Model Evaluation Report on DRIFT Version 3.7.23

Health and Safety Executive

RR1231 (2026)

Research Report

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Prepared 2025

First published 2026

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HSE uses the gas dispersion model DRIFT 3 in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazard sites. The development of DRIFT 3 is ongoing, motivated by the need for HSE's statutory advice to be based on an up-to-date dispersion model.

To ensure that DRIFT 3 remains fit for purpose it is important to continue to evaluate it and to assess the effect of changes to the model on its predictions. This report describes the evaluation of DRIFT 3.7.23 against a Model Evaluation Protocol (MEP) designed specifically for DRIFT, which contains scientific assessment, verification, validation and a user-oriented assessment. The DRIFT MEP also includes the testing of the model against a set of exemplar scenarios, representative of the types of scenarios typically modelled by HSE for the purposes of Hazardous Substances Consent assessment. Based on the evaluation of DRIFT 3.7.23 against the DRIFT MEP, DRIFT 3.7.23 is judged to be fit for purpose and suitable for use in HSE's regulatory work.

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

This report and the work it describes were funded by the Health and Safety Executive. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

Model Evaluation Report on DRIFT Version 3.7.23

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Acknowledgements

The authors would like to thank Dr Gemma Tickle of ESR Technology and GT Science & Software for her guidance on the DRIFT model.

The contribution of Dr Rachel Batt to the early stages of this project is gratefully acknowledged.

Key Messages

The Health and Safety Executive (HSE) uses the gas dispersion model DRIFT 3 in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazard sites. The development of DRIFT 3 is ongoing, motivated by the need to ensure that HSE's statutory advice is based on an up-to-date dispersion model.

To ensure that DRIFT 3 remains fit for purpose it is important to continue to evaluate it and to assess the effect of changes to the model on its predictions. This report describes the evaluation of DRIFT 3.7.23 against a Model Evaluation Protocol (MEP) designed specifically for DRIFT, which contains scientific assessment, verification, validation and a user-oriented assessment.

The physical, mathematical and numerical basis of DRIFT 3.7.23 has been reviewed, using information provided in reports and papers describing the DRIFT 3 mathematical model. DRIFT 3.7.23 was also assessed against a set of qualitative criteria, chosen to provide a high-level summary of its capabilities, and was found to satisfy all these criteria.

Evidence of verification has been obtained from the developer and documentation. The available evidence indicates that the developer has carried out sufficient verification to give confidence that the equations in DRIFT 3.7.23 have been programmed correctly.

DRIFT 3.7.23 has been validated against a range of experimental data at field and wind-tunnel scales. The DRIFT 3.7.23 predictions for the concentration and cloud width were compared to the experimentally measured values. The performance of DRIFT 3.7.23 was assessed using the Statistical Performance Measures (SPM) and associated acceptance criteria recommended in the LNG (liquefied natural gas) protocol for dense gas dispersion models. The SPM for the field-scale trials are within the acceptance criteria for both the concentration data and the cloud width data. All except one of the SPM for the wind-tunnel trials are within the acceptability ranges.

The DRIFT MEP also includes the testing of DRIFT 3 against a set of exemplar scenarios, representative of the types of scenarios typically modelled by HSE for the purposes of Hazardous Substances Consent assessment. For the majority of the scenarios modelled, there is good agreement between the outputs of DRIFT 3.7.23 and DRIFT 3.6.14 (the version currently used by HSE). In cases where there is a significant difference in the outputs, the difference can be explained with reference to changes in the model physics.

Based on the evaluation of DRIFT 3.7.23 against the DRIFT MEP, DRIFT 3.7.23 is judged to be fit for purpose and suitable for use in HSE's regulatory work. DRIFT 3.7.23 incorporates a significant number of enhancements and bug fixes, and is better able to model wall jets and buoyant lift off than DRIFT 3.6.14 and earlier versions of DRIFT.

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

Executive Summary

The Health and Safety Executive (HSE) uses the gas dispersion model DRIFT 3 (Dispersion of Releases Involving Flammables or Toxics) in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazard sites. The development of DRIFT 3 is ongoing, motivated by the need to ensure that HSE's statutory advice is based on an up-to-date dispersion model.

In June 2025, ESR Technology released DRIFT 3.7.23, which incorporates a number of model enhancements. These include modifications to the grounded-jet model and to the transition from jet to wind-blown spreading, to better match experimental data. Changes have also been made to the transition between the elevated and grounded models, to better model ground-level concentrations under buoyant lift off.

Background

Under respective Planning (Hazardous Substances) Regulations 2015 for England, Wales and Scotland, 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. The outputs of these assessments are also used to set Land Use Planning (LUP) zones around major hazard sites. DRIFT 3 is used by HSE in this assessment process.

Objectives

To ensure that DRIFT 3 remains fit for purpose it is important to evaluate it for the types of release scenarios typically modelled by HSE for Hazardous Substances Consent assessments and to assess the effect of changes to the model on its predictions. This report describes the evaluation of DRIFT 3.7.23 against a Model Evaluation Protocol (MEP) designed specifically for DRIFT.

DRIFT Model Evaluation Protocol

The DRIFT MEP contains scientific assessment, verification, validation and a user-oriented assessment. It is based on the LNG (liquefied natural gas) protocol for dense gas dispersion models developed by HSE for the US National Fire Protection Association. In the DRIFT MEP, the scientific assessment has been broadened to cover buoyant lift off and buoyant rise, and other model capabilities relevant to HSE's regulatory work. The validation database has been expanded to include passive releases and a larger range of

release substances and release types. It includes releases of both toxic and flammable substances.

The protocol also includes the testing of DRIFT 3 against a set of exemplar scenarios, representative of the types of scenarios typically modelled by HSE for the purposes of Hazardous Substance Consent assessment. The exemplar scenarios have been used to test the impact on HSE's statutory advice of moving to a new version of DRIFT 3.

Findings

Users can interact with DRIFT 3.7.23 using either the GUI or the COM interface. The GUI is intuitive to use and includes an inbuilt user manual. The COM interface guide would benefit from being revised and expanded to provide more detailed guidance for HSE users. A large amount of output is available in graphical or tabular form via both the GUI and the COM interface. For all types of release, the DRIFT outputs include all the information required for regulatory purposes.

The physical, mathematical and numerical basis of DRIFT 3.7.23 has been reviewed, using information provided in reports and papers describing the DRIFT 3 mathematical model. DRIFT 3.7.23 was also assessed against a set of qualitative criteria, which have been chosen to provide a high-level summary of its capabilities. DRIFT 3.7.23 was found to satisfy all these criteria.

Evidence of verification has been obtained from the developer and documentation. The available evidence indicates that sufficient verification has been carried out by ESR Technology to give confidence that the equations in DRIFT 3.7.23 have been programmed correctly.

A database of experimental datasets has been compiled to test the performance of DRIFT across its range of capability. For each trial in the DRIFT validation database, the DRIFT 3.7.23 predictions for the concentration and cloud width were compared to the experimentally measured values. The performance of DRIFT 3.7.23 was assessed using the Statistical Performance Measures (SPM) and associated acceptance criteria recommended in the LNG protocol for dense gas dispersion models.

For the field-scale experiments in the DRIFT validation database, all five SPM are within the acceptability range for both concentration and cloud width data.

For the wind-tunnel scale experiments, DRIFT tends to underpredict the measured concentrations. Underprediction of wind-tunnel concentration measurements has also been observed for other models, including previous versions of DRIFT. However, all except one of the SPM for the wind-tunnel concentration data are within their acceptability ranges. All the SPM for the cloud width data for the wind-tunnel scale trials are within the acceptability criteria.

There are several features of the wind-tunnel trials that differ from the field-scale trials. These include lower Reynolds number source and bulk flows (i.e. conditions closer to

laminar flow), a lack of wind meandering in the wind-tunnel trials, idealised source conditions, and the presence of geometrical features in some of the wind-tunnel trials (such as roughness elements and obstacles). These features may explain the underprediction of wind-tunnel concentration measurements in DRIFT 3.7.23.

A database of exemplar scenarios has been assembled, to test the performance of DRIFT for the types of scenarios typically modelled for the purposes of Hazardous Substances Consent assessment. The DRIFT 3.7.23 outputs for these exemplar scenarios have been compared with the outputs from DRIFT 3.6.14, the version of DRIFT currently used by HSE for regulatory purposes.

For the majority of the scenarios modelled, there is good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs. In cases where there is a significant difference between the outputs of the two versions of DRIFT, the reason for the difference can be explained with reference to changes in the model physics. The model enhancements that have had the largest impact on the model outputs are the improvements to the wall jet modelling and the changes to the transition between the grounded and elevated models.

Conclusions

Based on the evaluation of DRIFT 3.7.23 against the DRIFT MEP, it is concluded that DRIFT 3.7.23 is fit for purpose and is suitable for use in HSE's regulatory work, including Hazardous Substances Consent assessments.

DRIFT 3.7.23 incorporates a significant number of enhancements and bug fixes, and is better able to model wall jets and buoyant lift off than DRIFT 3.6.14 and earlier versions of DRIFT.

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1 Introduction

The gas dispersion model DRIFT 3 (Dispersion of Releases Involving Flammables or Toxics) has been developed for the Health and Safety Executive (HSE) by ESR Technology (Tickle and Carlisle, 2008, 2015).

HSE uses DRIFT 3 in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazard sites. Under respective Planning (Hazardous Substances) Regulations 2015 for England, Wales and Scotland, 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 (MHCLG, 2019). The outputs of these assessments are also used to set Land Use Planning (LUP) zones around major hazard sites (HSE, 2025).

DRIFT 3.6.14 was adopted for use by HSE following an extensive evaluation and testing programme. It was evaluated in accordance with a dense gas Model Evaluation Protocol, including validation of the model using experimental data (Cruse and Coldrick, 2022). The testing programme also assessed the performance of DRIFT 3.6.14 for modelling the types of release scenarios typically considered by HSE for Hazardous Substances Consent assessments (Cruse and Coldrick, 2022; McGillivray and Cruse, 2022; Lamb and Cruse, 2022; Chaplin and Cruse, 2022). The scenarios examined included releases of toxic or flammable pressure-liquefied gases and dispersion of vapour from pools of toxic or flammable liquids.

The development of DRIFT 3 is ongoing, motivated by the need to ensure that HSE's advice is based on an up-to-date dispersion model. In June 2025, ESR Technology released DRIFT 3.7.23. The model enhancements that were implemented between DRIFT 3.6.14 and DRIFT 3.7.23 are described in Section 1.1 below.

To ensure that DRIFT 3 remains fit for purpose it is important to continue to validate it against experimental data and to assess the effect of changes to the model on its predictions for the types of release scenarios typically modelled by HSE for Hazardous Substances Consent assessments. Accordingly, this report has three primary objectives:

- To evaluate DRIFT 3.7.23 against an MEP designed specifically for DRIFT
- To validate DRIFT 3.7.23 against an extended set of validation test cases
- To assess the use of DRIFT 3.7.23 for modelling the types of release scenarios typically modelled by HSE for Hazardous Substances Consent assessments

1.1 Model enhancements in DRIFT 3.7.23

The DRIFT 3 mathematical model is described by Tickle and Carlisle (2015). A full scientific assessment was carried out on DRIFT 3.6.4 (Coldrick and Webber, 2017). Coldrick and Webber (2017) summarised the key aspects of the model as implemented in DRIFT 3.6.4 and concluded that the mathematical basis of the model was sound. In their assessment of DRIFT 3.6.14, Cruse and Coldrick (2022) reviewed the changes to the model that were implemented between DRIFT 3.6.4 and DRIFT 3.6.14.

Further model enhancements have been implemented between DRIFT 3.6.14 and DRIFT 3.7.23. The versions between DRIFT 3.6.14 and DRIFT 3.7.23 were interim versions that were not used by HSE for the purposes of Hazardous Substances Consent assessment. Changes and enhancements to the model that have been implemented since DRIFT 3.6.14 include:

- the inclusion of a pool re-evaporation option to add the concentration from a direct source to the concentration from an evaporating pool
- changes to the grounded-jet model to suppress initial spreading, for better agreement with the wall jet data of Davis and Winarto (1980) – this was achieved using empirical suppression functions for wall jet entrainment and lateral spread
- modifications to the transition from jet to wind-blown spreading and to the entrainment to better match the Desert Tortoise trials (Goldwire et al., 1985) and comparisons with other models
- a change to the interpolation between the elevated and grounded models, to better model ground-level concentrations under buoyant lift off
- changes to the elevated jet entrainment, to better match experimental data
- modifications to improve the modelling of jets in cross-flows, including suppression of the initial cross-flow entrainment and change to the constraints used for axisymmetry for elevated releases
- improvements to the initialisation of the thin 'pancake' cloud over an area source to rectify the unphysically large initial contour sizes sometimes observed for very short duration releases in earlier versions of DRIFT
- the inclusion of binary interaction parameters for the hydrogen peroxide-water system
- a switch to using a fit to the Tillner-Roth (Tillner-Roth and Friend, 1998) correlation for the ammonia-water interaction coefficients – the Tillner-Roth correlation is based on a wider set of conditions than the Wheatley correlation (Wheatley, 1987) that was used previously
- modifications to the vapour deposition model to include new user inputs of surface resistance and a fixed vapour deposition velocity
- the addition of atmospheric pressure as a model input – this parameter defaults to 101325 Pa
- the facility to specify parameters that change the atmospheric turbulence via the COM interface

1.2 DRIFT Model Evaluation Protocol

DRIFT 3.6.4 and DRIFT 3.6.14 were evaluated using the LNG (liquefied natural gas) protocol for dense gas dispersion models that was developed by Ivings et al. (2016). In their evaluation of DRIFT 3.6.4, Coldrick and Webber (2017) noted that DRIFT can model the dispersion of a wide range of gases and aerosols, so reviewing DRIFT using a protocol specific to LNG is not entirely appropriate. To address this concern, a DRIFT Model Evaluation Protocol has been developed (Cruse, Coldrick and Ivings, 2026), which has been designed to test the full range of DRIFT's capabilities.

The DRIFT Model Evaluation Protocol includes scientific assessment, verification, validation and a user-oriented assessment, following the approach recommended in the Framework for model evaluation in HSE (Coldrick, 2018). It is based on the LNG protocol for dense gas dispersion models developed by Ivings et al. (2016).

The scientific assessment has been broadened to cover buoyant lift off and buoyant rise, and other model capabilities relevant to HSE's regulatory work. The validation database has been expanded to include passive releases and a larger range of release substances and release types. It includes releases of both toxic and flammable substances.

The protocol also includes the testing of DRIFT 3 against an exemplar database. The exemplar scenarios are representative of the types of scenarios typically modelled by HSE for the purposes of Hazardous Substance Consent assessment. The exemplar scenarios will be used to test the impact on HSE's statutory advice of moving to a new version of DRIFT 3. The exemplar database contains a representative subset of the scenarios used to assess the performance of DRIFT 3.6.4 and DRIFT 3.6.14 (Cruse, Lamb and McGillivray, 2017; Cruse and Coldrick, 2022; McGillivray and Cruse, 2022; Lamb and Cruse, 2022; Chaplin and Cruse, 2022).

1.3 Structure of report

This report describes the evaluation of DRIFT 3.7.23 against the DRIFT Model Evaluation Protocol. The remainder of the report is structured as follows:

- Section 2 provides an overview of the scientific assessment of DRIFT 3.7.23 – the model questionnaire that was completed as part of the scientific assessment is reproduced in Appendix A
- Section 3 summarises the model verification that has been performed to date
- Section 4 describes the validation database and the evaluation of DRIFT 3.7.23 against the database
- Section 5 summarises the user-oriented assessment of DRIFT 3.7.23
- Section 6 describes the exemplar database and compares the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for the scenarios within the database
- The conclusions of this work are presented in Section 7

2 Scientific assessment

The aim of the scientific assessment is to demonstrate that the underlying mathematical model in DRIFT 3 has a sound scientific basis. The approach to scientific assessment is described in the DRIFT MEP (Cruse et al., 2026) and follows the approach adopted in the LNG MEP (Ivings et al., 2016).

2.1 Model questionnaire

The physical, mathematical and numerical basis of DRIFT 3.7.23 has been reviewed, using information provided in reports and papers describing the DRIFT 3 mathematical model. To facilitate this review, a specially designed questionnaire was completed. The questionnaire designed for the DRIFT MEP was derived from the questionnaires in the LNG Model Evaluation Protocol (Appendix B of Ivings et al., 2016) and the SMEDIS Model Evaluation Protocol, Version 2.0 (7 December 2000) (Carissimo et al., 2001; Daish et al., 2000).

Previous versions of DRIFT were assessed against the LNG MEP questionnaire (Ivings et al., 2007, 2016). Additional questions have been included in the DRIFT MEP questionnaire to fully assess DRIFT's capability to model the dispersion of a wide range of gases and aerosols. Topics covered by the additional questions include:

- Buoyant lift off and buoyant rise
- Deposition
- Re-evaporation
- Interactions with moist air

Further modifications have been made to the questionnaire to enable DRIFT's use for regulatory purposes to be assessed. The DRIFT MEP questionnaire facilitates the collection of more detailed information on the following topics:

- Concentration-related output (with a particular focus on dose calculations)
- Substance property databases

2.2 Qualitative assessment criteria

DRIFT 3.7.23 was also assessed against a set of qualitative criteria, which have been chosen to provide a high-level summary of its capabilities. To pass the model evaluation, DRIFT 3.7.23 must satisfy each of the criteria.

The criteria given in the LNG MEP (Ivings et al., 2016) have been adopted for use in the DRIFT MEP, with some modifications. These criteria have been supplemented by new criteria, which are needed to reflect the wider scope of the DRIFT 3 assessment (in terms

of the range of substances and source terms that need to be considered) and the way in which the DRIFT 3 model is used for regulatory purposes.

The qualitative assessment criteria that are considered in the DRIFT MEP are given below. They are divided into two groups: scientific criteria and input and output criteria. Criteria that are new or have been significantly modified from the criteria in the LNG MEP are marked with asterisks.

Scientific criteria

- Key details of the model available for scientific assessment
- Model based on accepted/published science
- Model accepts a credible source term, including pool sources (low-momentum area), jet sources (vapour and two-phase) and instantaneous sources (vapour and two-phase)*
- Model accounts for the effects of wind speed
- Model accounts for the effects of humidity*
- Model accounts for the effects of surface roughness
- Model accounts for the effects of atmospheric stability
- Model accounts for passive dispersion
- Model accounts for gravity-driven spreading
- Model accounts for the effects of buoyancy on dilution
- Model accounts for buoyant lift off and buoyant rise*
- Numerical methods are based on accepted/published good practice

Input and output criteria

- Model produces output suitable for assessment against MEP statistical performance measures
- Model can access data from HSE's SPI (Substance Property Information) files*
- Model can calculate the dose received by outdoor and indoor recipients*
- Model can calculate dose isopleths*
- Model exports data in a format suitable for use in HSE's risk calculation model*
- Model can be run in batch mode (through the COM interface)*

2.3 Outcome of DRIFT 3.7.23 scientific assessment

The completed model questionnaire is reproduced in full in Appendix A. DRIFT 3.7.23 was found to satisfy all the qualitative assessment criteria.

2.4 Evaluation of key scientific changes

A number of scientific enhancements have been implemented in DRIFT 3.7.23. These represent continuous improvement of the model.

The scientific assessment presented in Appendix A does not provide individual commentary on each enhancement. Where applicable, improvements to DRIFT have been tested by the model developer and shown to give improved performance (Tickle, 2025a,b,c).

This section describes the most significant scientific changes to the model in more detail and summarises the testing of these changes that has been carried out by the model developer.

2.4.1 Wall jets

DRIFT 3.7.23 includes changes to the wall-jet entrainment and spreading models, for better agreement with the wall jet data of Davis and Winarto (1980). A full description of these changes is given in Tickle (2025c).

In DRIFT, wall jet entrainment includes contributions from both top entrainment and edge entrainment of ambient air. DRIFT 3.7.23 includes modifications to the parametrisation of both top and edge entrainment. These modifications better account for the effects of the zone of flow establishment and the transition from momentum jet to gravity dominated or passive dispersion, whilst accounting for the suppression of vertical mixing for a stably stratified dense cloud or enhancement of vertical mixing for a buoyant cloud.

Tickle (2025c) presents comparisons of DRIFT 3.6.14, DRIFT 3.7.19 and DRIFT 3.7.22 with the wall jet data of Davis and Winarto (1980) and demonstrates that the wall jet model implemented in DRIFT 3.7.22 provides the best match to the behaviour observed experimentally. Tickle (2025c) also notes that DRIFT's broad agreement with the centreline velocity decay data of Rajaratnam (1976) is maintained in DRIFT 3.7.22.

No further changes to wall jet modelling have been implemented between DRIFT 3.7.22 and DRIFT 3.7.23, so these conclusions are also expected to apply to DRIFT 3.7.23.

2.4.2 Transition from wall jet to passive spreading

DRIFT 3.7.23 includes modifications to the transition from jet to passive spreading to better match the Desert Tortoise trials (Goldwire et al., 1985) and comparisons with other models. A detailed description of these changes is given in Tickle (2025c).

Versions of DRIFT prior to DRIFT 3.7.15 could retain the wall jet spreading rate far downstream, to a point where the cloud had slowed down to close to the wind speed and could no longer be considered to behave as a momentum jet. This was mainly an issue for very large release rates and could result in too wide a cloud and thus too much mixing and dilution, due to the large top surface area of the cloud.

ESR Technology investigated different options for addressing this issue, which are described in Tickle (2025a,b,c). The approach adopted in DRIFT 3.7.22 and DRIFT 3.7.23 is for the transition from linear wall jet spreading to passive spreading to occur when the entrainment rate of air into the plume is no longer dominated by jet entrainment.

Tickle (2025c) presents comparisons of DRIFT 3.7.19 and DRIFT 3.7.22 with the Desert Tortoise trials (Goldwire et al., 1985). The transition from wall jet to passive spreading implemented in DRIFT 3.7.22 gives better agreement with the experimental data than the approach adopted in DRIFT 3.7.19.

