N/A	No	No	No
Temperature	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)	288 K	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)
Relative humidity	Assumed zero water vapour	60%	N/A	60%	60%	60%
Reference height	10 m	10 m	N/A	10 m	10 m	10 m
Roughness length	0.3 m	0.1 m for rural or 0.3 m for suburban	0.1 m	0.1 m for rural or 0.3 m for suburban	0.1 m	0.1 m

<i>Input</i>	<i>Ethylene (DRIFT 2.31)</i>	<i>Ethylene (DRIFT 3.6.14 with new assumptions)</i>	<i>LPG (CRUNCH)</i>	<i>LPG (DRIFT 3.6.14 with new assumptions)</i>	<i>Methane (DRIFT 3.5)</i>	<i>Methane (DRIFT 3.6.14 with new assumptions)</i>
Wind angle from North	N/A	270°	N/A	270°	270°	270°
Pasquill stability	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)
Wind speed	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)
Receiver height	Use centreline height	Use centreline height	N/A	Use centreline height	Use centreline height	Use centreline height

6.3 INPUT VALUES USED FOR INSTANTANEOUS FLASHING RELEASE ASSESSMENTS

Table 64 summarises the input values used in DRIFT 2.31 or DRIFT 3.6.4 and the final recommended inputs used in DRIFT 3.6.14, when carrying out the *o*-cresol, isobutane and propane assessments described in Section 4. Where the same input has different names in DRIFT 2.31 and DRIFT 3.6.14, the DRIFT 2.31 name is given in brackets.

Table 64 DRIFT input values used for the isobutane, propane and *o*-cresol consent assessments described in Section 4

<i>Input</i>	<i>Isobutane (DRIFT 2.31)</i>	<i>Isobutane (DRIFT 3.6.14 with new assumptions)</i>	<i>Propane (DRIFT 2.31)</i>	<i>Propane (DRIFT 3.6.14 with new assumptions)</i>	<i>o-Cresol (DRIFT 3.6.4)</i>	<i>o-Cresol (DRIFT 3.6.14 with new assumptions)</i>
Release type	Instantaneous	Instantaneous	Instantaneous	Instantaneous	Instantaneous	Instantaneous
Phase (cloud state)	Superheated Liquid/ Two-Phase	Superheated Liquid/ Two-Phase	Superheated Liquid/ Two-Phase	Superheated Liquid/ Two-Phase	Superheated Liquid/ Two-Phase	Superheated Liquid/ Two-Phase
Substance	Isobutane	Isobutane	Propane	Propane	<i>o</i> -Cresol	<i>o</i> -Cresol
Temperature	Output from IRATE	Output from ACE	Output from IRATE	Output from ACE	Output from IRATE	Output from ACE
Liquid fraction	1	Output from ACE	1	Output from ACE	1	Output from ACE
Rainout fraction ¹	0	0	0	0	0	0
Contaminant fraction	Output from IRATE	Output from ACE	Output from IRATE	Output from ACE	Output from IRATE	Output from ACE
Contaminant mass	1,056,000 kg	Output from ACE	548,400 kg	Output from ACE	4000 kg	Output from ACE
Stationary initial cloud	N/A	No	N/A	No	N/A	No
Assume unit aspect ratio	N/A	No	N/A	No	No	No
Initial cloud radius	Output from IRATE	Output from ACE	Output from IRATE	Output from ACE	Output from IRATE	Output from ACE
Location (initial displacement)	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
Weather scheme	Pasquill	Pasquill	Pasquill	Pasquill	Pasquill	Pasquill

<i>Input</i>	<i>Isobutane (DRIFT 2.31)</i>	<i>Isobutane (DRIFT 3.6.14 with new assumptions)</i>	<i>Propane (DRIFT 2.31)</i>	<i>Propane (DRIFT 3.6.14 with new assumptions)</i>	<i>o-Cresol (DRIFT 3.6.4)</i>	<i>o-Cresol (DRIFT 3.6.14 with new assumptions)</i>
Input inversion height	N/A	No	N/A	No	No	No
Temperature	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)	288.15 K (D5) or 278.15 K (F2)
Relative humidity	70%	60%	70%	60%	60%	60%
Reference height	10 m	10 m	10 m	10 m	10 m	10 m
Roughness length	0.1 m	0.1 m	0.1 m	0.1 m	0.1 m	0.1 m
Wind angle from North	270°	270°	270°	270°	270°	270°
Pasquill stability	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)	D (day) or F (night)
Wind speed	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)	5 m/s (day) or 2 m/s (night)
Receiver height	Use centreline height	Use centreline height	Use centreline height	Use centreline height	Use centreline height	Use centreline height

¹For instantaneous releases, the rainout is considered within ACE, not DRIFT

6.4 LOWER FLAMMABLE LIMIT (LFL) VALUES

The values of the concentration for the LFL for each of the substances considered in this report are given in Table 65.

Table 65 Values of the LFL for each substance

<i>Substance</i>	<i>LFL concentration (volume-%)</i>
Hydrogen	4
Methane/LNG	5
Ethylene	2.3
Propane	2
<i>o</i> -Cresol	1.4
Isobutane	1.8

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HSE uses gas dispersion modelling in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazards sites. To update its dispersion modelling capability, HSE commissioned ESR Technology to develop a new version of the gas dispersion model DRIFT. The new version, DRIFT 3, includes a significant number of modelling enhancements over the version previously used within HSE (DRIFT 2.31). These include the extension of the model to treat buoyant plumes and time varying releases. Before DRIFT 3 is adopted for use by HSE, it must undergo thorough evaluation and assessment for a range of release scenarios. The initial phases of the DRIFT 3 testing programme used DRIFT 3.6.4 and are described in reports RR1100 and RR1101. Further testing is described in four reports including this one: RR1165, RR1166, RR1167 and RR1168. The four reports cover the evaluation of the model and assessment for a range of scenarios using the enhanced version DRIFT 3.6.14.

This report describes an assessment of the performance of DRIFT 3.6.14 for modelling the dispersion of flammable vapour. The assessment is for three release scenarios: vapour evolved from pools of flammable liquids, flashing jet releases of flammable substances, and instantaneous flashing releases of flammable substances. These scenarios are typically used by HSE to assess Hazardous Substances Consent applications and set Land Use Planning zones around major hazards sites and pipelines. This report describes sensitivity tests which show that DRIFT 3.6.14 works reliably for these scenarios. As a result of this assessment and accompanying model evaluation (see RR1165), DRIFT 3.6.14 has been adopted by HSE to model the dispersion of flammable vapour for these three release scenarios.