2.4.3 Buoyant lift off

DRIFT 3.7.23 incorporates a change to the interpolation parameter controlling the transition between the elevated and grounded models, to better model ground-level concentrations under buoyant lift off. The interpolation parameter has been tuned to optimise plume lift-off predictions using wind-tunnel data on buoyant area sources (Hall and Walker, 2000).

Tickle (2025a) presents a comparison of DRIFT 3.6.15 and DRIFT 3.7.19 with the buoyant plume experiments of Hall and Walker (2000) and the buoyant puff experiments of Hall, Walker and Tily (2001). Tickle (2025a) concluded that the retuning in DRIFT 3.7.19 had led to an overall improvement in the agreement with the plume data, but that there was little change for the puff predictions.

No further changes to the interpolation parameter have been implemented between DRIFT 3.7.19 and DRIFT 3.7.23, so these conclusions also apply to DRIFT 3.7.23.

2.4.4 Elevated free jets

DRIFT 3.7.23 includes an empirical delay to the centreline concentration decay of elevated momentum jet releases, to account for the zone of flow establishment. This is based on the data of Forstall and Shapiro (1950).

Tickle (2025c) presents a comparison of the DRIFT 3.7.22 concentration predictions and the data of Forstall and Shapiro for jets of air in a coflowing stream of air. There is good agreement between the experimentally measured decay in the centreline concentration and the model predictions.

No further changes to the modelling of elevated free jets have been implemented between DRIFT 3.7.22 and DRIFT 3.7.23, so these conclusions also apply to DRIFT 3.7.23.

2.5 Limits of applicability

2.5.1 Sources

The source must correspond to either a heavy, passive or buoyant gas, aerosol cloud or momentum jet. It may be instantaneous, continuous, finite duration, or time varying. Low-momentum area sources must be ground based. Pools, jet sources and flashing instantaneous releases are routinely considered within DRIFT.

DRIFT can model the dispersion of a gas or aerosol cloud consisting of a mixture of contaminant gas, contaminant liquid, dry air, water vapour and water liquid. Any appropriate temperature may be input. The thermodynamic effects of vaporisation and

condensation are included. However, DRIFT does not model the region of expansion from liquid storage to a vapour cloud containing solids, such as is observed for CO_2 releases.

DRIFT does not directly model chemical reactions. However, for ammonia, hydrogen fluoride and hydrogen peroxide dispersing in moist air, DRIFT accounts for the heat of mixing and the non-ideality of the solution. Oligomerisation is considered for hydrogen fluoride.

2.5.2 Environments

DRIFT accounts for the wind speed and atmospheric stability in its calculations. The minimum wind speed that can be input in the GUI is 0.1 m/s.

The primary parameters are friction velocity, roughness length and Monin-Obukhov length. The Monin-Obukhov length can be input directly or estimated internally within DRIFT from Pasquill or Holtslag schemes.

DRIFT can only model flat terrain, although multiple buildings and fences can be modelled. Any buildings or fences are assumed to be cuboidal or rectangular. There is no requirement to model obstacles or complex terrain for regulatory purposes, as relevant information on the site layout is rarely available.

2.5.3 Targets/output

A large amount of output is available in graphical or tabular form.

3 Verification

Verification is the process of checking that the computer implementation of a model matches its mathematical basis. Under the MEP of Ivings et al. (2016) verification is treated passively as part of the scientific assessment, rather than as a separate exercise. This approach has also been adopted in the DRIFT MEP (Cruse et al., 2026). Therefore, evidence of verification is obtained from the developer and documentation and is recorded in the model evaluation report.

3.1 Verification undertaken

DRIFT makes use of established and thoroughly tested third party software libraries and numerical solvers. The model developers therefore consider that verification of the specific solutions of DRIFT is in general sufficient to ensure that the equations themselves are programmed correctly (Coldrick and Webber, 2017).

3.1.1 DRIFT 2.31

Verification of DRIFT 2.31 is discussed in detail by Jones et al. (1993). The method used consisted of:

- examination of graphs of a large number of variables plotted against one another to check that the results were ‘qualitatively sensible’
- deeper follow-up tests where results were unexpected

These tests included comparisons of model outputs with approximate analytical solutions, including:

- the expected increase of the top area of an instantaneously released cloud with time
- the downwind advection velocity
- the asymptotic power law decrease of concentration
- the integrated thermodynamic balance in the cloud
- the behaviour of height and width in continuous releases with momentum

DRIFT 2.31 was developed by AEA Technology (ESR Technology was later formed from the engineering, safety and risk business of AEA Technology). DRIFT 2.31 was developed according to the Model Evaluation Group (MEG) guidelines (MEG, 1994a,b). The development of DRIFT 2 predated AEA Technology’s certification to ISO 9000. However, software verification (as defined by the MEG) was an important element in its development.

3.1.2 DRIFT 3.6

DRIFT 3.6 was developed by ESR Technology, which operates a Quality Management System that complies with the requirements of ISO 9001:2015.

Verification of DRIFT 3.6 is discussed in Tickle (2012) and Tickle, Godaliyadde and Carlisle (2012). Tickle (2012) gives a comparison of DRIFT 3.6.1 against DRIFT 2.31 and several experimental datasets. This is presented as a verification check that the models broadly agree where expected. DRIFT 3 is a complete reprogramming of the DRIFT model, but the comparison to a previous version of the model that has undergone verification provides additional assurance that DRIFT 3 is programmed correctly.

Tickle et al. (2012) cover two aspects: the lift off of buoyant puffs in low wind and thermodynamic modelling of HF-isobutane mixtures. DRIFT's buoyant puff rise model is based on that of Turner (1973) and comparison with an analytical solution to Turner's model is used to verify DRIFT's computer implementation. Tickle et al. (2012) demonstrate that DRIFT 3.6.1 predictions for HF mixtures are in agreement with a thermodynamic model for HF mixtures.

In their evaluation of DRIFT 3.6.4, Coldrick and Webber (2017) noted that the instantaneous and continuous release modules share a lot of common code, so DRIFT's verification in one scenario carries over to the other. They concluded that sufficient verification of DRIFT 3.6 was carried out to give confidence that the equations had been programmed correctly.

3.1.3 DRIFT 3.7

DRIFT 3.7 was developed by ESR Technology, which operates a Quality Management System that complies with the requirements of ISO 9001:2015.

Verification of DRIFT 3.7.19, DRIFT 3.7.21 and DRIFT 3.7.22 is discussed in a series of reports by Tickle (2025a,b,c). In these reports, Tickle describes the physics underpinning the most significant scientific changes to be implemented in DRIFT 3.7. These changes are summarised in Section 2.4 and include improvements to the modelling of momentum jets, the transition from momentum jet spreading to passive spreading and buoyant lift off. For each model enhancement, Tickle presents comparisons of DRIFT 3.7 with previous versions of DRIFT and relevant experimental data, providing assurance that the modification has been implemented correctly.

No significant changes to DRIFT's mathematical model have been implemented between DRIFT 3.7.22 and DRIFT 3.7.23, so the verification testing documented by Tickle (2025a,b,c) is also applicable to DRIFT 3.7.23.

3.2 Conclusions

The evidence presented in Tickle (2025a,b,c) indicates that sufficient verification has been carried out by ESR Technology to give confidence that the equations in DRIFT 3.7.23 have been programmed correctly.

4 Validation

Ivings et al. (2013) define validation as *'the process of showing that the model reproduces measurements of physical parameters, such as concentration, to satisfactory accuracy and across its claimed range of applicability, i.e. represents the "real world".'*

For each new version of DRIFT, it is important that HSE is able to carry out model validation that is independent of the validation undertaken by the model developers. To achieve this aim, a database of experimental datasets has been assembled. The validation test cases in the database have been run in DRIFT 3.7.23, and the model outputs have been compared to the experimental data.

The starting point for the DRIFT validation database was the database created for the LNG protocol for dense gas dispersion models (Stewart et al., 2016). The LNG database is necessarily focused on dense gas releases, and the majority of the experimental data relates to releases from pools or area sources. To better represent the full range of releases that DRIFT can model, the DRIFT validation database has been expanded to include passive releases and a larger range of release substances and release types. It includes releases of both toxic and flammable substances.

4.1 DRIFT validation database

The following subsections summarise the release scenarios and data sources used in the DRIFT validation database.

4.1.1 Liquefied Natural Gas (LNG) database

The LNG Model Evaluation Protocol (MEP) of Ivings et al. (2007) sets out a process by which LNG dispersion models can be assessed. The MEP was funded by the Fire Protection Research Foundation (FPRF) of the National Fire Protection Association (NFPA) and the work was carried out by HSE. Validation against experimental data was identified as a critical part of this process. Following the publication of Ivings et al. (2007), a database of experimental data was curated to feed into the MEP process (*LNG Model Validation Database, Version 11.0,* Coldrick, Lea and Ivings, 2010).

In 2016 the MEP process was reviewed, resulting in an update to the Model Evaluation Protocol (Ivings et al., 2016) and the publication of an updated model validation database (*LNG Model Validation Database, Version 12,* Stewart et al., 2016). An update to the database was motivated by several factors. No new experimental datasets were added, but more data was provided for existing experiments. Additionally, the updated database includes changes to model input data. For example, a number of issues were identified with the specification of the BA-Hamburg trials in Version 11 of the database. After consultation with researchers who took part in the original work, corrections were incorporated into Version 12 of the database. Further details are provided in Stewart et al. (2016), as well as in subsequent sections of this report.

The LNG database contains data from eight experimental campaigns. The Maplin Sands, Burro, Coyote and Falcon field trials all studied releases of LNG onto water. The Thorney Island field trials consisted of vapour releases of Freon-12/nitrogen mixtures. The CHRC, BA-Hamburg and BA-TNO wind-tunnel experiments studied continuous releases from area vapour sources.

The LNG database contains 33 individual trials, 27 of which have been included in the DRIFT validation database. As noted by Coldrick and Webber (2017), DRIFT is intended for modelling releases over flat terrain and with simple obstructions such as fences and buildings. Many of the test cases in the LNG database can be simplified to fit in with these capabilities without introducing excessive approximations and assumptions. However, some of the test cases are outside the scope of DRIFT, so have not been included in the DRIFT validation database. All of the omitted test cases are from wind-tunnel experiments: four BA-Hamburg releases onto sloping terrain; and two BA-TNO datasets with off-axis sensors.

DRIFT 3.6.4 and DRIFT 3.6.14 were validated against Version 11 of the LNG database (Coldrick and Webber, 2017; Cruse and Coldrick, 2022). DRIFT 3.7.23 has been validated against the revised Version 12 database. Version 12 of the database contains changes to both model input data and experimental measurements, so caution is required when comparing the performance of different versions of DRIFT against the LNG database.

4.1.2 Passive releases

Coldrick and Webber (2017) identified the Hanford (Nickola, Ramsdell and Ludwick, 1970) and Prairie Grass (Barad, 1958) trials as suitable datasets against which to validate DRIFT's passive dispersion capabilities. DRIFT 3.6.4 and DRIFT 3.6.14 were validated against these datasets (Coldrick and Webber, 2017; Cruse and Coldrick, 2022), but this validation was not a formal part of the Model Evaluation Protocol and was not recorded in the Model Evaluation Report.

Selected trials from the Hanford and Prairie Grass datasets have now been included in the DRIFT validation database. The Hanford trials included in the DRIFT validation database are field-scale continuous releases of the radioactive tracer krypton-85. The Prairie Grass field trials are 10-minute continuous releases of sulphur dioxide (SO_2) from a low-level source.

4.1.3 Additional data sources

Additional experimental datasets have been identified to expand the range of release substances and release types in the DRIFT validation database.

The substances covered by the additional datasets are:

- ammonia (Desert Tortoise (Goldwire et al., 1985) and FLADIS (Nielson and Ott, 1996a))
- carbon dioxide (CO2PIPETRANS (Witlox, 2012))
- chlorine (Jack Rabbit II (Mazzola et al., 2021))

- hydrogen fluoride (Goldfish (Blewitt et al., 1987) and URAHFREP (Porter and Nussey, 2001))

As noted previously, the LNG database consists mainly of low-momentum releases from area sources. The wind-tunnel trials in the database are continuous, but the release rates are so low (of the order of 0.001 kg/s) that they cannot be considered to be jets. This gap is addressed by the inclusion of the CO2PIPETRANS, Desert Tortoise, FLADIS, Goldfish and URAHFREP trials, which were all jet releases.

The addition of the URAHFREP and Goldfish hydrogen fluoride (HF) trials expands the DRIFT validation database to include field-scale releases involving HF thermodynamics. It should be noted, however, that ESR Technology tested DRIFT against the URAHFREP data during development, so a comparison of DRIFT with the URAHFREP data does not constitute fully independent validation.

HF and ammonia are both hygroscopic, so these test cases could be used to evaluate the way in which reactions with water are incorporated in DRIFT, and to check how sensitive the model outputs are to the humidity.

4.1.4 Summary of the experimental trials in the DRIFT MEP validation database

A summary of the experimental trials included in the DRIFT MEP validation database, at both field and wind-tunnel scale, is presented in Table 1. The database includes 13 experimental campaigns at field scale and three at wind-tunnel scale.

Table 1 Summary of the field and wind-tunnel experiments included in the current DRIFT MEP validation database.

Trial	Substance	Experimental scale	Cases included in DRIFT MEP validation database
BA-Hamburg (1991) Nielson and Ott (1996a)	Sulphur hexafluoride (SF_6)	Wind tunnel	DA0120, DAT223 (unobstructed) 039051, 039072 (upwind fence) DA0501, DA0532 (downwind fence) 039094, 039097 (circular fence)
BA-TNO (1991) Nielson and Ott (1996a)	Sulphur hexafluoride	Wind tunnel	FLS – 3D mapping
CHRC (2006) Havens and Spicer (2005, 2006); Havens, Spicer and Sheppard (2007)	Carbon dioxide (CO_2)	Wind tunnel	A (without obstacles) B (with storage tank and dike) C (with dike)

Trial	Substance	Experimental scale	Cases included in DRIFT MEP validation database
Maplin Sands (1980) Puttock, Blackmore and Colenbrander (1982); Colenbrander, Evans and Puttock (1984a,b,c)	LNG	Field	27, 34, 35 (all dispersion over sea)
Burro (1980) Koopman et al. (1982a,b)	LNG	Field	3, 7, 8, 9
Coyote (1981) Goldwire et al. (1983)	LNG	Field	3, 5, 6
Falcon (1987) Brown et al. (1990)	LNG	Field	1, 3, 4 (all with a vapour barrier fence)
Thorney Island (1982-1984) McQuaid and Roebuck (1985); McQuaid (1987)	Freon-12 / nitrogen mixture	Field	45, 47 (both continuous)
Jack Rabbit II[+] (2015-2016) Mazzola et al. (2021)	Chlorine	Field	1, 6, 7
CO2PIPETRANS[+] (2011) Witlox (2012)	Carbon dioxide	Field	1, 2, 3, 5, 6, 11 (liquid, cold releases) 8, 8R, 9 (vapour, supercritical releases)
Hanford[+] (1967) Nickola et al. (1970)	Tracer (Krypton-85)	Field	1, 2, 3, 4, 5
Prairie Grass[+] (1956) Barad (1958)	Sulphur dioxide (SO_2)	Field	9, 10, 32, 33, 36
Desert Tortoise[+] (1983) Goldwire et al. (1985)	Ammonia (NH_3)	Field	1, 2, 3, 4
FLADIS[+] (1993-1994) Nielson and Ott (1996b)	Ammonia	Field	9, 16, 24
Goldfish[+] (1986) Blewitt et al. (1987)	Hydrogen fluoride (HF)	Field	1, 2, 3
URAHFREP[+] (1997-2001) Porter and Nussey (2001)	Hydrogen fluoride	Field	7, 9, 10, 12

[+] Not included in Version 12 of the LNG database (Stewart et al., 2016).

4.2 Physical comparison parameters

The parameters used to compare the model predictions with the experimentally measured data are referred to as physical comparison parameters. In the DRIFT MEP, the physical comparison parameters used in the validation of previous versions of DRIFT (Coldrick and Webber, 2017; Cruse and Coldrick, 2022) and recommended by Ivings et al. (2007) have been adopted:

- Maximum concentration across an arc at radius/distance x from the source
- Cloud width across an arc at radius/distance x from the source

Detailed information about these physical comparison parameters and their derivation can be found in Ivings et al. (2016).

4.2.1 Calculation of the maximum concentration

The maximum concentration across each arc is derived from the concentration data recorded during the trial. Each concentration sensor records the time-varying concentration at a particular location over the duration of the release, which must then be converted into a steady-state representation of the cloud.

For some of the datasets in the LNG database, concentration values are provided for two averaging times. A short averaging time (typically 1 s) gives the peak instantaneous concentration value, and a long averaging time (often of the order of 100 s) gives the peak averaged concentration value for the release duration. Both sets of concentration values have been included in this validation exercise where available.

For the Burro and Coyote trials, the LNG database (Stewart et al., 2016) presents averaged concentration data calculated using two different methodologies: (i) a fixed averaging-time window, similar to that used in Version 11 of the LNG database and Hanna, Strimaitis and Chang (1993b); (ii) a rolling average. For all other trials in the LNG database, only the concentrations calculated using the fixed averaging-time window are provided. For consistency, the concentrations calculated using the fixed averaging-time window were used in this analysis for all trials.

For the passive datasets, concentration data is taken from Modelers' Data Archive (Hanna et al., 1993b) which reports only the maximum concentration at a given downwind distance.

In DRIFT, plume meander is a function of the averaging time. Meander takes into account lateral spreading of the cloud due to transient wind direction, commonly encountered in field-scale trails. For wind tunnel experiments with a controlled and conditioned inflow, meander is expected to be negligible. Therefore, when DRIFT is run against wind tunnel experiments, the averaging time is set to 1 s because the plume meander model is not applicable. For the field trials, the averaging time in DRIFT is chosen to match the averaging time of the experimentally measured concentration values.

4.2.2 Calculation of the cloud width

Following the approach of Ivings et al. (2016), the cloud width across an arc was calculated using a formula derived from the standard deviation of a frequency distribution (Pasquill and Smith, 1983):

$$\sigma_y^2 = \frac{\sum Cy^2}{\sum C} - \left[\frac{\sum Cy}{\sum C}\right]^2$$

where σ_y is the cloud width, C is the concentration recorded at each sensor and y is its crosswind displacement.

Cloud widths have not been calculated for trials in which the cloud was bifurcated or badly aligned with the sensor array. Cloud width data is not available for the BA Hamburg wind-tunnel experiments in which there was only one sensor at each downwind distance.

For most of the datasets in the DRIFT validation database, only cloud widths calculated using the long-time averaged concentrations are available. However, for the FLADIS experiments, Nielson and Ott (1996b) present cloud widths calculated using both the short-time averaged and long-time averaged concentrations. Both sets of FLADIS cloud width data have been used in this validation exercise.

4.3 Validation of DRIFT 3.7.23 against the DRIFT validation database

4.3.1 BA-Hamburg

The BA-Hamburg wind-tunnel trials of sulphur hexafluoride (SF_6) were conducted in the open circuit wind tunnel at the Meteorological Institute at the University of Hamburg in Germany. Details of the experiments, including data, can be found in Schatzmann, Marotzke and Donat (1991), Marotzke (1993), and in the REDIPHEM database (Nielsen and Ott, 1996a). The experiments studied both continuous and instantaneous releases into a boundary-layer shear flow with obstacles. However, only continuous releases are considered in this validation exercise. Gas was injected through the tunnel floor with a circular source of diameter 0.07 m. A circular cap was placed approximately 0.05 m above the orifice to generate a radial flow. Schematics of the various geometries can be found in Nielsen and Ott (1996a) and are reproduced in Figure 1 for the cases included in the DRIFT validation database.

Stewart et al. (2016) highlighted a number of inconsistencies in Version 11 of the LNG database relating to: (i) the geometry of the obstructions; (ii) the characteristic length scale; (iii) the sensor locations; (iv) the source and ambient temperatures; and (v) the surface roughness height. These inconsistencies were corrected in Version 12 of the database. Stewart et al. (2016) processed the REDIPHEM data of Nielsen and Ott (1996a) by time averaging the concentration data over the maximum duration available in the dataset once a steady-state condition had been reached.

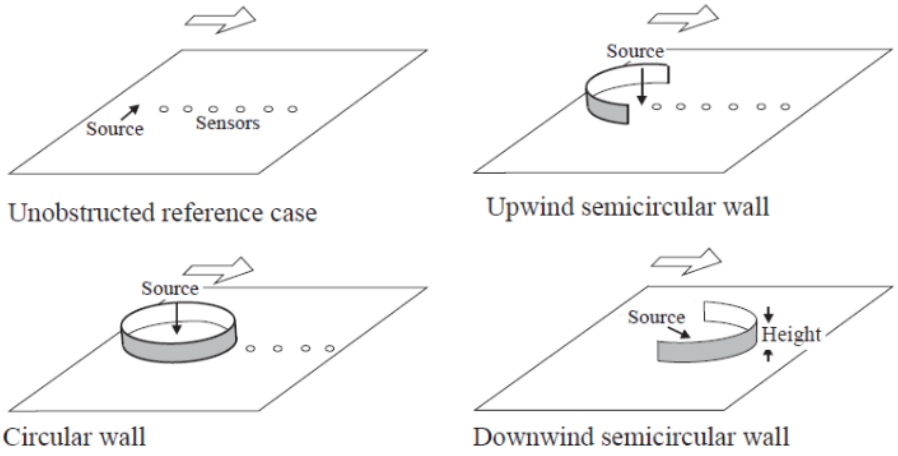


Figure 1 Schematic of the chosen trials from the BA-Hamburg experiments. Taken from Nielsen and Ott (1996a).

Dimensions and locations of all Hamburg trial obstructions are provided in Stewart et al. (2016). DRIFT 3.7.23 includes a fence obstruction model which is described in Webber et al. (1994). In brief, DRIFT takes the following parameters as input for the fence model: (i) height; (ii) downwind location; (iii) length. Each fence is assumed to be straight, therefore the downwind semicircular wall is represented in DRIFT as a straight fence with the same height, and a length equal to the diameter. Upwind fences have no effect in DRIFT; therefore, the upwind semicircular wall trial is effectively modelled as unobstructed. The circular wall trial can be modelled with an arrangement of fences, but here the method of Coldrick and Webber (2017) is followed. The cloud is assumed to expand and fill the circular wall, creating a low-momentum source with a diameter constrained by the wall. In the experiment the circular wall has height 30.1 mm, but DRIFT 3.7.23 is not able to model an elevated low-momentum area source.

Following Coldrick and Webber (2017) and Cruse and Coldrick (2022), dilution over the source is activated in the DRIFT model.

Figure 2 presents a comparison of the DRIFT 3.7.23 concentration predictions with the BA-Hamburg experimental data. In the first BA-Hamburg unobstructed trial, DRIFT underpredicts concentrations by approximately a factor of 2. This may be due to increased dilution over the source from the model, although the predictions for the second unobstructed trial look reasonable.

For the upwind wall cases, the DRIFT 3.7.23 predictions and the experimental data are in close agreement, despite the fact that the upwind semicircular wall is not modelled in DRIFT.

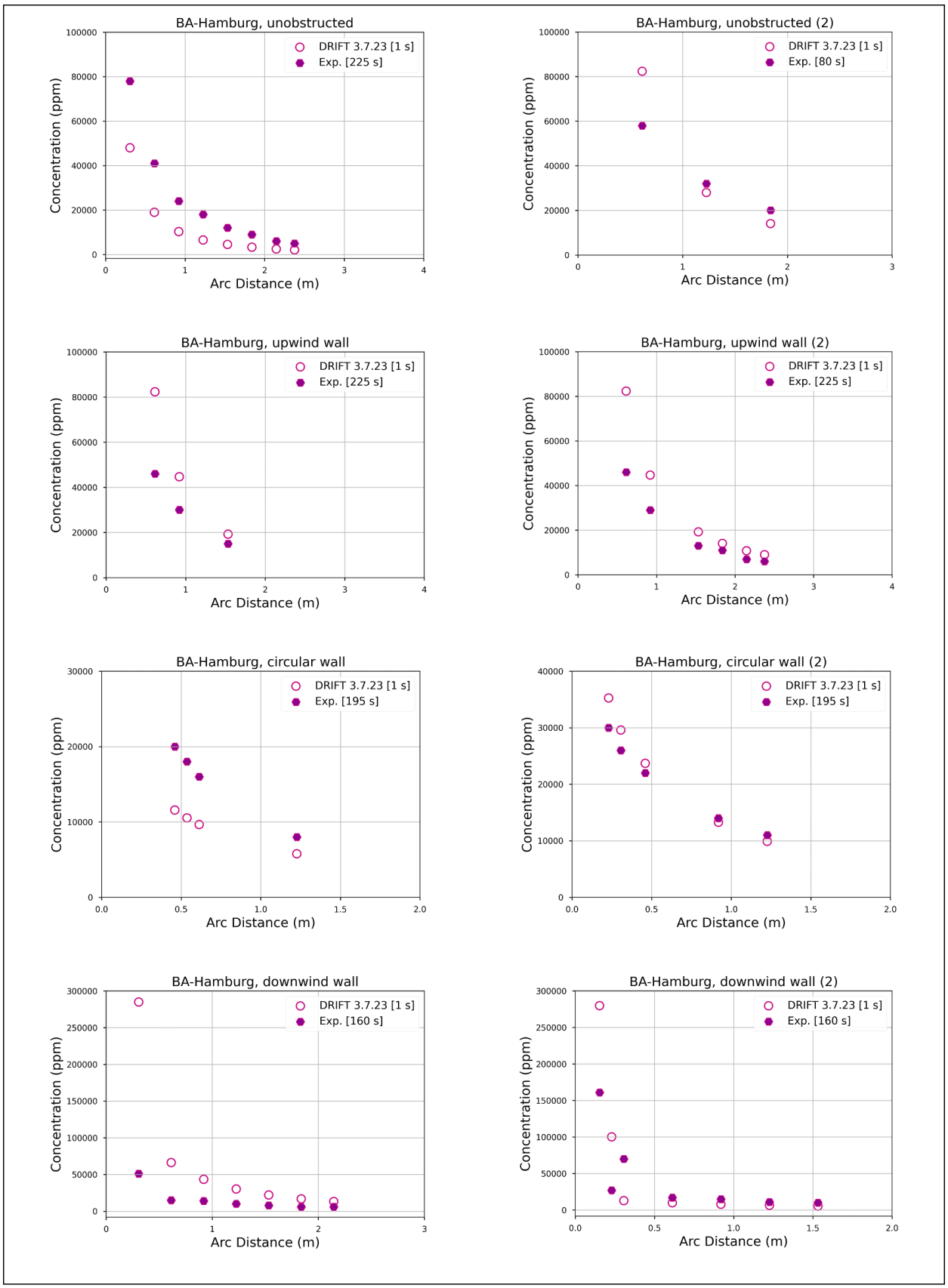


Figure 2 Observed and predicted maximum arcwise concentration data for BA-Hamburg wind-tunnel trials. Square brackets indicate averaging time.

For the trials where the source is surrounded by a circular wall, the experimental set-up is different from what is modelled in DRIFT. Instead of a circular bund which gradually fills

with vapour, likely entraining ambient air in the process until it reaches the top of the bund and begins to spill over, DRIFT represents this as a low-momentum area source with diameter equal to that of the circular wall. The agreement between the DRIFT 3.7.23 predictions and the measured concentrations is much better for the second circular wall trial than for the first circular wall trial. Figure 3 presents scale drawings of both trials. Poor agreement between the measured and predicted concentrations for the first circular wall trial could be due to the size difference between the 70 mm source and the circular wall.

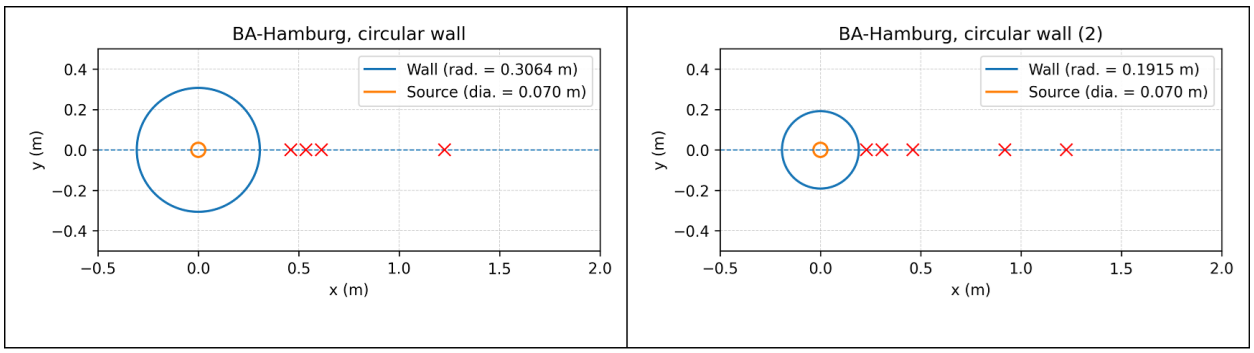


Figure 3 Scale drawings of the two circular wall geometries from the BA-Hamburg trials. Sensor locations are marked with a red cross.

In the first downwind wall experimental trial, the wall extends to 0.3064 m in the downwind direction. The first sensor is located on the tunnel floor at 0.3065 m, which is therefore directly behind the wall. DRIFT overpredicts concentrations at this position by a factor of more than 5, but given the sensor location relative to the obstruction, this will clearly be a challenge for the DRIFT fence model.

4.3.2 BA-TNO

The TNO-FLS experiment sits within the BA-TNO series of wind-tunnel studies, as summarised by Nielsen and Ott (1996a).

Compared to other experiments undertaken in the series, the single TNO-FLS trial had a greater coverage of sensors in the downwind, crosswind and vertical directions. In addition, it was unobstructed. This allowed three-dimensional mapping of concentrations, capturing cloud width and height. Sulphur hexafluoride (SF_6) gas was released from a floor-level source of diameter 0.107 m at a release rate of 1.045 g/s for 1000 s. The motivation for this experiment was to provide reference data for development and validation of a digital image processing (DIP) measurement technique.

Figure 4 presents a comparison of the DRIFT 3.7.23 predictions and the measured concentrations for the FLS trial. Concentration at the closest arc to the source (0.64 m) is underpredicted in the model by roughly a factor of 2.5. At this arc, the cloud width reported in the experiment is 0.18 m, while DRIFT predicts a narrower cloud of width 0.12 m. Stewart et al. (2016) report model studies where underprediction of the FLS data is seen, and this has also been observed in previous validation studies of DRIFT (Coldrick and Webber, 2017; Cruse and Coldrick, 2022).

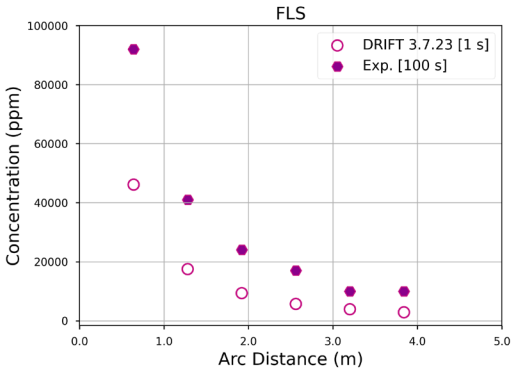


Figure 4 Observed and predicted maximum arcwise concentration data for BA-TNO FLS. Square brackets indicate averaging time.

4.3.3 CHRC

A number of dense gas dispersion tests have been conducted in the Chemical Hazards Research Center (CHRC) ultra-low-speed wind tunnel at the University of Arkansas. Havens and Spicer (2006) investigated low momentum CO_2 dispersion with tank and dike obstructions near the source. Three cases were considered: (A) no obstacles; (B) dike surrounding a storage tank; (C) dike only. Tests were carried out at a scale of 150 to 1 (field to wind-tunnel scale). Havens and Spicer (2006) describe the A, B and C trials in more detail, but a summary of the trials used for this validation exercise is provided in Table 2.

Table 2 Summary of the CHRC trials and DRIFT modelling assumptions.

Trial	Description	DRIFT modelling assumptions
A	CO_2 release, area vapour source without obstacles	CO_2 release, low-momentum area source with no obstacles
B	CO_2 release, area vapour source with a tank and a dike	CO_2 release, low-momentum area source with a fence and a building
C	CO_2 release, area vapour source with a dike only	CO_2 release, low-momentum area source with a fence positioned downwind from the source

Their 2006 study extended previous wind-tunnel experiments (Havens and Spicer, 2003), in which a smooth wind-tunnel floor was used. A staggered array of uniform roughness elements was placed on the wind-tunnel floor to generate turbulence properties and a boundary layer comparable, upon scaling, to field-scale wind conditions. Each roughness element was approximately 38 mm in height. Concentration data was recorded at a height of 5 mm, as close to the floor as possible. Sensors were therefore placed within the roughness elements, and this altered lateral profiles of concentration which displayed peaks and troughs depending on the location of sensors within the array. Plume visualisation snapshots, included in Havens and Spicer (2006), suggest that the flow may be partially channelled through gaps. A roughness length can be input into DRIFT which alters the approach flow, suitable for an array of roughness elements in the flow

conditioning section of a wind tunnel. However, DRIFT does not directly resolve the roughness elements surrounding a release.

Mean velocity and concentrations were measured in the lateral and vertical directions. Asymmetries in the lateral profiles of concentration were observed and believed to be due to a slight slope in the wind-tunnel floor. The authors noted that the wind-tunnel floor was levelled to a tolerance of 0.254 mm during construction.

The tank (trial B) led to greater dilution of the gas cloud and therefore lower concentrations when compared to the 'no-obstacles' case (trial A). However, this trend was not observed with the dike (trial C). It was found that suppressed gravity spreading near to the source as a result of the dike led to concentrations similar to the unobstructed case of trial A.

A low-momentum area source is modelled to represent the area vapour source of the experiments. To account for obstacles, DRIFT has sub-models for buildings and fences. This process is described in Webber et al. (1994) and Coldrick and Webber (2017). The modelling assumptions used in DRIFT are summarised in Table 2.

Figure 5 presents a comparison of the DRIFT predictions with the CHRC experimental data. In trial A, DRIFT 3.7.23 significantly underpredicts concentrations near to the source (<1 m). The same behaviour was observed for DRIFT 3.6.4 (Coldrick and Webber, 2017). Coldrick and Webber (2017) suggest underprediction may be caused by DRIFT over-diluting the source. A similar trend of underprediction near the source is also observed for trials B and C.

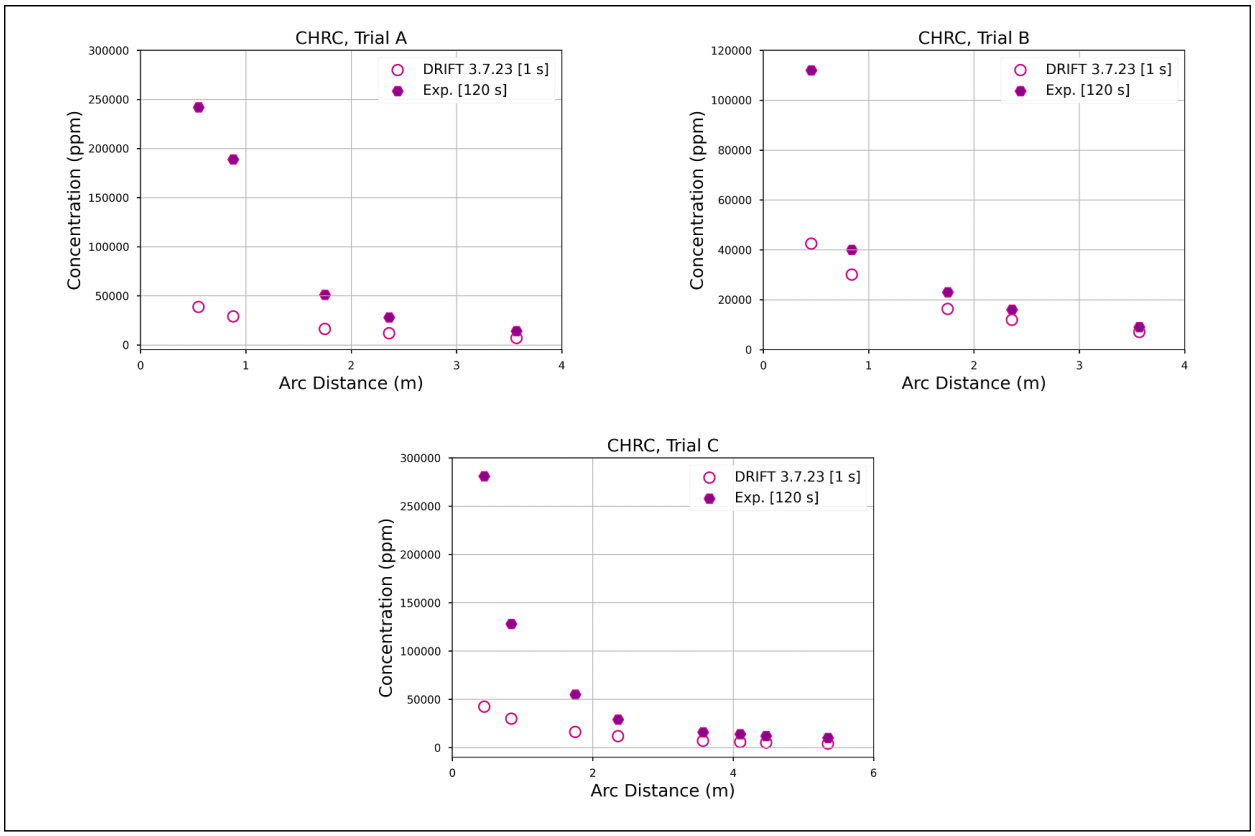


Figure 5 Observed and predicted maximum arcwise concentration data for CHRC. Square brackets indicate averaging time.

4.3.4 Maplin Sands

The Maplin Sands experiments conducted by Shell Research Ltd in 1980 involved spills of liquefied natural gas (LNG) and refrigerated liquid propane (LPG) onto sea water. Experiments were undertaken at the Proof and Experimental Establishment of the British Ministry of Defence (MOD) on the north bank of the Thames estuary on the Maplin Sands tidal mudflats. The aim of the experiments was to study dispersion and flammability of dense and cold gases. Both instantaneous and continuous releases were conducted, although only continuous releases have been included in the DRIFT validation database (consistent with the validation study of Hanna et al. (1993b) and the LNG database). Details of the experiments can be found in Puttock et al. (1982), Ermak et al. (1989), and Hanna et al. (1993b).

A dike was constructed to retain a 300 m diameter shallow pond. In total, 360 instruments (200 of which were gas sensors) were mounted onto 71 floating pontoons and deployed in wide arcs across the expected cloud path. A total of 34 trials were conducted, of which 11 were ignited. Puttock et al. (1982) provide a description of trials where good quality data was obtained, and also discuss issues faced where poor or no data was recorded.

For the current validation study, three continuous LNG releases are modelled: trials 27, 34 and 35. Although trial 27 was ignited, useful dispersion data was collected up until the point of ignition.

Figure 6 presents a comparison of the DRIFT 3.7.23 predictions with the Maplin Sands experimental data. For all the Maplin Sands trials, DRIFT underpredicts the measured concentrations. Hanna et al. (1993a,b) tested 14 hazard response models against eight gas dispersion experiments, including Maplin Sands, and several models within that study also reported significant underpredictions. Uncertainties in the Maplin Sands data are summarised in Stewart et al. (2016) and Batt (2021). These include poor sensor coverage and high winds causing narrow plumes to miss sensors. In addition, there was no splash plate to direct the source radially across the pond, and it is likely that the resulting plunging jet source led to greater dispersion than would have occurred from an area source. Stewart et al. (2016) recommend running sensitivity analysis on the source conditions due to the uncertainty in the vaporisation rate.

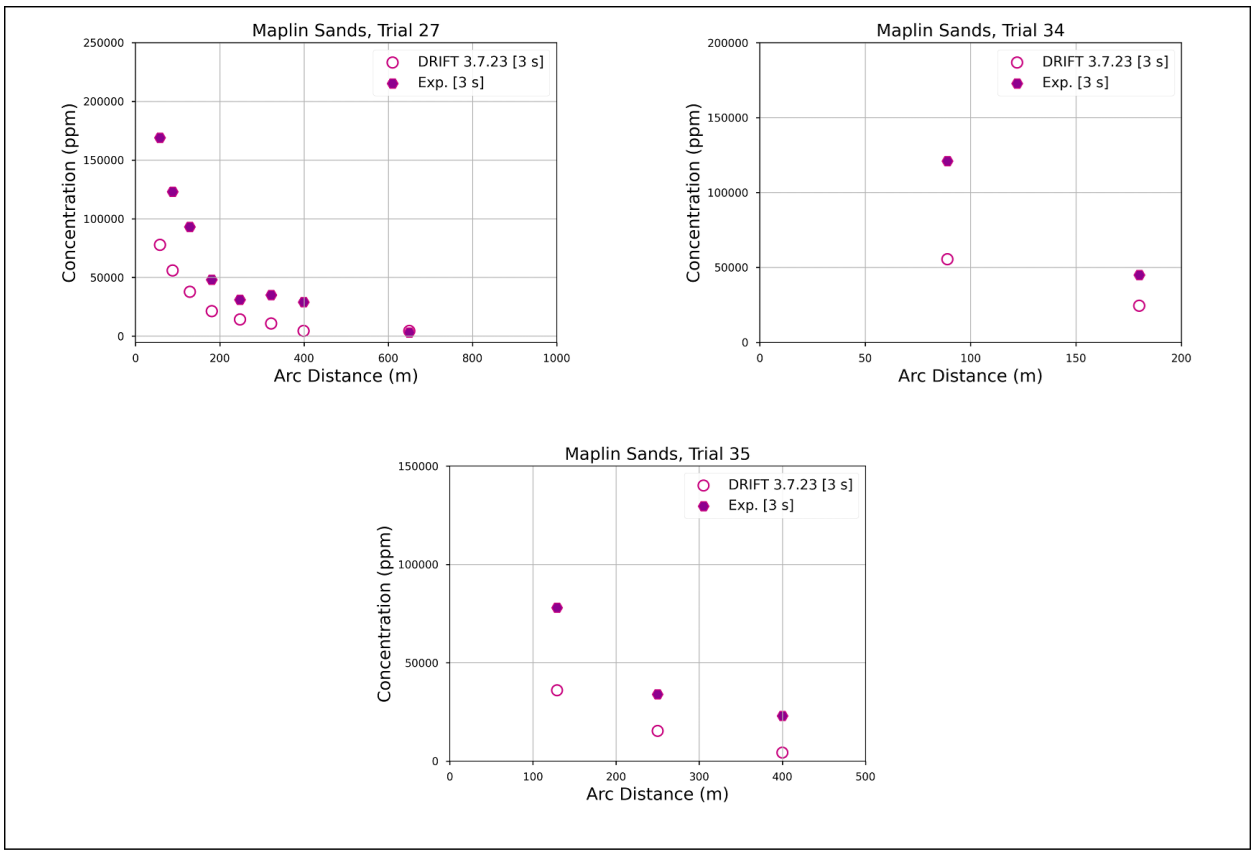


Figure 6 Observed and predicted maximum arcwise concentration data for Maplin Sands. Square brackets indicate averaging time.

4.3.5 Burro

The Burro trials were a series of large-scale experimental tests conducted by the Lawrence Livermore National Laboratory (LLNL) in 1980 at the Naval Weapons Center (NWC), China Lake, California. These trials focused on studying the dispersion behaviour of dense gas clouds resulting from the release of LNG. There were nine spills of between 24 m^3 and 39 m^3 of LNG onto water. The experiments are described in Koopman et al. (1982a,b), Ermak et al. (1982) and Ermak et al. (1989).

The LNG was discharged from a 250 mm diameter pipe vertically down into a pond. The pond was approximately 58 m in diameter and 1 m in depth. A steel plate was positioned 2 cm below the water surface directly below the pipe to direct LNG radially across the pond.

Downwind of the release, the terrain sloped upwards in the region 0 to 80 m. As a result, the ground level at 80 m is approximately 7 m above the water surface level. From 80 m onwards the terrain was relatively level (Ermak et al., 1982). DRIFT 3.7.23 cannot account for sloping ground, and therefore the ground is assumed to be flat everywhere.

Concentration arcs were located at 57 m, 140 m, 400 m and 800 m downwind. Each arc consisted of about 7 stations, and concentration was measured at heights of 1 m, 3 m and 8 m. At each arc, the maximum concentration was typically recorded at 1 m height,

although not always. Each trial returned arcmax concentrations at four downwind positions, apart from the following omissions (Stewart et al., 2016):

- Trial 7: 0% concentration measured at 800 m.
- Trial 9: Rapid Phase Transition (RPT) explosions affected the sensors on the 57 m arc and therefore no data is presented in the LNG database at that location.

Table 3 presents the weather conditions for the Burro trials. It was noted in Ermak et al. (1982) that trial 8 was particularly interesting due to the potential terrain effects. In addition, FERC (2011) also notes that the influence of terrain on the cloud dispersion is a source of uncertainty in the Burro trials. Trial 8 was conducted in low wind (1.8 m/s at 2 m) stable weather conditions (E). The cloud produced was considerably wider than observed in other trials and even developed a bifurcation. This is evident in Figure 7, where snapshots of the Burro 6 and 8 trials are compared. Trial 6 reaches a quasi-steady state and is significantly narrower than trial 8.

Table 3 Weather conditions for Burro trials 3, 7, 8 and 9. Wind speeds were recorded at a height of 2 m.

	Trial 3	Trial 7	Trial 8	Trial 9
Pasquill stability	C	D	E	D
Wind speed (m/s)	5.4	8.4	1.8	5.7
Monin-Obukhov length (m)	-9.1	-113.6	16.5	-140.8
Friction velocity (m/s)	0.250	0.375	0.074	0.250

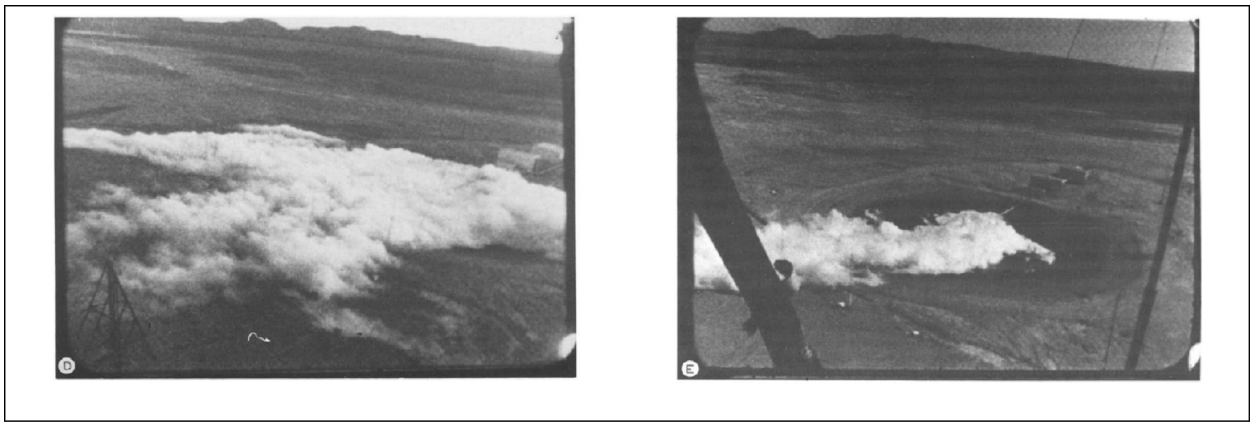


Figure 7 Left: snapshot of the vapour cloud in Burro 8 at 160 s demonstrating bifurcation. Right: Burro 6 after a quasi-steady state has been achieved. Both images from Ermak et al. (1982).

Figure 8 presents a comparison of the DRIFT 3.7.23 predictions with the Burro experimental data. There are considerable differences between the experimental concentrations obtained using the short and long averaging times. This difference between

averaging durations is not evident for the DRIFT runs. For trials 3 and 8, DRIFT does not capture the peak instantaneous concentration values observed in the experiments.

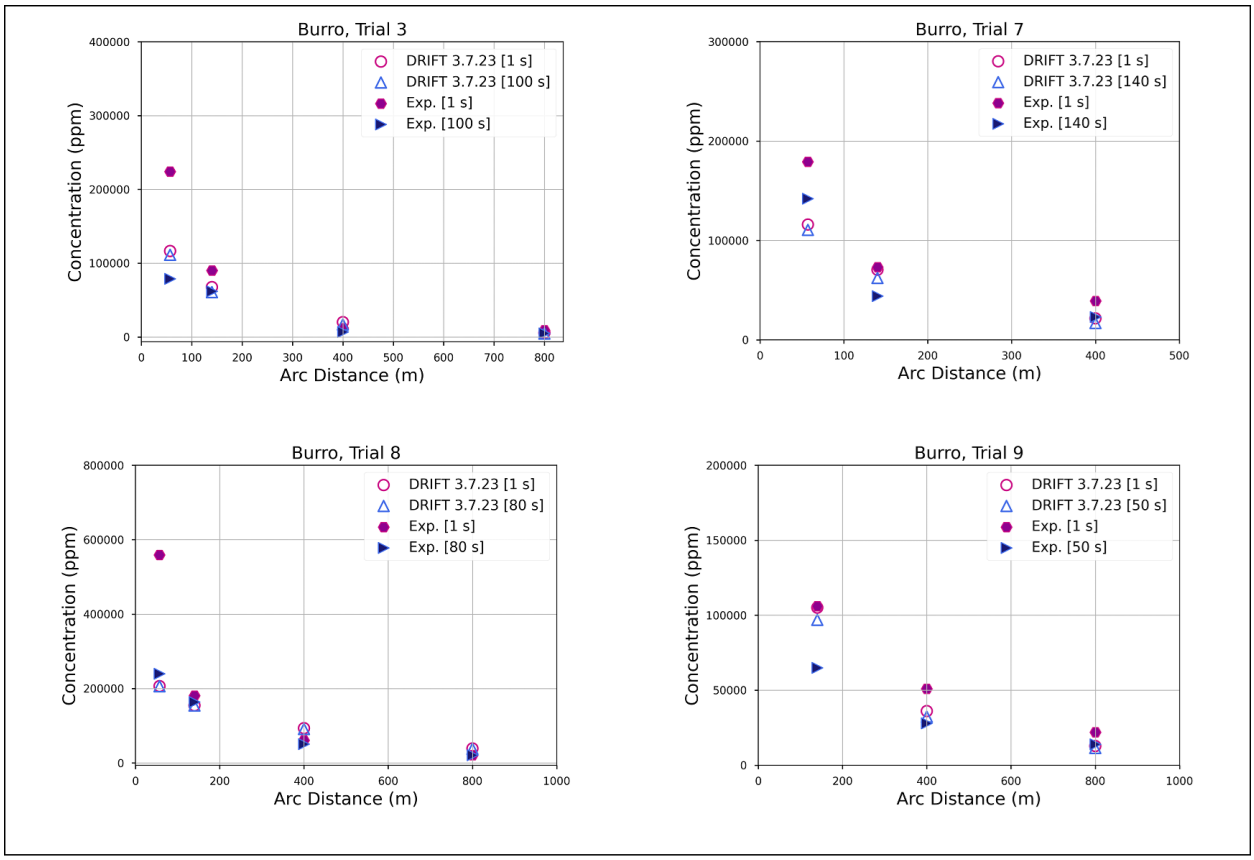


Figure 8 Observed and predicted maximum arcwise concentration data for Burro. Square brackets indicate averaging time.

4.3.6 Coyote

The Coyote LNG experiments closely followed the format of the Burro trials, with the aim of investigating the vapour burns and Rapid Phase Transitions (RPTs) that had been observed during some of the Burro tests. Conducted at the same test site, the Coyote series included five experiments on vapour dispersion and burning, as well as five focused on RPTs. The spill volumes ranged from 3.3 m³ to 28 m³. The experiments are described in Goldwire et al. (1983). The experimental configuration was identical to the Burro set up described in Section 4.3.5. LNG was released vertically downward from a pipe into a water basin.

Figure 9 presents a comparison of the DRIFT 3.7.23 predictions with the Coyote experimental data. For trials 3 and 5, DRIFT is generally underpredicting concentrations within 200 m of the source. Different behaviour is observed in trial 6. At the first sensor, DRIFT predictions are close to the experimental concentrations calculated using a short averaging time. However, the agreement between model and experiment weakens at larger arc distances. This was also reported in Coldrick and Webber (2017) for DRIFT 3.6.4.

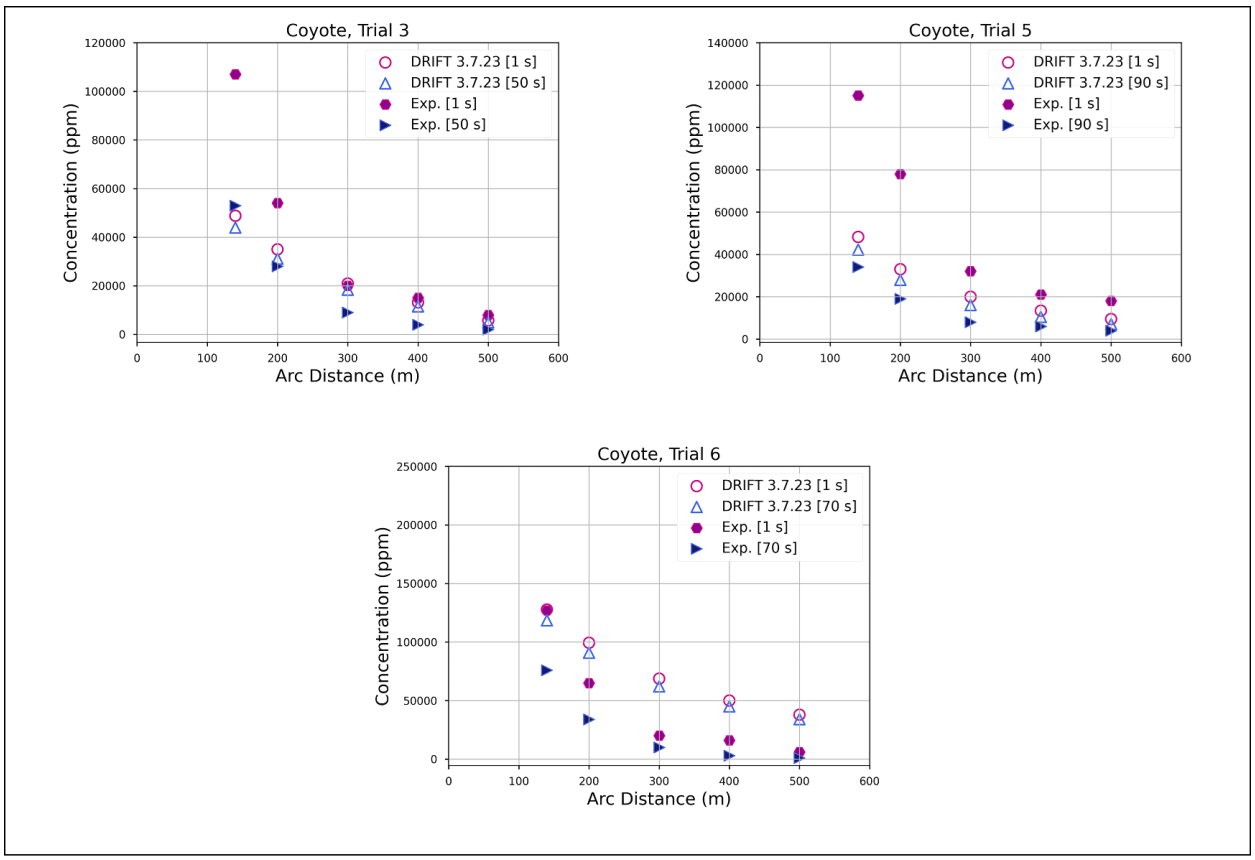


Figure 9 Observed and predicted maximum arcwise concentration data for Coyote. Square brackets indicate averaging time.

4.3.7 Falcon

The Falcon experiments were a series of five large-scale LNG spill tests carried out by the Lawrence Livermore National Laboratory. The trials took place at Frenchman Flat in Nevada, an extremely flat playa with little vegetation. The experiments are detailed in Brown et al. (1990). The purpose of the experiments was to evaluate the effectiveness of vapour fences as a mitigation technique for accidental releases of LNG, in addition to providing a dataset for model validation purposes. An 8.7 m tall vapour barrier was constructed out of fibreglass cloth, which enclosed a water pond onto which LNG was released. A billboard (17.1 m wide, 13.3 m tall) constructed from the same material as the vapour barrier was erected upwind of the spill pond to generate turbulence, typical of a storage tank. The spill pond had dimensions 40 m by 60 m, and was filled to a depth of approximately 0.76 m. The pond was specially designed and equipped with a circulating system to maximise evaporation. A multi-exit spill ‘spider’ arm was used to radially distribute LNG across the pond surface. Gavelli et al. (2009) discuss the complexities of the spider arm source using video footage of the release, complemented with CFD modelling.

The experiments involved five spills in total of between 20 m^3 and 63 m^3. However, extensive data was lost on trial 2, and accidental ignition of the plume occurred in trial 5. Trials 2 and 5 have therefore not been included in the DRIFT validation database.

In DRIFT, it is possible to model evaporation from a pond surrounded by a fence. However, this analysis follows the method of Coldrick and Webber (2017), which takes the entire fenced area and considers this to be the evaporating source.

Figure 10 presents a comparison of the DRIFT 3.7.23 predictions with the Falcon experimental data. There is slight overprediction of concentration in trial 1, but otherwise the DRIFT 3.7.23 predictions are in close agreement with the experimental data.

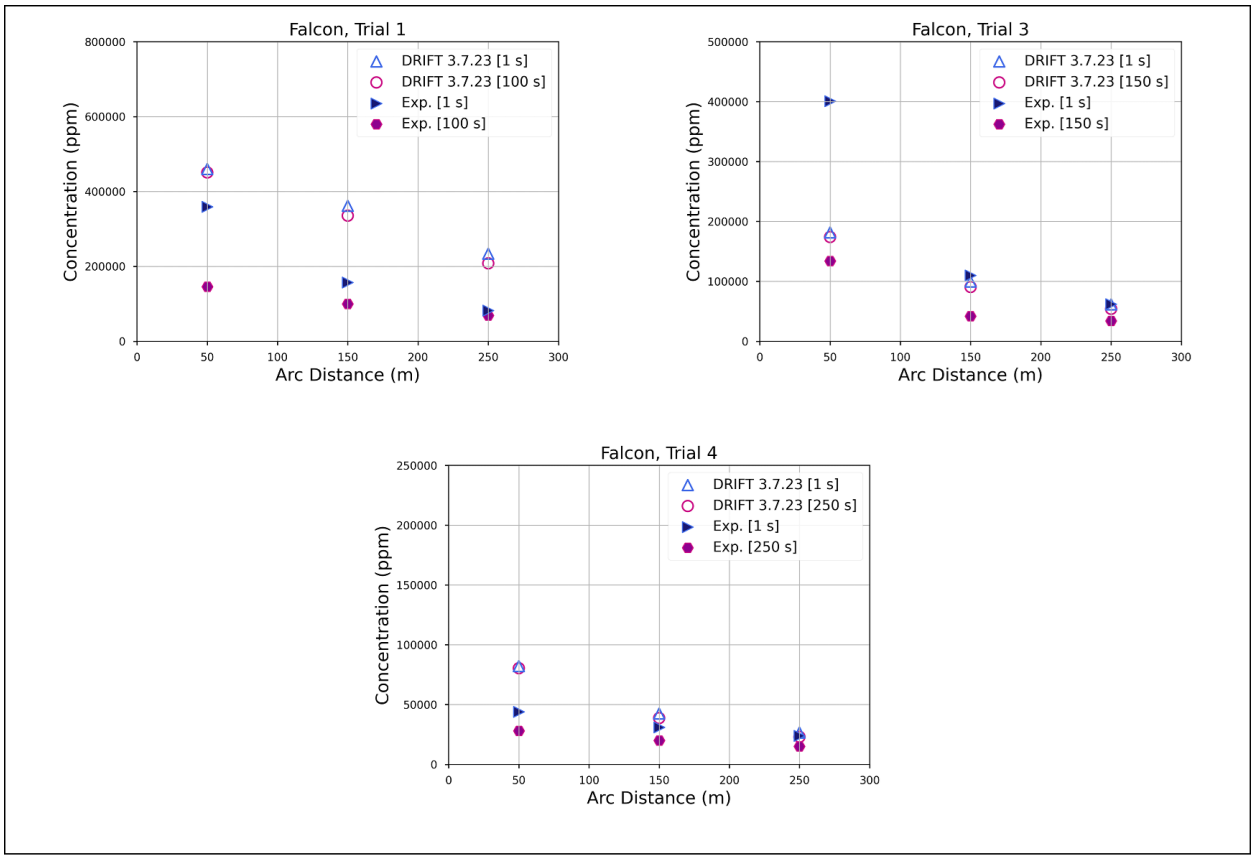


Figure 10 Observed and predicted maximum arcwise concentration data for Falcon. Square brackets indicate averaging time.

4.3.8 Thorney Island

A programme of Heavy Gas Dispersion Trials (HGDT) was conducted from 1982 to 1984 at an abandoned Royal Air Force airfield on Thorney Island, West Sussex, UK. The trials were led by HSE. The initial phase of the HGDT programme consisted of fixed-volume instantaneous releases of Freon-12 and nitrogen from a tent with collapsible sides. Before the second phase commenced, an extra three trials (45, 46, 47) were conducted on continuous releases, as described in McQuaid (1987). The programme is also documented on the Atmospheric Dispersion Modelling Liaison Committee's (ADMLC) website[1].

Only trials 45 and 47 are included in the DRIFT validation database because the wind was highly variable in trial 46. Figure 11 presents a schematic of the gas injection source, taken

[1] https://admlc.com/thorney-island/ (accessed November 2025)

from McQuaid (1987). Gas is injected vertically upwards into a plate and then travels horizontally as a low-momentum source.

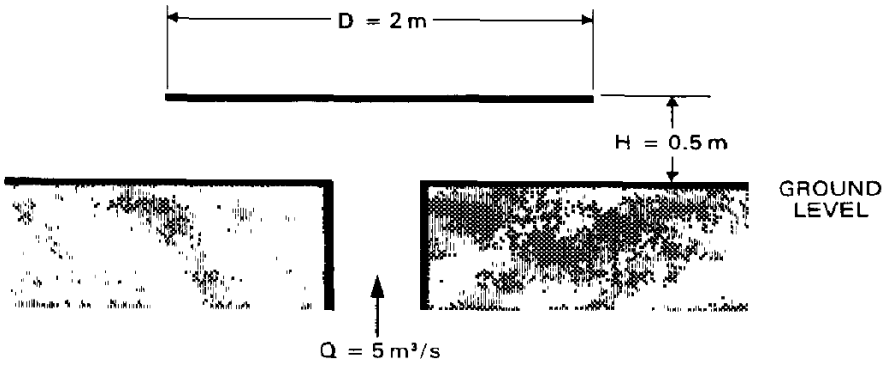


Figure 11 Thorney Island vertical duct source. Image from McQuaid (1987).

Figure 12 presents a comparison of the DRIFT 3.7.23 predictions with the Thorney Island experimental trials 45 and 47. For both trials, DRIFT underpredicts concentration initially, and slightly overpredicts the concentration further downwind.

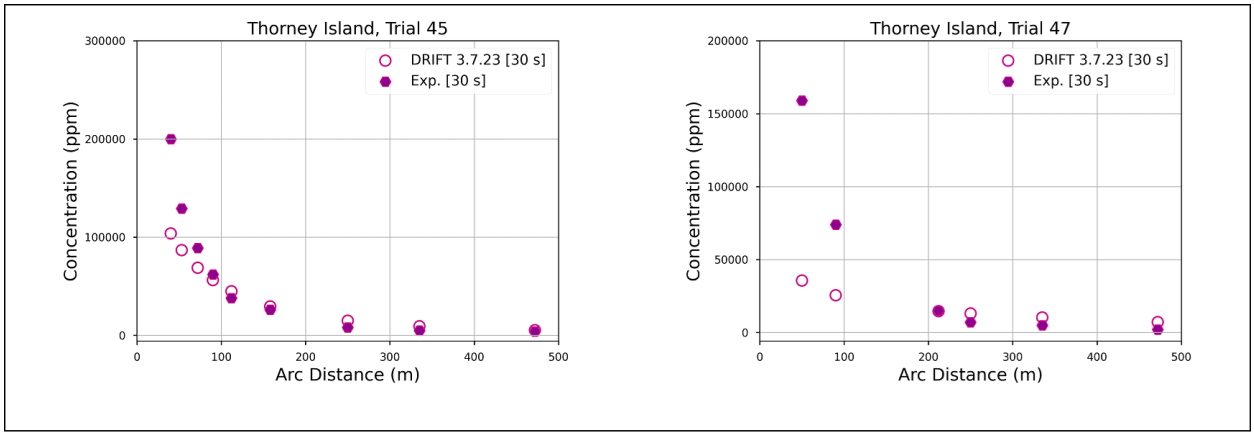


Figure 12 Observed and predicted maximum arcwise concentration data for Thorney Island. Square brackets indicate averaging time.

4.3.9 Jack Rabbit II

In 2015 and 2016, large-scale releases of chlorine were conducted by the US Army at the Dugway Proving Ground in Utah. A summary of the experimental trials is presented in Table 4. Each trial in phase I (1-5) was a vertical downward impinging jet through a 6-inch diameter hole from a height of 1 m. In addition, a grid of Conex containers was placed around the release point to simulate a mock urban array. The second phase of trials (6-9) was conducted without the Conex containers, and the release orientation was varied. DRIFT has been used by HSE to study the Jack Rabbit trials on multiple occasions – see Section 10 of Gant et al. (2022) and references therein.

Mazzola et al. (2021) chose trials 1, 6 and 7 for their model comparison exercise. A discussion on the data suitability of each trial and rationale for choosing these particular three trials is provided in Mazzola et al. (2021) and Gant et al. (2021), but also briefly

described here in Table 4. Trials 1, 6 and 7 have been included in the DRIFT validation database and are modelled here.

Table 4 Description of the Jack Rabbit II chlorine trials.

Trial	Phase/year	Inventory (tonnes)	Obstructions	Release orientation	Comment
1[a]	I, 2015	4.545	Conex containers	Vertically down	Good
2	I, 2015	8.192	Conex containers	Vertically down	Concentrations lower than trial 1, upon scaling[b]
3	I, 2015	4.568	Conex containers	Vertically down	High wind, narrow plume passed between sensors
4	I, 2015	7.017	Conex containers	Vertically down	High wind variability
5	I, 2015	8.346	Conex containers	Vertically down	High wind variability
6[a]	II, 2016	8.391	None	Vertically down	Good video footage
7[a]	II, 2016	9.072	None	45° down	Close to horizontal release
8	II, 2016	9.120	None	Vertically up	Rapid source dilution[c]
9	II, 2016	17.700	None	Vertically down	No load cells; possibility of partially blocked orifice

[a] Deemed suitable for model validation in Mazzola et al. (2021), where detailed source conditions were provided as part of a model intercomparison exercise.

[b] Scaling: maximum concentration divided by the total mass of chlorine released.

[c] Subject of a separate model validation exercise in Hanna et al. (2021).

Figure 13 presents a comparison of the DRIFT 3.7.23 predictions with the Jack Rabbit II experimental data for trials 1, 6 and 7. DRIFT substantially overpredicts (by roughly a factor of 10) the concentration in trial 1 at the first sensor located at 200 m. However, as discussed in Gant et al. (2022), there were only 3 sensors on the arc at 200 m, and the plume centreline could have missed these sensors.

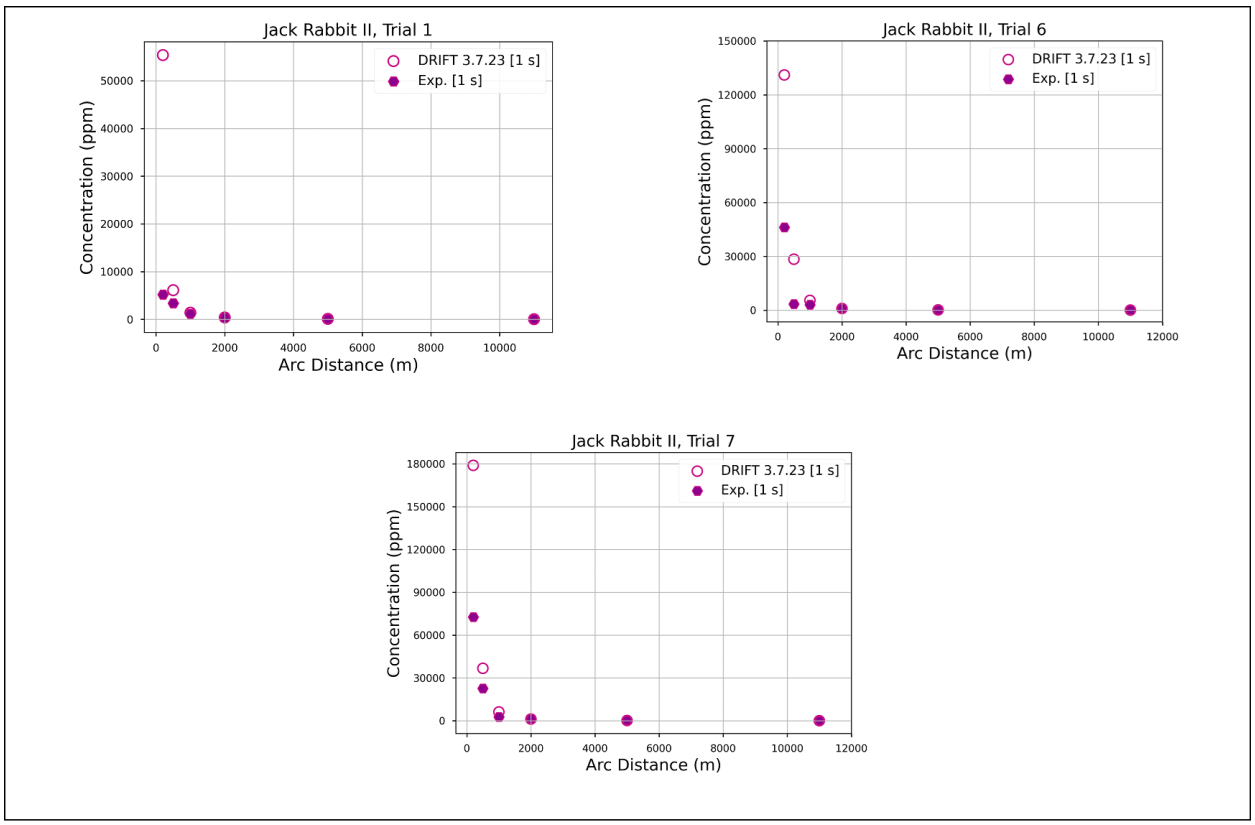


Figure 13 Observed and predicted maximum arcwise concentration data for Jack Rabbit II. Square brackets indicate averaging time.

Mazzola et al. (2021) report downwind locations where concentration data was recorded, but the sensors became saturated. This information has been recorded in Table 5. When cross-referenced against the concentration plots in Figure 13, it can be seen that some of these positions coincide with the arc distances where DRIFT is overpredicting concentration data.

Table 5 Downwind locations where sensors saturated (from Mazzola et al. (2021)).

Trial	Distance (km)
1	0.2, 5.0
6	0.5, 5.0
7	1.0, 11.0

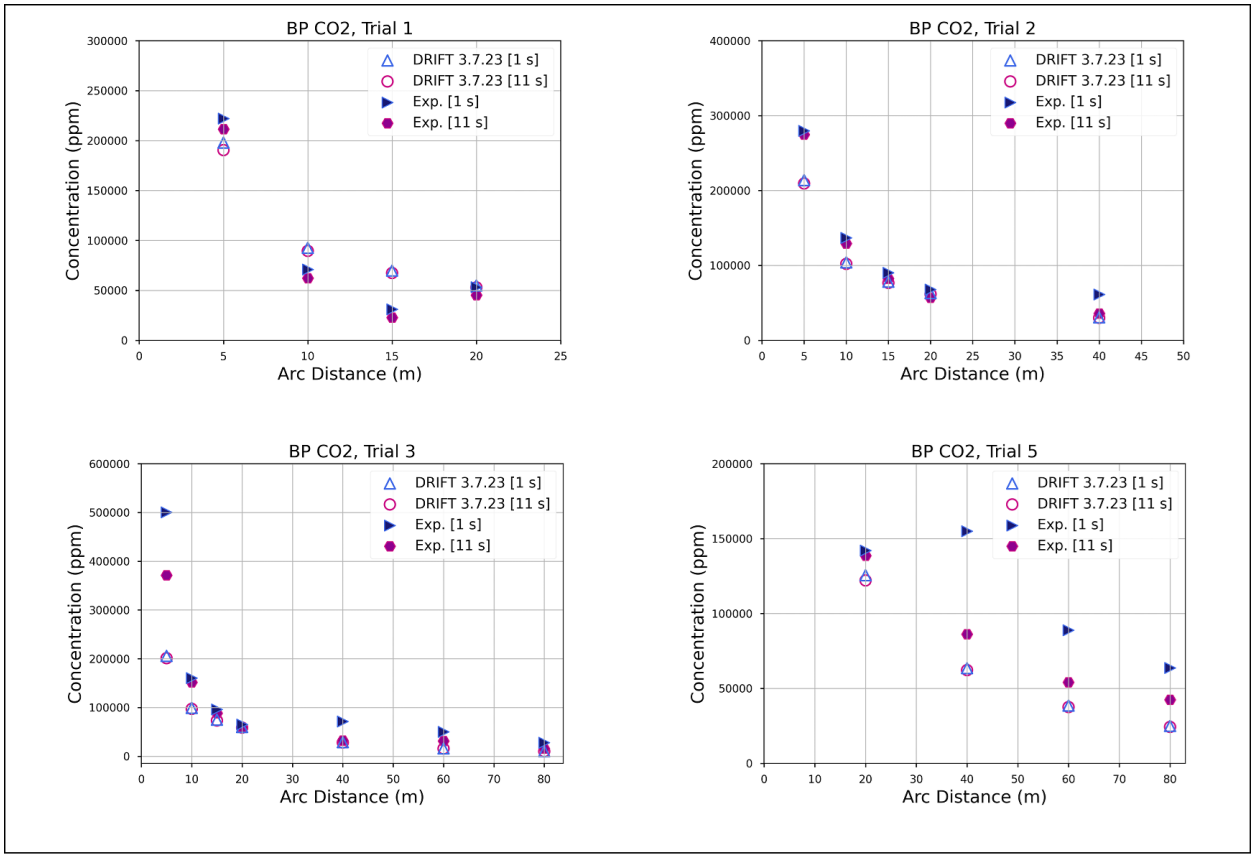
4.3.10 CO2PIPETRANS (BP DF1 CO_2)

As part of the CO2PIPETRANS joint industry project (JIP), DNV released data from the BP DF1 CO_2 research project undertaken in 2006. Liquid and supercritical phase CO_2 was released through holes with a range of diameters. Of the 12 trials undertaken, nine were approved for public distribution by the project steering committee. Data is available for the following trials: 1, 2, 3, 5, 6, 8, 8R (repeat of 8), 9 and 11. These releases were free horizontal releases, apart from 3 and 6 which occurred through a short extension tube. Of

the three trials not available, two were releases onto an instrumented plate (trials 4 and 7), and one was a downward impinging release into the ground (trial 10).

Source conditions are taken from the post-expansion data of Witlox (2012), which was generated using the dispersion model Phast. This is described in Tickle (2021), where the process of Witlox, Harper and Oke (2009) and Webber (2011) is followed to model two-phase CO_2. In this process, below the triple point, the saturated liquid vapour pressure curve is replaced by the solid sublimation-vapour pressure curve. Additionally, the heat of sublimation of solid CO_2 is substituted for the heat of vaporisation of liquid CO_2.

Figure 14 presents a comparison of the DRIFT 3.7.23 predictions with the BP DF1 experimental measurements. The DRIFT predictions show a monotonic decrease in concentration with downwind distance, as is expected, but the experimental data does not. The anomalies in the experimental data are reported and discussed in Witlox (2012). These datapoints have been left in this report for completeness. Overall, there is sufficient good quality experimental data to confirm that DRIFT is in good agreement with the experiment.



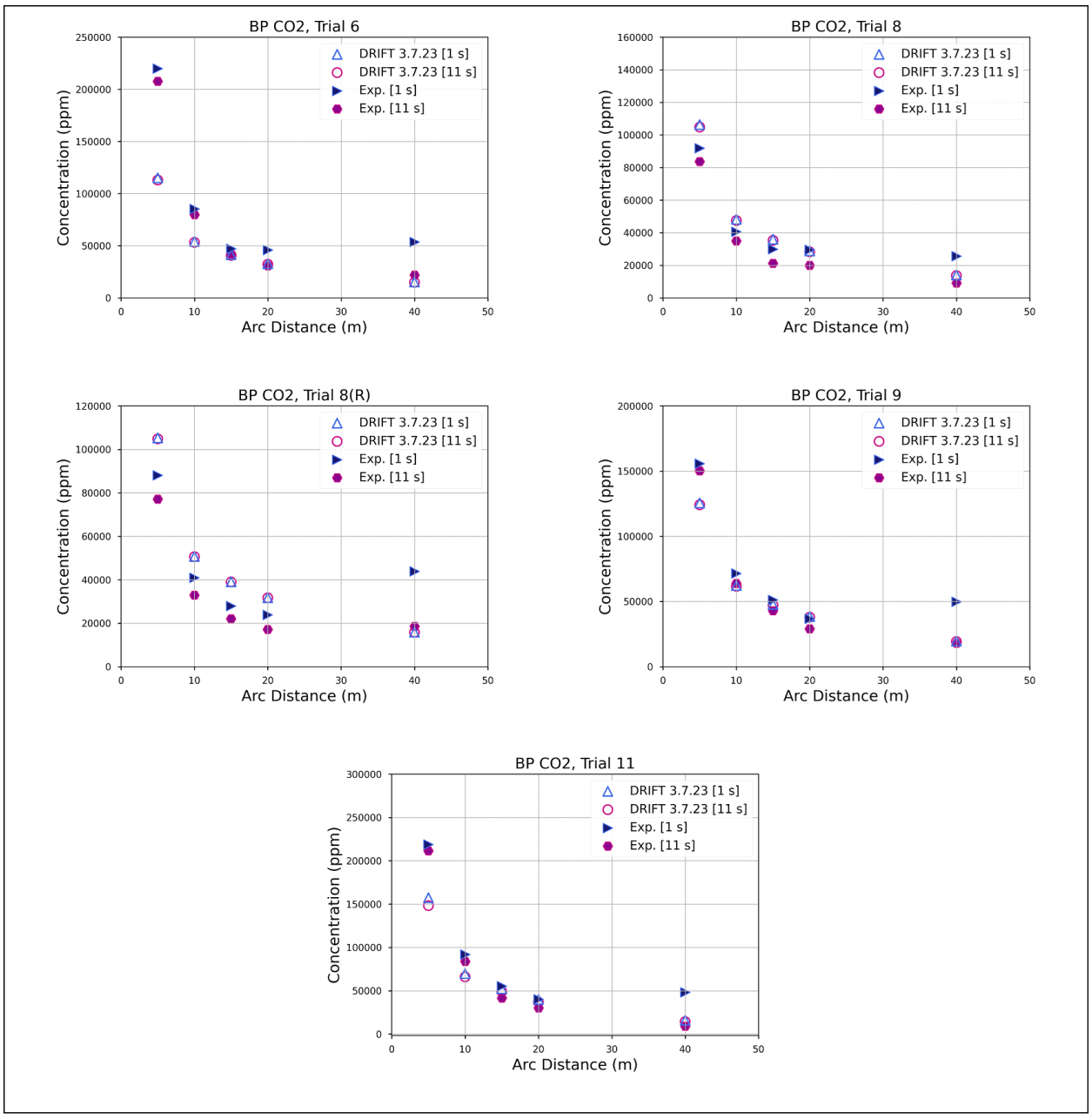


Figure 14 Observed and predicted maximum arcwise concentration data for CO2PIPETRANS. Square brackets indicate averaging time.

4.3.11 Hanford

The Hanford passive dispersion experiments, conducted in 1967 at the Atomic Energy Commission's Hanford reservation, investigated the dispersion of the inert radioactive tracer krypton-85. These experiments are described in Nickola et al. (1970). In total, 13 trials were performed, five of which were continuous and are considered here. The continuous releases ran for between 10 and 20 minutes, with concentration sensors positioned 200 m and 800 m downwind of the source. Nickola et al. (1970) present time series of both meteorological and concentration data. The terrain at the test site was largely flat.

To produce the source, krypton was mixed with argon gas. The ratio of argon to krypton was not specified, and therefore the release rate is unknown. In this study, the release rate

is adjusted until DRIFT reproduces the experimental concentration (obtained using an averaging time of 38 s) at the first arc at 200 m. This first data point therefore provides no information on DRIFT's performance, but it is possible to compare data at the 800 m arc. This approach was used in previous evaluations of DRIFT and is in line with the method suggested by Hanna et al. (1993b). However, the Hanford trials are therefore excluded from the Statistical Performance Measure (SPM) analysis presented later in this report.

Figure 15 presents DRIFT 3.7.23 predictions for Hanford trials 1, 2, 3, 4 and 5. Given the scaling at the first downwind position of 200 m, only the 800 m arc data can be used to judge the performance of DRIFT. It can be seen that DRIFT predictions are in close agreement with experiment for the arc at 800 m, apart from a slight overprediction of roughly a factor of 2 for trial 1.

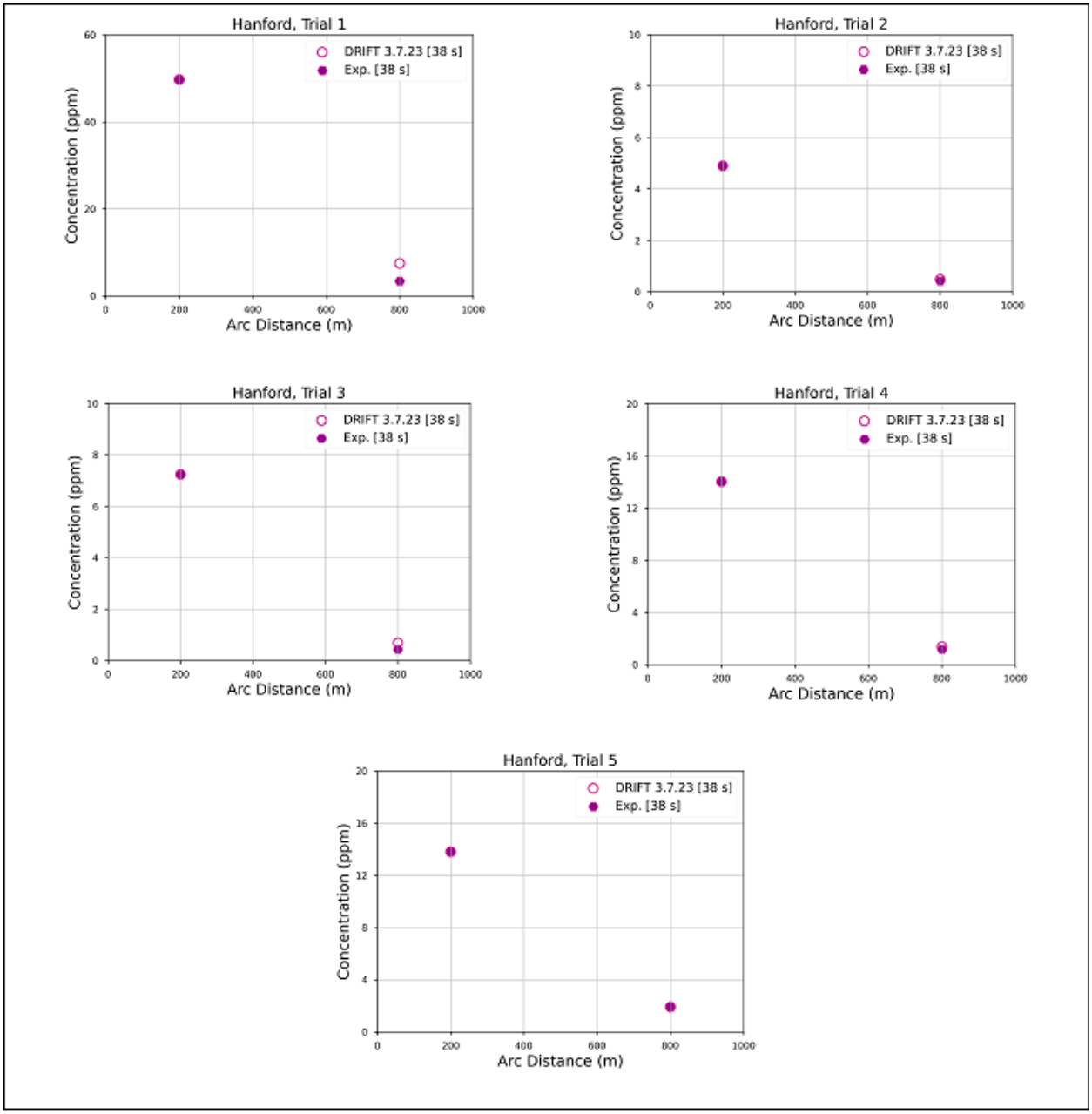


Figure 15 Observed and predicted maximum arcwise concentration data for continuous Hanford trials. Square brackets indicate averaging time.

4.3.12 Prairie Grass

Project Prairie Grass was a series of field experiments conducted in the summer of 1956 in Nebraska. The experiments are described in Barad (1958). The purpose of Prairie Grass was to investigate the diffusion of a tracer gas (sulphur dioxide) under a variety of weather conditions. Experiments were carried out both during the day and at night. In total, 70 trials were performed, five of which have been modelled for the present evaluation, corresponding to those used in the validation study of Tickle et al. (2012).

Sulphur dioxide vapour at atmospheric pressure and temperature was released from a 50 mm diameter pipe at a height of approximately 0.5 m (see Figure 16). Details of the release conditions and concentration measurements are provided in Barad (1958).

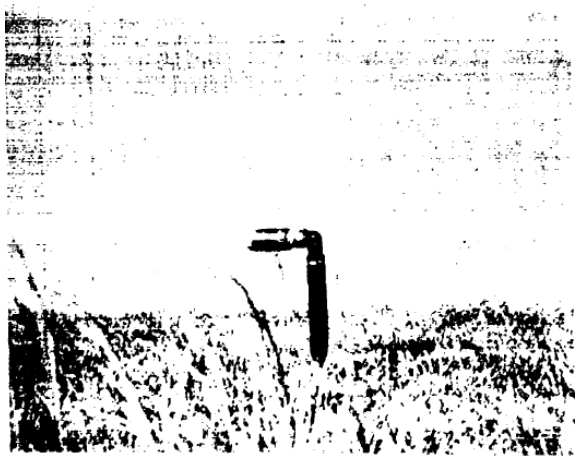


Figure 16 Release configuration for the Prairie Grass experiments – a 50 mm diameter pipe, with the orifice orientated parallel to the floor. Image taken from Barad (1958).

Concentration sensors were positioned on arcs 1.5 m above the ground at downwind distances of 50 m, 100 m, 200 m, 400 m and 800 m. Meteorological observations were made at a height of 2 m at two separate locations for temperature, wind speed and wind direction. Table 6 presents weather data for each trial, including wind speed and Pasquill Stability. The test site consisted of nominally flat terrain covered with native prairie grasses.

Table 6 Wind speed and Pasquill stability class of each Prairie Grass trial.

Trial	Wind speed (m/s)	Pasquill stability
9	6.9	C (slightly unstable)
10	4.6	B (unstable)
32	2.2	F (stable)
33	8.5	D (neutral)
36	1.9	F (stable)

Figure 17 presents concentration data for Prairie Grass trials 9, 10, 32, 33 and 36. DRIFT 3.7.23 predictions are especially close to the experimental data for trials 9 and 33, where the wind speed is high and the stability ranges from neutral to slightly unstable. Trials 32 and 36 show model underprediction, roughly by a factor of 2. These trials are both Pasquill stability class F (stable), and relatively low wind speed. Trial 10 (Pasquill class B, unstable) displays the opposite behaviour, as DRIFT reports concentrations higher than those observed experimentally. These findings are consistent with previous investigations of Prairie Grass using DRIFT, see for example Tickle (2012).

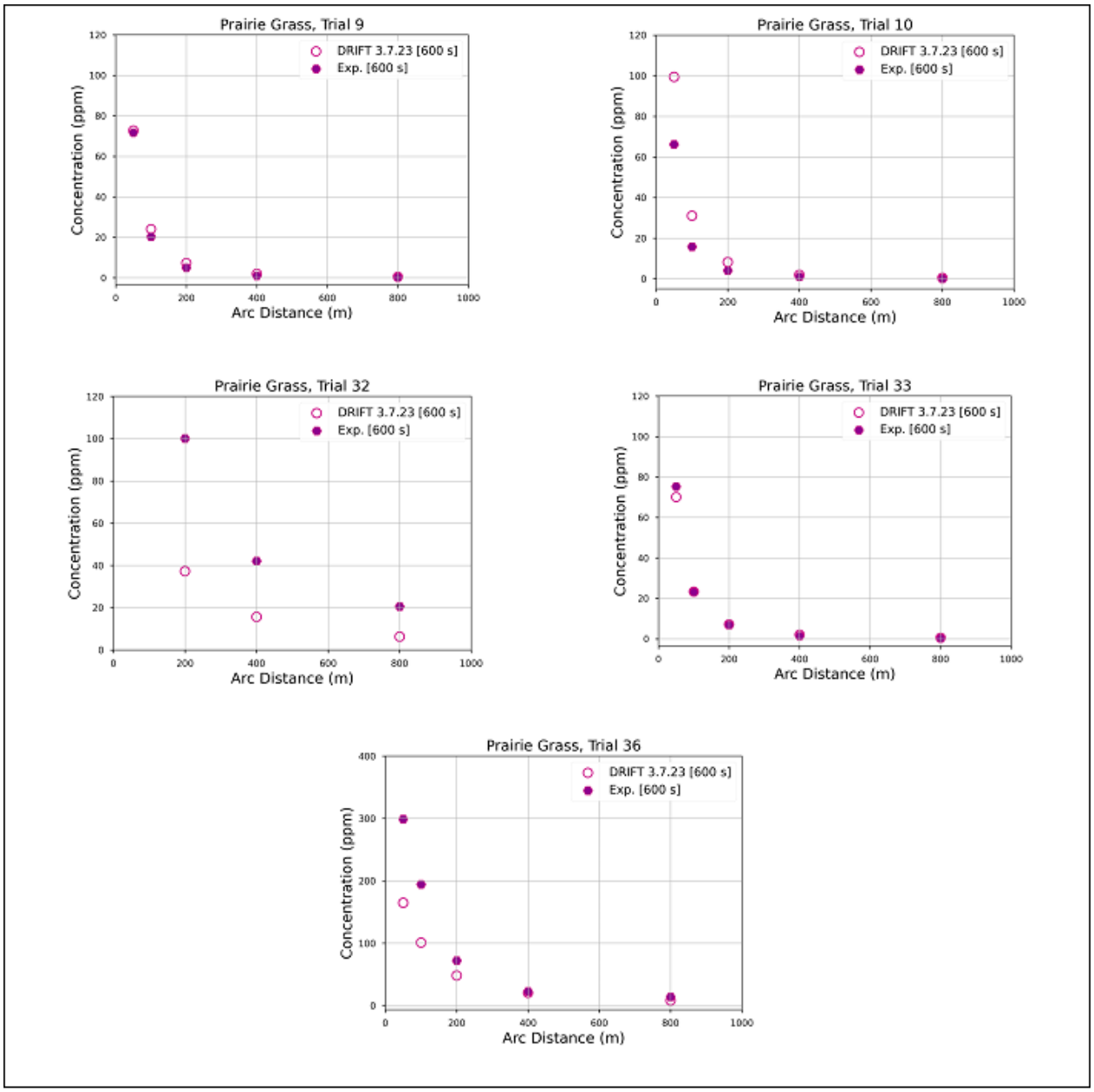


Figure 17 Observed and predicted maximum arcwise concentration data for Prairie Grass. Square brackets indicate averaging time.

4.3.13 Desert Tortoise

The Desert Tortoise trials were a series of four ammonia releases conducted in 1983 at Frenchman Flat, in the Nevada desert. They are the largest scale atmospheric dispersion experiments conducted to date on pressure-liquefied ammonia. The project was

conducted by the Lawrence Livermore National Laboratory for the United States Coast Guard and The Fertilizer Institute, under the auspices of the US Department of Energy. Details of the experimental trials are provided in Goldwire et al. (1985).

Releases were directed horizontally from a nozzle at a height of 0.79 m. They involved releases of between 10 tonnes and 41 tonnes of ammonia, release rates of between 81 kg/s and 133 kg/s, and gas concentrations measured downwind at distances of 100 m and 800 m. Sensor arcs were also placed further downwind (1.4 km, 2.8 km and 5.5 km), although this data is not reported in the current validation exercise. Rain on days leading up to the experiments resulted in surface water on the ground for trials 1 and 2. Some of this standing water was still present during trial 3 but was completely dried up by trial 4. Otherwise, the terrain was flat, dry and with negligible vegetation.

Approximately 18% of the liquid flashed into vapour as it exited the pipe (Hanna et al., 1993b). However, little to no liquid was observed to pool on the ground. Hanna et al. (1993b) note that at the 100 m arc '*In most cases, nearly all of the plume was below the 6 m level of the towers and within the lateral domain of the towers.*'. The Desert Tortoise data is therefore a useful addition to the validation exercise to assess changes to the wall jet modelling introduced in DRIFT 3.7.21. A model comparison exercise for the Jack Rabbit III project was undertaken to evaluate the performance of various dispersion models, including DRIFT 3.7.19 (Gant et al., 2025). This exercise included some of the Desert Tortoise trials.

Figure 18 presents a comparison of the DRIFT predictions with the Desert Tortoise data.

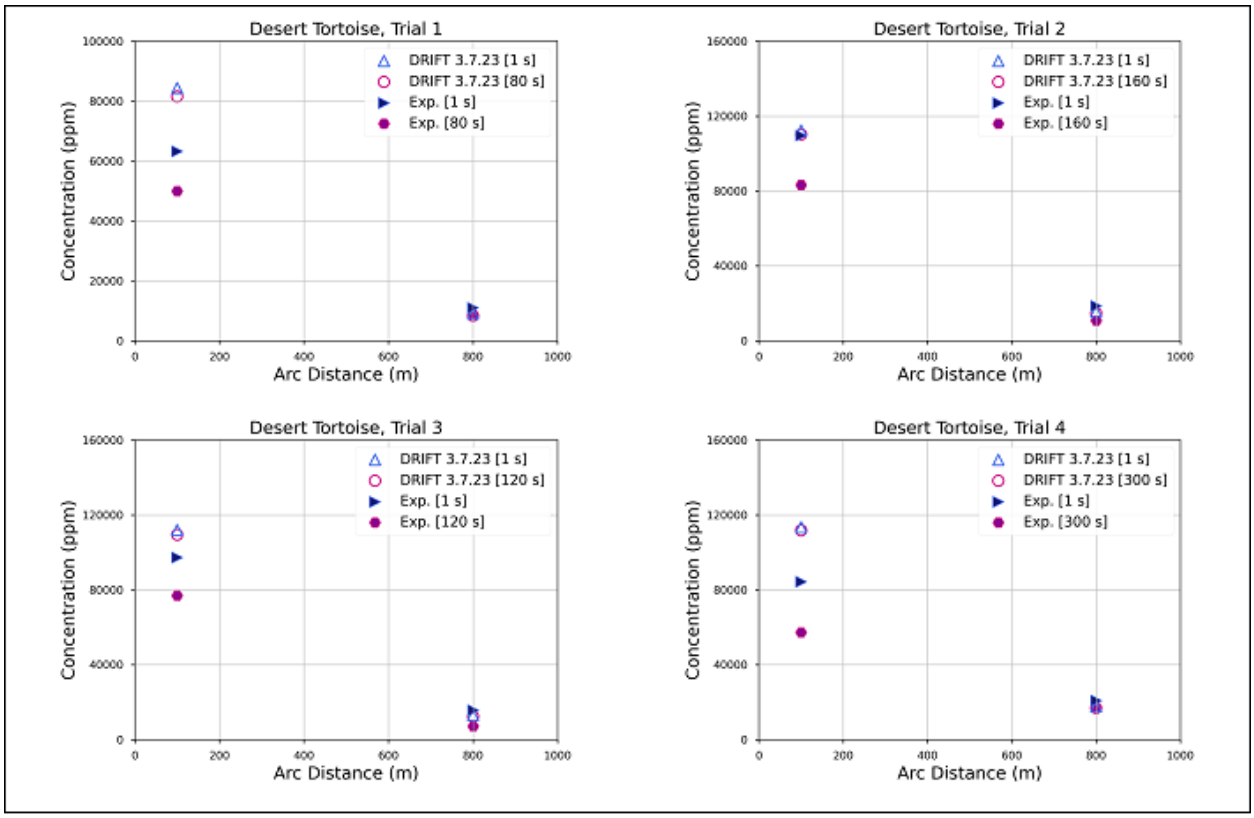


Figure 18 Observed and predicted maximum arcwise concentration data for Desert Tortoise. Square brackets indicate averaging time.

The DRIFT 3.7.23 results and experimental data are in close agreement for the 800 m arc, and reasonable agreement is found at the closest arc, especially for the short-time averaged concentrations.

4.3.14 FLADIS

The FLADIS experiments, conducted in 1993 to 1994, were similar to the Desert Tortoise experiments, but at a much smaller scale, with pressure-liquefied ammonia discharge rates of between 0.25 kg/s and 0.55 kg/s. The trials were conducted at the Hydro-Care test site in Landskrona, Sweden, close to the Öresund strait. The test site had some vegetation (0.1 m to 0.3 m high grass) and buildings upwind of the release (see Nielsen and Ott, 1996b). A model comparison exercise for the Jack Rabbit III project was undertaken to evaluate the performance of various dispersion models, including DRIFT 3.7.19 (Gant et al., 2025). This exercise included some of the FLADIS trials.

The releases selected here were all directed horizontally from a height of 1.5 m and there was no rainout of liquid ammonia on the ground. Concentrations were measured at distances of approximately 20 m, 70 m and 240 m. In addition to concentration data, the composition of the aerosols was also measured in the near-field.

Figure 19 presents a comparison of the DRIFT 3.7.23 predictions with the FLADIS experimental data for a range of averaging times. Close agreement between the predicted and measured concentrations is found for all averaging times for all trials tested.

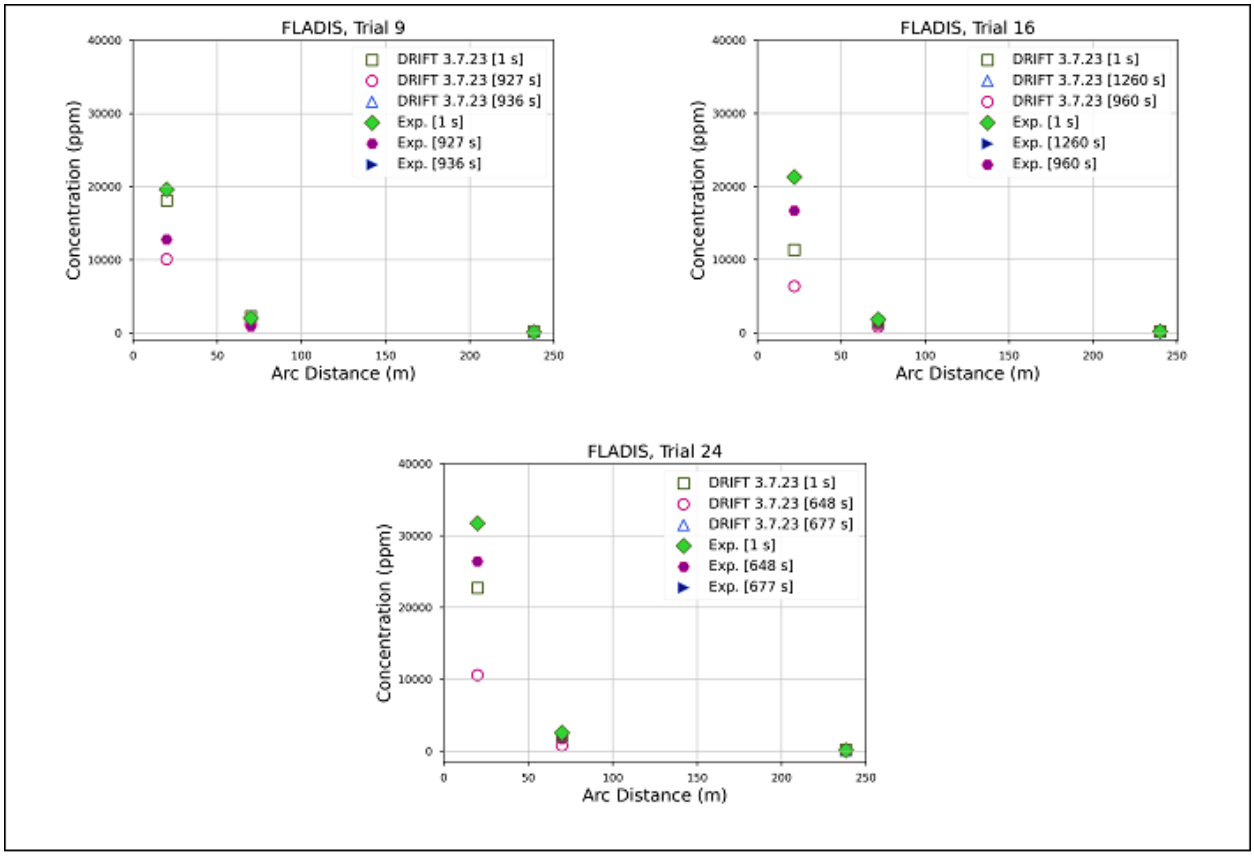


Figure 19 Observed and predicted maximum arcwise concentration data for FLADIS. Square brackets indicate averaging time.

4.3.15 Goldfish

The Goldfish experimental trials, conducted by Lawrence Livermore National Laboratory and Amoco Oil Company, were a series of six experiments involving releases of superheated anhydrous hydrofluoric acid, also known as hydrogen fluoride (HF). These experiments were conducted in the summer of 1986 at the Department of Energy (DOE) Liquefied Gaseous Fuels Facility (LGF), located on the Nevada Test Site at Frenchman Flat. Details of the Goldfish experiments are provided in Blewitt et al. (1987). The purpose of the tests was to investigate source characteristics and provide data for dispersion model validation. Three trials investigated the effectiveness of water spray mitigation and are not featured here.

HF is hygroscopic and undergoes an exothermic reaction when it comes into contact with water. At the time of the Goldfish experiments, little was known regarding the complex dispersion of HF given its properties when mixed with moist air. HF was pressurised using nitrogen padding, stored at approximately 40 °C, and released from a 4-inch diameter orifice to produce a horizontal jet. Blewitt et al. (1987) remark that no rainout on to the test pad was observed. Concentration data was collected at sensor arcs located at downstream distances of 0.3 km, 1 km and 3 km.

Figure 20 presents the DRIFT 3.7.23 predictions against Goldfish experimental data. For trials 2 and 3, DRIFT underpredicts concentration data at the first sensor by roughly a factor of 2. Better agreement is obtained further downwind, and for trial 1.

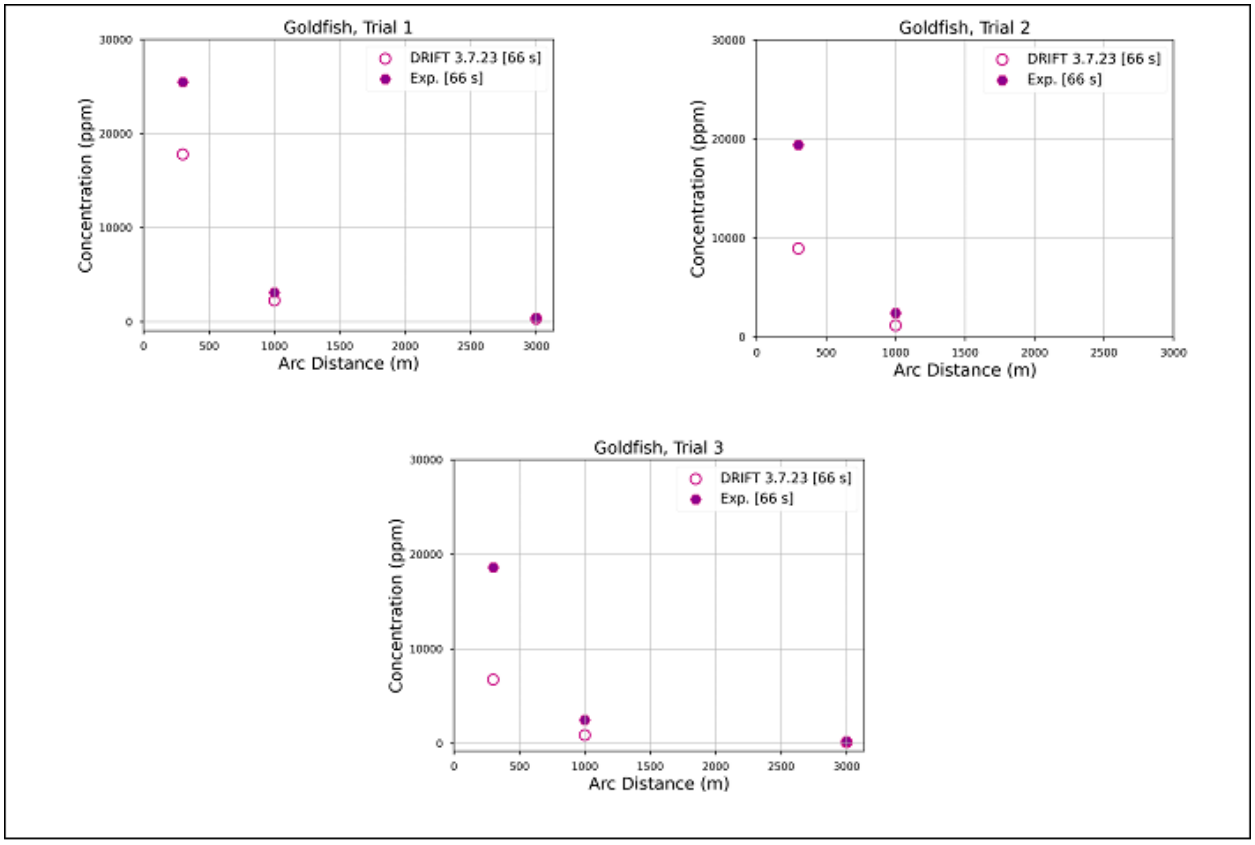


Figure 20 Observed and predicted maximum arcwise concentration data for Goldfish. Square brackets indicate averaging time.

4.3.16 URAHFREP

The URAHFREP (Understanding the dispersion of industrial Releases of Anhydrous Hydrogen Fluoride and the associated Risks to the Environment and People) project investigated the dispersion behaviour of hydrogen fluoride (HF) through field and wind-tunnel tests. The project was undertaken as part of the EC's Fourth Framework Programme and ran from 1997 to 2001. Details of the programme can be found in Porter and Nussey (2001) with additional information in Ott and Jørgensen (2002). The aim of the project was to investigate buoyancy and potential lift-off behaviour of the HF cloud. Small-scale wind-tunnel trials were undertaken during the project, but these will not be described in any further detail here nor included in the DRIFT validation database. The wind-tunnel tests are reported in Hall and Walker (2000) and Hall et al. (2001).

The URAHFREP Campaign 2 field trials were conducted at Porton Down, UK, at what was then the DERA (Defence Evaluation and Research Agency) site and is now the Dstl (Defence Science and Technology Laboratory) site. A total of 12 trials took place in August 2000. Campaign 2 was so named because Campaign 1 was abandoned the year before.

Relative humidities ranged from 46% to 92%. In contrast, the Goldfish experiments (also releases of HF), were undertaken in the dry atmosphere of the Nevada Test Site at Frenchman Flat. The relative humidity range for Goldfish trials 1 to 3 (included in the DRIFT validation database) was 4.9% to 17.7%.

HF was released as a horizontal pressure-liquefied jet from a height of 1.2 m. Due to site limitations it was necessary to keep the release rate relatively low (~0.1 kg/s). Greater buoyancy effects on dispersion are expected for larger release rates (Tickle et al., 2012).

To aid plume visualisation, a small amount of ammonia was released through an additional nozzle located near the HF nozzle. Ammonia reacts with HF producing solid NH_4F aerosol. No ammonia was released during trial 1, and the visibility of the plume extended roughly 30 m to 40 m. In contrast, when ammonia was released, the plume was visible for one kilometre or more.

Figure 21 displays screenshots of the plume in trial 12, roughly 114 s after release. Trial 12 was discussed in detail in Ott and Jørgensen (2002) and Tickle et al. (2012). It was noted that a dip in the experimental concentration data may have been due in part to buoyant rise, causing the cloud to miss sensors. In the bottom left subfigure of Figure 21, the cloud is seen to have lifted away from the ground. However, this is intermittent behaviour, and the cloud appears to be grounded at this same position for different times. Some of the observed behaviour in trial 12 may be attributed to the effect of atmospheric updrafts and downdrafts in unstable atmospheric conditions, although it might also be influenced by cloud buoyancy induced by HF thermodynamic interaction with atmospheric humidity. In DRIFT the effect of atmospheric updrafts and downdrafts is included as an additional vertical spread on the time averaged plume (based on the probability density model of Weil et al. (1997)), whereas the HF thermodynamics model influences the cloud buoyancy and buoyant rise.

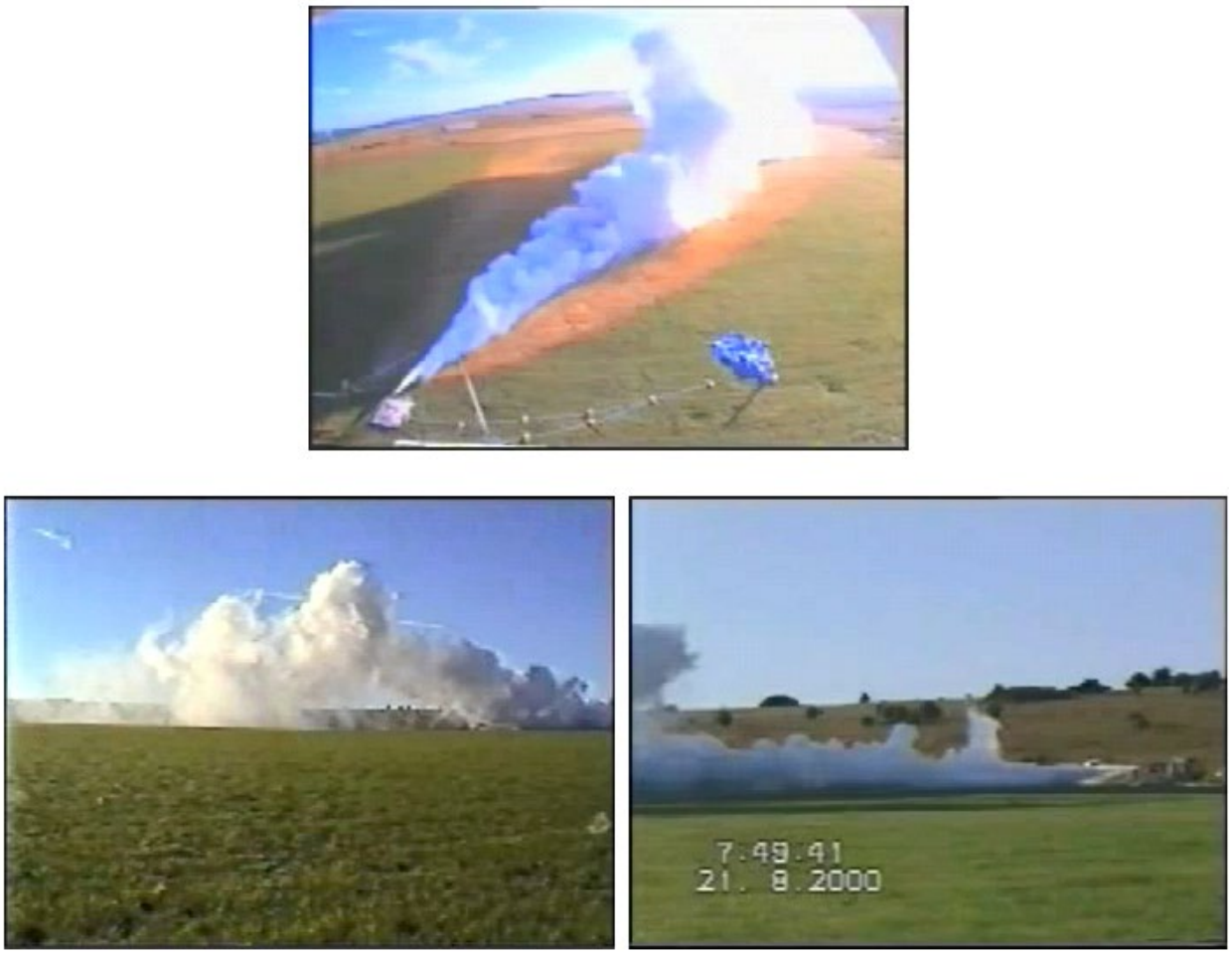


Figure 21 Screenshots from URAHFREP trial 12. The time stamp on the video displays 7:49:41, roughly 114 seconds into the release. Three different views of the cloud. Top: aerial view, bottom left: side view, bottom right: a closer view of the source.

Figure 22 presents a comparison of the DRIFT 3.7.23 predictions with URAHFREP field trials 7, 9, 10 and 12. Sensor concentration data at 1 km is omitted from this figure to aid visibility. This applies to trials 7, 9 and 12 where the experimental concentrations obtained at 1 km using a short averaging time were 1.0 ppm, 1.2 ppm and 5.0 ppm, respectively.

At sensor arcs 20 and 30 m, DRIFT underpredicts long-time averaged concentrations in trials 9 and 10. This is consistent with the results of Tickle et al. (2012), who used an earlier version of DRIFT (version 3.6.15). Closer agreement is reached further downwind. For trial 12 at 20 m, the experimental measurements and DRIFT predictions are indistinguishable. However, a rapid drop in concentration is observed for the experimental data between 20 and 30 m, perhaps due to cloud buoyancy effects which have been discussed.

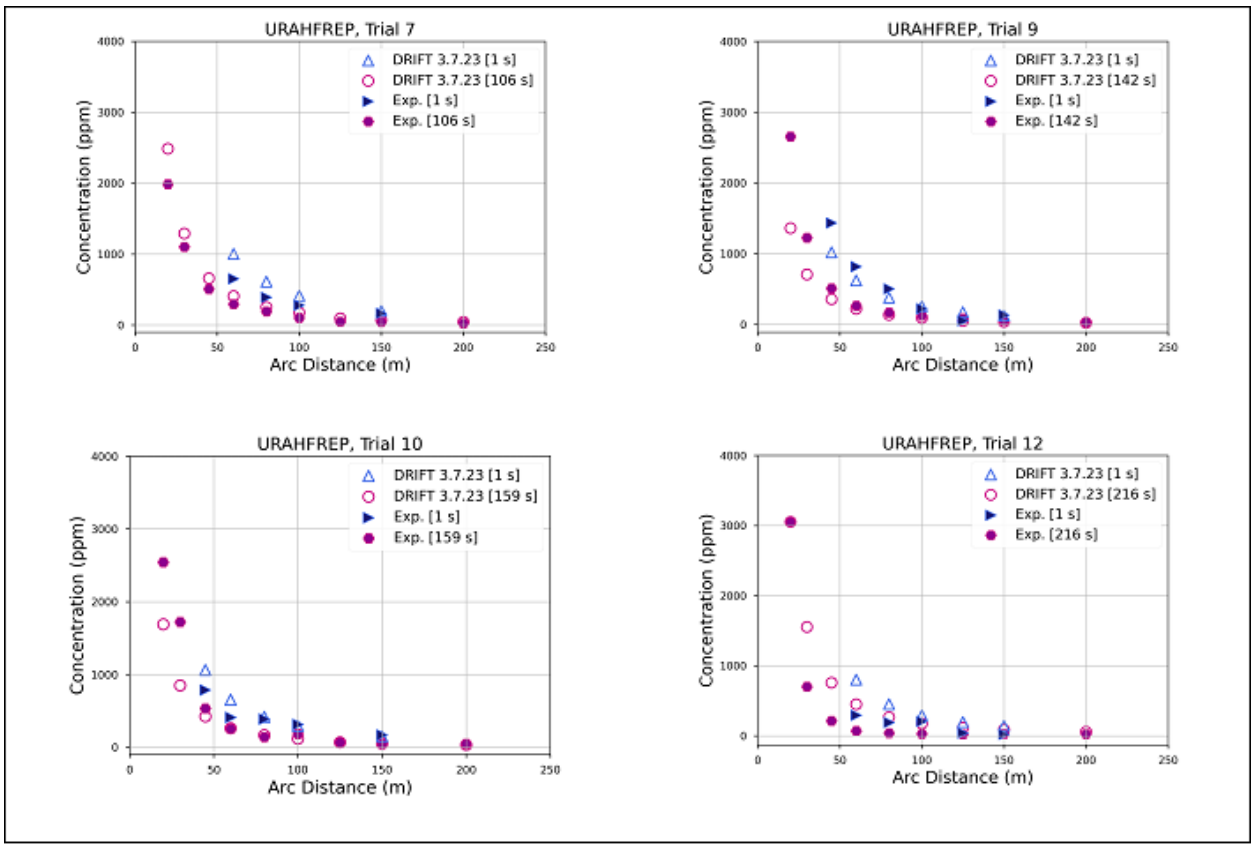


Figure 22 Observed and predicted maximum arcwise concentration data for URAHFREP. Square brackets indicate averaging time.

4.4 Aggregate scatter data – concentrations and cloud widths

Plots of centreline concentrations have been presented to assess the performance of DRIFT 3.7.23 against experimental data for each experimental trial.

The data is now categorised by experimental scale (field or wind-tunnel) and averaging time (short or long). Scatter plots for short-time averaged concentrations and long-time averaged concentrations across all field trials are presented in Figure 23 and Figure 24, respectively. No short-time averaged concentration data is available for wind-tunnel experiments, only long-time averaged concentrations, which are presented in Figure 25.

DRIFT 3.7.23 appears to perform equally well for both averaging times. Further discussion is left to the statistical analysis presented in Section 4.5.

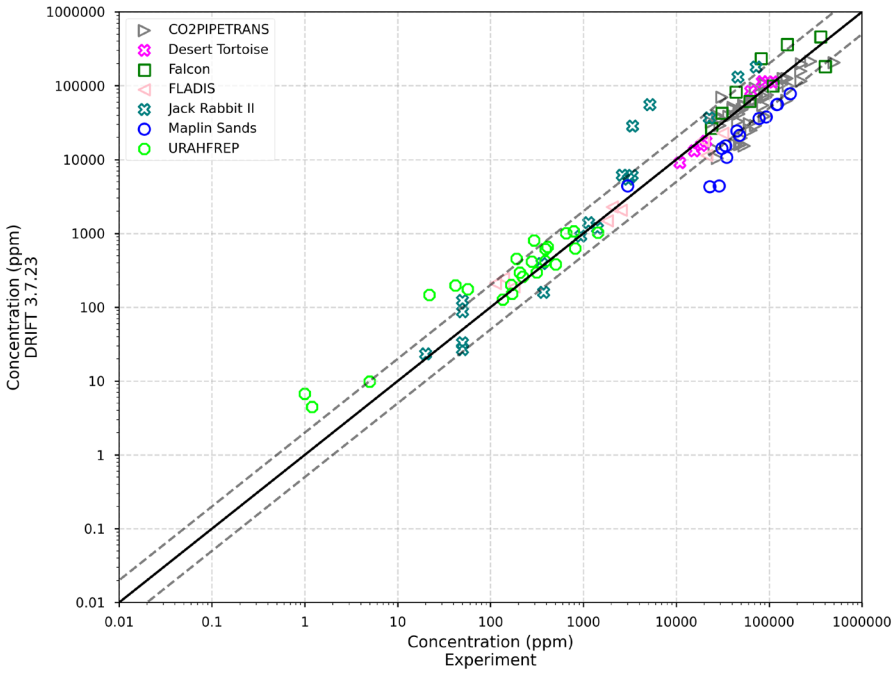


Figure 23 Short-time averaged concentration data scatter for all field trials. Solid line indicates where predicted is equal to measured. Dashed lines indicate a factor of two under- and overprediction.

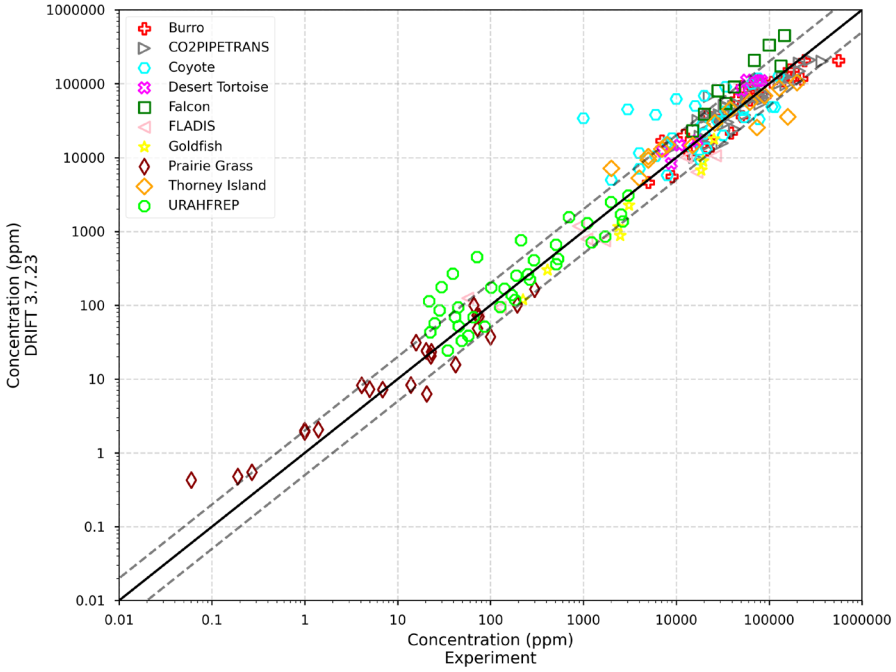


Figure 24 Long-time averaged concentration data scatter for all field trials. Solid line indicates where predicted is equal to measured. Dashed lines indicate a factor of two under- and overprediction.

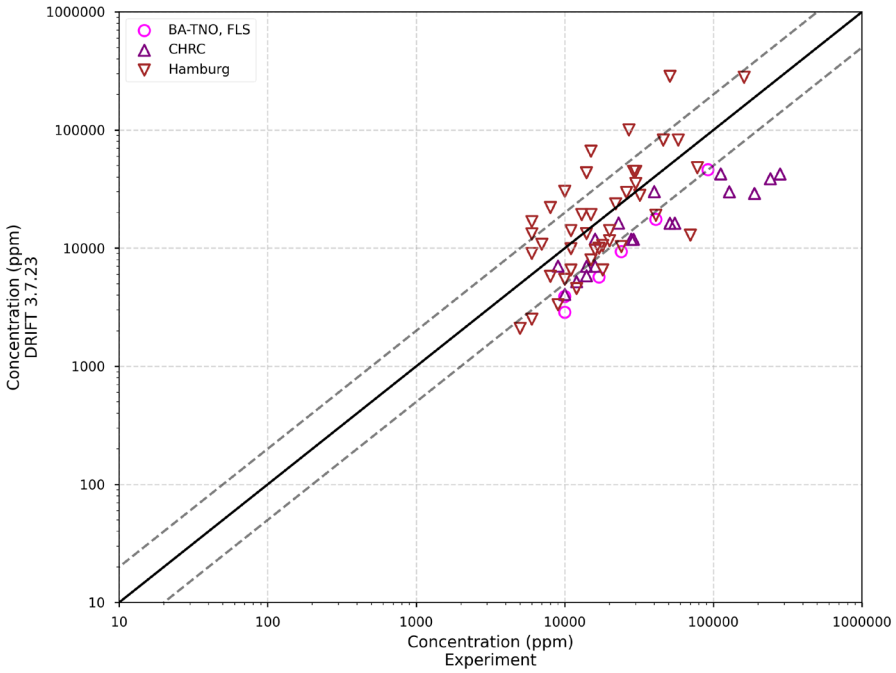


Figure 25 Long-time averaged concentration data scatter for all wind-tunnel trials. Solid line indicates where predicted is equal to measured. Dashed lines indicate a factor of two under- and overprediction.

Cloud widths calculated using the short-time averaged concentrations are only available for the FLADIS experiments (Nielson and Ott, 1996b). A scatter plot for this data is presented in Figure 26. A scatter plot for cloud widths calculated using the long-time averaged concentrations is presented in Figure 27 for all field trials.

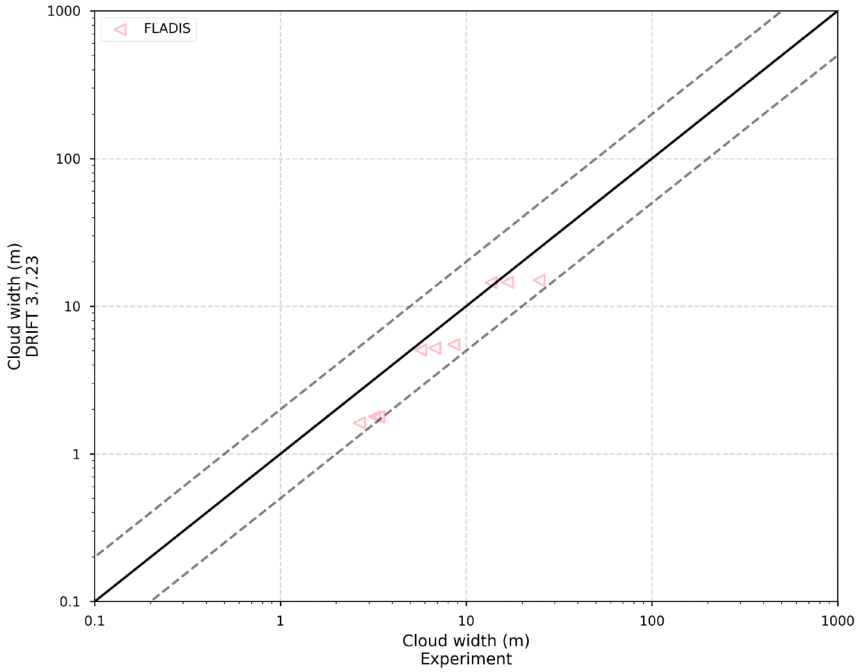


Figure 26 Short-time averaged cloud width data scatter for the FLADIS field trials. Solid line indicates where predicted is equal to measured. Dashed lines indicate a factor of two under- and overprediction.

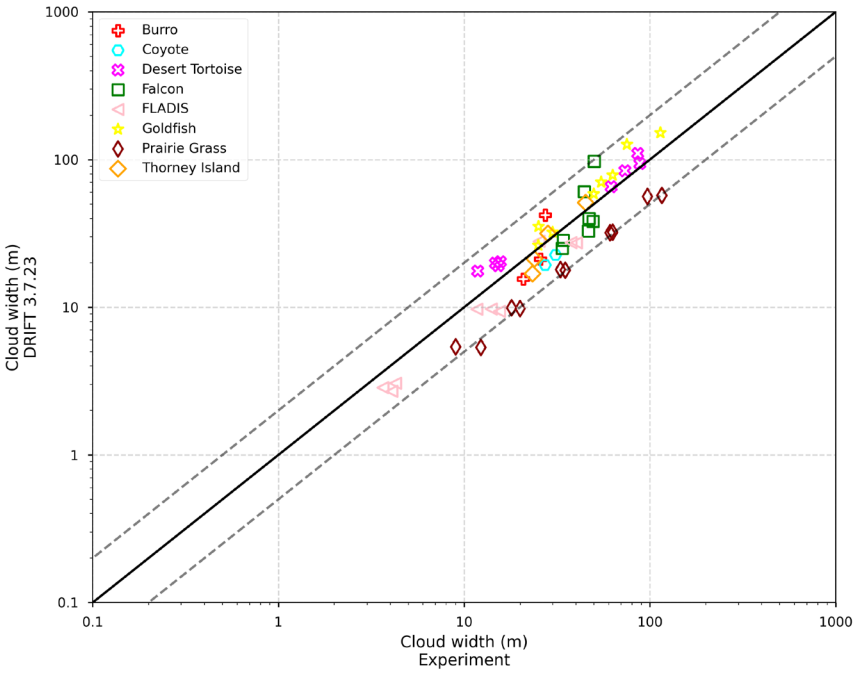


Figure 27 Long-time averaged cloud width data scatter for all field trials. Solid line indicates where predicted is equal to measured. Dashed lines indicate a factor of two under- and overprediction.

A scatter plot for cloud widths calculated using the long-time averaged concentrations is presented in Figure 28 for the wind-tunnel experiments. There is very good agreement between the predicted and experimentally measured cloud widths for both field and wind-tunnel scale experiments.

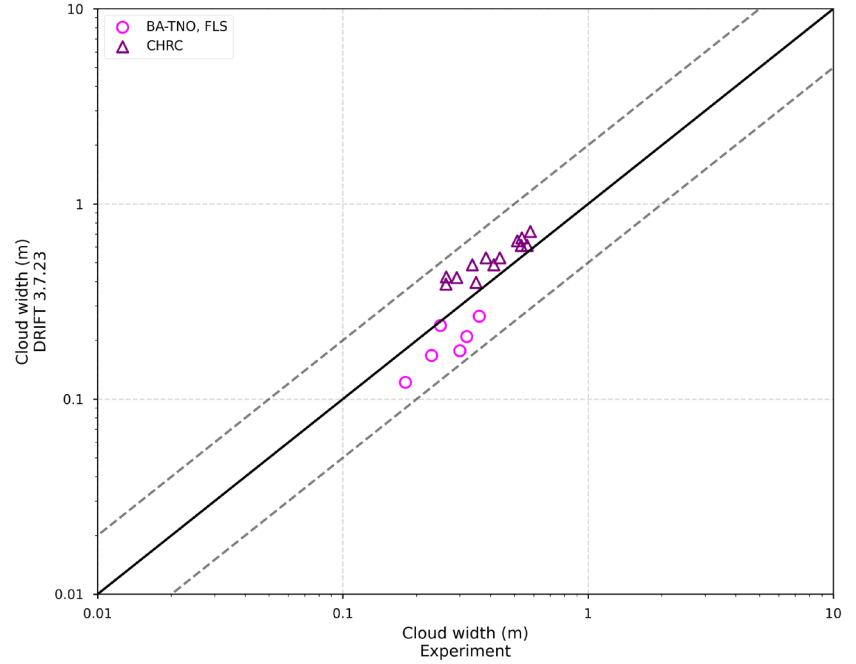


Figure 28 Long-time averaged cloud width data scatter for all wind-tunnel trials. Solid line indicates where predicted is equal to measured. Dashed lines indicate a factor of two under- and overprediction.

4.5 Evaluation against quantitative assessment criteria

The Statistical Performance Measures (SPM) recommended by Ivings et al. (2016) have been used to assess the performance of DRIFT 3.7.23. These are shown in Table 7, where C_m denotes the concentrations measured experimentally and C_p denotes the concentrations predicted by the model. Angled brackets denote an ensemble average over pairs of measured and predicted data. The quoted acceptability ranges are those defined by Ivings et al. (2016), based on the work of Chang and Hanna (2004) and Hanna et al. (1993a,b, 2004). Ivings et al. (2016) note that the experiments used to inform the work of Chang and Hanna (2004) and Hanna et al. (2004) are not exclusively dense gas dispersion experiments. These SPMs and acceptability ranges have therefore been used for all the trials in the DRIFT validation database. The same SPMs can be applied to the plume widths.

Table 7 Statistical performance measures (SPM) used to assess the performance of DRIFT. The SPMs are defined here for measured and predicted concentrations, but also apply to other measures, such as cloud width. Angled brackets denote an ensemble average over pairs of measured and predicted data.

SPM	Definition	Description	Acceptability range[a]
Mean Relative Bias (MRB)	$\mathrm{MRB} = \left\langle \frac{C_m - C_p}{\frac{1}{2}(C_p + C_m)} \right\rangle$	Indicates under- or overprediction on average	$-0.4 < \mathrm{MRB} < 0.4$
Mean Relative Square Error (MRSE)	$\mathrm{MRSE} = \left\langle \frac{(C_p - C_m)^2}{\frac{1}{4}(C_p + C_m)^2} \right\rangle$	Indicates scatter (variance)	$\mathrm{MRSE} < 2.3$
Fraction within a factor of two (FAC2)	$0.5 \leq \frac{C_p}{C_m} \leq 2.0$	Proportion of model predictions that fall within a factor of two of the measured values	$\mathrm{FAC2} > 0.5$
Geometric mean bias (MG)	$\mathrm{MG} = \exp\left\langle \ln\left(\frac{C_m}{C_p}\right) \right\rangle$	Indicates under- or overprediction on average, without being overly sensitive to extreme values	$0.67 < \mathrm{MG} < 1.5$
Geometric variance (VG)	$\mathrm{VG} = \exp\left\langle \left[\ln\left(\frac{C_m}{C_p}\right)\right]^2 \right\rangle$	Indicates the variance relating to MG	$\mathrm{VG} < 3.3$

[a] As defined in Ivings et al. (2016).

For $C_p = C_m$, both the geometric mean bias (MG) and the geometric variance (VG) equal 1. However, $\mathrm{MG} = 1$ does not necessarily mean a 'perfect' model where $C_p = C_m$ for all data

pairs. For example, it is possible to achieve $\mathrm{MG} = 1$ if underestimates and overestimates cancel one another out.

Figure 29 presents a plot of geometric variance (VG) against geometric mean bias (MG) for the concentration data. Again, the data has been categorised into experimental scale (field or wind-tunnel) and averaging time (short or long).

Also included in the VG versus MG plot are the following:

- vertical dot-dashed lines at $\mathrm{MG} = 0.5, 2.0$, indicating factor of two under- and overprediction
- a dashed line of $\mathrm{VG} = \exp(\ln \mathrm{MG})^2$, defining the minimum possible values of VG for a given MG
- a solid-line box enclosing the acceptability range, as presented in Table 7 and defined in Ivings et al. (2016)

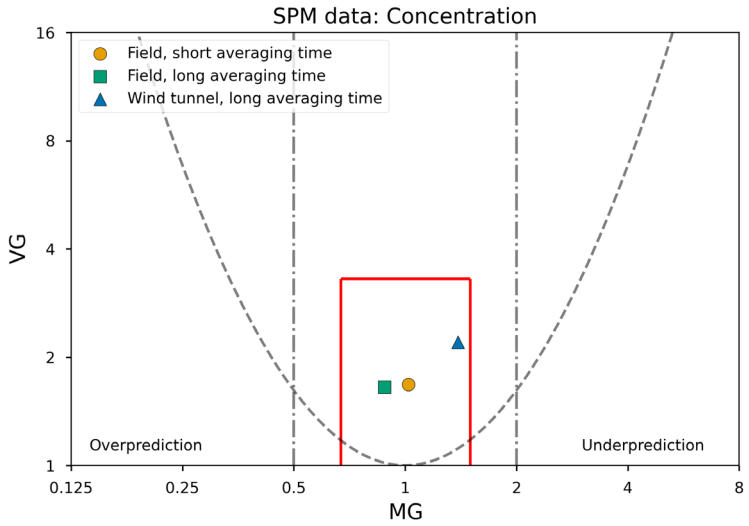


Figure 29 Geometric variance (VG) versus geometric mean bias (MG) based on concentration data.

Both sets of concentration data (short and long averaging times) for the field-scale experiments are within the acceptance criteria. They have a geometric mean bias of approximately 1, and a geometric variance below 2. Wind-tunnel scale results are also within the acceptance criteria, although there is a tendency for model underprediction.

Additional SPM data relating to the concentration data is given in Table 8. For the field-scale trials (both averaging times), MRB, MRSE and $\mathrm{FAC2}$ are within their acceptability ranges. For the wind-tunnel scale experiments, $\mathrm{FAC2} = 0.49$ indicates that just under 50% of the data is within a factor of two of the measured values. This is slightly outside the acceptability range of $\mathrm{FAC2} > 0.5$. Other measures are within their acceptability ranges.

Table 8 Statistical performance measures (SPM) data for field and wind-tunnel scale concentration data, with different averaging times.

Scale	Averaging time	MRB	MRSE	FAC2	MG	VG
Field	Short	0.03	0.40	0.67	1.02	1.68
Field	Long	-0.10	0.36	0.75	0.88	1.65
Wind-tunnel	Long[a]	0.30	0.62	0.49	1.39	2.20

[a] Averaging time of 1 s used in DRIFT, see Section 4.2.1.

SPM data has also been calculated from cloud width data and is displayed in Figure 30. Additional SPM data relating to the cloud width is given in Table 9. Although the cloud width predictions are within the acceptability criteria for all measures reported in Table 9, DRIFT 3.7.23 tends to slightly underpredict the cloud width for field trials and slightly overpredict the cloud width for wind-tunnel experiments.

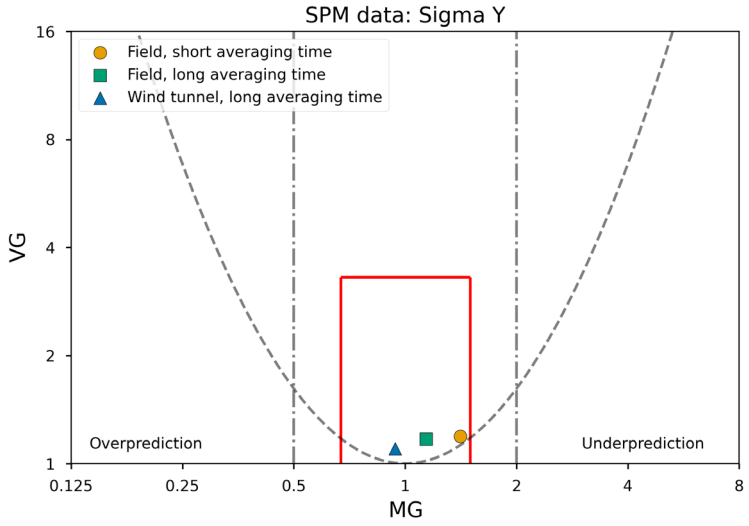


Figure 30 Geometric variance (VG) versus geometric mean bias (MG) based on cloud width data.

Table 9 Statistical performance measures (SPM) data for field and wind-tunnel scale cloud width data, with different averaging times.

Scale	Averaging time	MRB	MRSE	FAC2	MG	VG
Field	Short	0.34	0.16	1.00	1.41	1.19
Field	Long	0.13	0.15	0.94	1.14	1.17
Wind-tunnel	Long[a]	-0.07	0.09	1.00	0.94	1.10

[a] Averaging time of 1 s used in DRIFT, see Section 4.2.1.

4.6 Conclusions

This section has covered validation of DRIFT 3.7.23, following the definition of Ivings et al. (2013), where validation is the process of showing that a model accurately reproduces observed physical parameters across its intended range. Here the observed physical parameters are concentration and cloud width.

A database of experimental datasets has been collated. This work builds upon previous validation of DRIFT (Coldrick and Webber, 2017; Cruse and Coldrick, 2022), with some notable additions. Firstly, the latest version of the LNG database, Version 12 (Stewart et al. 2016) has been incorporated into this exercise. This contains data from eight experimental campaigns, covering a range of substances (LNG, CO_2, SF_6 and Freon-12), at both field and wind-tunnel scales. Secondly, the DRIFT validation database has been expanded with the addition of more experimental data relevant to the physics encountered in HSE's regulatory use of dispersion modelling. As a result, the model is validated against a greater range of plume behaviour (dense, passive), substances (ammonia, chlorine, HF), and release types (momentum jets).

Statistical performance measures (SPM) data have been calculated, where data has been categorised into experimental scale (field or wind-tunnel) and averaging time (short or long). There are five SPM measures, each of which has an acceptability range (Ivings et al., 2016). For the field-scale experiments, both concentration and cloud width data fall within the acceptability range for all five SPM.

For several of the wind-tunnel trials, DRIFT 3.7.23 predicts lower concentrations than those measured at the sensor nearest to the source, leading to underpredictions of concentration further downwind. This behaviour was also observed in previous DRIFT validation exercises (Coldrick and Webber, 2017; Cruse and Coldrick, 2022). However, all SPM for the wind-tunnel scale experiments are within their acceptability ranges, apart from $\mathrm{FAC2}$ for the concentration data. This takes a value of 0.49, slightly outside the acceptability range of $\mathrm{FAC2} > 0.5$.

There are several features of the wind-tunnel trials that differ from the field-scale trials. These include lower Reynolds number source and bulk flows (i.e. conditions closer to laminar flow) and a lack of wind meandering in the wind-tunnel trials, idealised source conditions, and the presence of geometrical features in some of the wind-tunnel trials (such as roughness elements and obstacles). These features may explain the underprediction of wind-tunnel concentration measurements in DRIFT 3.7.23.

The overall results from the model validation exercise demonstrate that DRIFT 3.7.23 is fit for purpose.

5 User-oriented aspects of the model

In the DRIFT Model Evaluation Protocol (Cruse et al., 2026), user-oriented aspects of the model are assessed through completion of the model questionnaire. The relevant subsections of the DRIFT 3.7.23 model questionnaire are reproduced in Section A4 of the appendices. The key points from the model questionnaire are summarised below.

5.1 Summary of model questionnaire findings

Users can interact with DRIFT 3.7.23 using either the GUI (Graphical User Interface) or the COM (Component Object Model) interface. The COM interface provides a programmatic means of inputting data, running the model and extracting output.

The GUI is intuitive to use and includes context-sensitive help and an inbuilt user manual. Further guidance on running DRIFT through the GUI is provided by ESR (2022). The COM interface was originally designed as a testing tool for model developers, but in recent years, the number of HSE users running DRIFT via the COM interface has increased. The COM interface guide (Walton, 2011) would benefit from being revised and expanded to provide more detailed guidance for these users.

For HSE users, two substance property databases are available within DRIFT 3.7.23: the ESR substance database and HSE's substance property database. The ESR substance database contains the substance property information required by DRIFT for 54 substances. It cannot be edited by general users. HSE's substance property database is in the form of SPI (Substance Property Information) files (Macbeth, 2004). 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. DRIFT's facility to read in data from SPI files enables HSE to add new substances to DRIFT when required for regulatory or research purposes.

Model output is displayed in the GUI in graphical and tabular format and can also be extracted using the COM interface. Table contents can be copied and pasted into other applications such as Excel. For all types of release, the DRIFT outputs include all the information required for HSE's current regulatory purposes.

For instantaneous, steady continuous and most finite duration releases, the user can generate custom tables that can include any global or component variables output by DRIFT. This facility is not required for regulatory work but can be useful for diagnostic purposes. Custom tables are not available for time-varying releases or for finite duration releases generated from .gasp files generated by the pool spreading and vaporisation model GASP (Gas Accumulation over Spreading Pools; Webber, 1990).

6 Exemplar testing

The aim of the exemplar testing is to assess the effect of changes to the model on its predictions for the types of release scenarios typically modelled by HSE for Hazardous Substances Consent assessments. The scenarios in the exemplar database have been chosen to cover the full range of scenarios modelled by HSE and include pool releases, flashing jet releases and flashing instantaneous releases of toxic and flammable substances. Releases from vessels, pipework and pipelines are included. The exemplar cases are scenarios that make a significant contribution to LUP (land use planning) zones, so the database is necessarily focused on larger releases.

The exemplar database contains a representative subset of the scenarios used to assess the performance of DRIFT 3.6.4 and DRIFT 3.6.14. These scenarios are described in detail in the series of HSE Research Reports that documents the testing of DRIFT 3.6 (Chaplin and Cruse, 2022; Cruse and Coldrick, 2022; Cruse, Lamb and McGillivray, 2017; Lamb and Cruse, 2022; McGillivray and Cruse, 2022).

6.1 Approach

The exemplar scenarios have been run in DRIFT 3.7.23 using a spreadsheet tool that has been developed for this purpose. The spreadsheet can extract the required DRIFT outputs and compare the outputs of two versions of DRIFT. The DRIFT 3.7.23 outputs have been compared with the outputs from DRIFT 3.6.14, the version of DRIFT currently used by HSE for regulatory purposes.

The comparisons between the outputs of DRIFT 3.7.23 and DRIFT 3.6.14 are described in Sections 6.2 to 6.5. In cases where there is a significant difference between the outputs of the two versions of DRIFT, the reason for the difference is explained, with reference to changes in the model physics.

The exemplar testing is a requirement of the DRIFT MEP to ensure consistency and robustness in the use of DRIFT for regulatory purposes. The exemplar testing also allows the performance of DRIFT to be assessed for scenarios which may lie beyond the range of the available validation data.

6.1.1 Physical comparison parameters

In the DRIFT MEP, the physical comparison parameters for the exemplar scenarios are the DRIFT outputs that are used in the calculation of LUP zones.

When a release of a toxic substance is modelled for regulatory purposes, DRIFT is used to calculate the isopleths within which the dose received is greater than the SLOT DTL (Specified Level of Toxicity, Dangerous Toxic Load) of the substance. The SLOT DTL is assumed to be equivalent to the LD1 (Lethal Dose 1), the dose that causes approximately 1% mortality in a normal population (HSE, no date). The SLOT DTL is also referred to as

the HSE Dangerous Dose for toxic substances, which is defined as the dose which is sufficient to cause:

- severe distress to almost everyone exposed to it
- a substantial fraction of the exposed population to require medical attention
- serious injuries to some people, requiring prolonged treatment
- possible fatalities to highly susceptible people

Separate calculations are carried out for outdoor and indoor recipients.

In the DRIFT MEP, the physical comparison parameters used for releases of toxic substances are:

- the maximum downwind distance to the SLOT DTL
- the maximum upwind distance to the SLOT DTL
- the maximum width of the SLOT DTL isopleth
- the downwind distance to the maximum width

When a release of a flammable substance is modelled for regulatory purposes, DRIFT is generally used to calculate the isopleths within which the concentration exceeds the lower flammable limit (LFL). In the DRIFT MEP, the physical comparison parameters used for the majority of the flammable release scenarios are:

- the maximum downwind distance to the LFL
- the maximum upwind distance to the LFL
- the maximum width of the LFL isopleth
- the downwind distance to the maximum width

The DRIFT output may also be used as an input for a VCE (Vapour Cloud Explosion) model. In such cases, the relevant physical comparison parameters are:

- the maximum flammable mass of the cloud
- the time at which the maximum flammable mass occurs (known as the ‘worst-case time’)

6.2 Pool releases

The exemplar database contains a number of pool releases, to examine the performance of DRIFT 3 when modelling the dispersion of vapour evolved from evaporating pools. For these scenarios, the pool spreading and vaporisation model GASP (Webber, 1990) was used to generate a source term for DRIFT 3. Pool sources are modelled in DRIFT 3 as gaseous low-momentum area sources using the finite duration sub-model.

6.2.1 Toxic exemplar scenarios

To study the dispersion of vapour evolved from pools of toxic substances, methyl iodide and ethylene oxide scenarios have been included in the exemplar database. The

scenarios are described in detail in Cruse, Lamb and McGillivray (2017) and Cruse and Coldrick (2022), and are summarised in Table 16 in Section B1 of the appendices. For each substance, an instantaneous release and a continuous release have been included in the database.

For methyl iodide, the continuous release scenario in the exemplar database is a release through a 250 mm diameter hole in a tank. The release rate was determined using the liquid flow rate sub-model (Serghides, 1984) within STREAM (HSE's in-house suite of programs to calculate outflow from vessels and pipes) and was found to be 462 kg/s for 364 s. The instantaneous release scenario is catastrophic failure of a tank, which is assumed to result in a pool containing 65.5 tonnes of methyl iodide.

For ethylene oxide, the release scenarios in the exemplar database are catastrophic failure of the storage vessel, resulting in the release of 90 tonnes of ethylene oxide, and a 50 mm diameter hole in the storage tank, resulting in the release of 45 tonnes of ethylene oxide at a rate of 37.4 kg/s (as determined using the liquid flow rate sub-model within STREAM).

Each scenario has been modelled in D2.4, D4.3, D6.7 and F2.4 weather conditions, which are the standard weather conditions used by HSE when modelling releases of toxic substances for the purposes of Hazardous Substances Consent assessment. (The letters D and F represent Pasquill stability classes: D denotes neutral conditions and F denotes stable conditions. The associated number gives the wind speed in metres per second at a reference height of 10 m.)

6.2.2 Flammable exemplar scenarios

To study the dispersion of vapour evolved from pools of flammable substances, LNG (liquefied natural gas) and liquefied hydrogen scenarios have been included in the exemplar database. The scenarios are summarised in Table 17 in Section B1 of the appendices. The LNG scenarios and the liquefied hydrogen tanker scenarios are described in detail in Chaplin and Cruse (2022).

The LNG release scenarios in the exemplar database correspond to a site containing one single-walled LNG storage tank, with a capacity of 21,000 tonnes, and comprise:

- catastrophic failure of the vessel and failure of the high wall bund
- major joint failure of the vessel and failure of the high wall bund (1000 mm hole)
- minor joint failure of the vessel and failure of the high wall bund (300 mm hole)
- catastrophic failure of the tank only with the high wall bund remaining intact
- failure of the LNG pipework during export from the tank

Each LNG scenario has been modelled in D2.4, D4.3, D6.7 and F2.4 weather conditions, which are the standard weather conditions used by HSE when modelling releases of flammable substances for the purposes of Hazardous Substances Consent assessment.

Two liquefied hydrogen tanker scenarios are included in the exemplar database: catastrophic failure of a tanker containing 3.5 tonnes of liquefied hydrogen and a

continuous release through a 50 mm hole in the same tanker, which was modelled as a 14.3 kg/s release of duration 245 s.

These scenarios have been modelled in D2.4, D4.3, D6.7 and F2.4 weather conditions. D10 and D15 weather conditions have also been modelled, as buoyant lift off of a cloud is considered less likely at higher wind speeds. Modelling high wind speeds ensures that scenarios that could harm a receiver at ground level are being considered.

Two further liquefied hydrogen scenarios are included in the exemplar database, to represent the types of scenarios that may result in a vapour cloud explosion (VCE): catastrophic failure of a 5 tonne storage tank and catastrophic failure of a 40 tonne storage tank. Each scenario has been modelled in D2.4, D4.3, D6.7 and F2.4 weather conditions. For these scenarios, the physical comparison parameter is the flammable mass of the cloud, which is used as an input to HSE's VCE model.

6.2.3 Comparison of DRIFT 3.7.23 and DRIFT 3.6.14

6.2.3.1 Ethylene oxide and methyl iodide

There is good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for the ethylene oxide and methyl iodide exemplar scenarios. For all the ethylene oxide scenarios, all the physical comparison parameters obtained in DRIFT 3.7.23 are within 3% of the values predicted by DRIFT 3.6.14. For methyl iodide, almost all the physical comparison parameters predicted by DRIFT 3.7.23 are within 2% of the values predicted by DRIFT 3.6.14, with the remaining outputs being within 7%.

6.2.3.2 Liquefied natural gas

DRIFT 3.7.23 incorporates improvements to the initialisation of the thin 'pancake' cloud over a low-momentum area source. These improvements rectify the unphysically large initial contour sizes observed in DRIFT 3.6.14 for scenarios in which the vapour evolved from the pool is not predicted to disperse far downwind. The LNG release scenarios representing leaks in a vessel or pipework onto dry soil in D4.3 and D6.7 weather conditions are affected by this issue. As a consequence, significant differences are observed between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs, as shown in Figure 31 for a major joint failure of the vessel in D4.3 weather conditions onto dry soil.

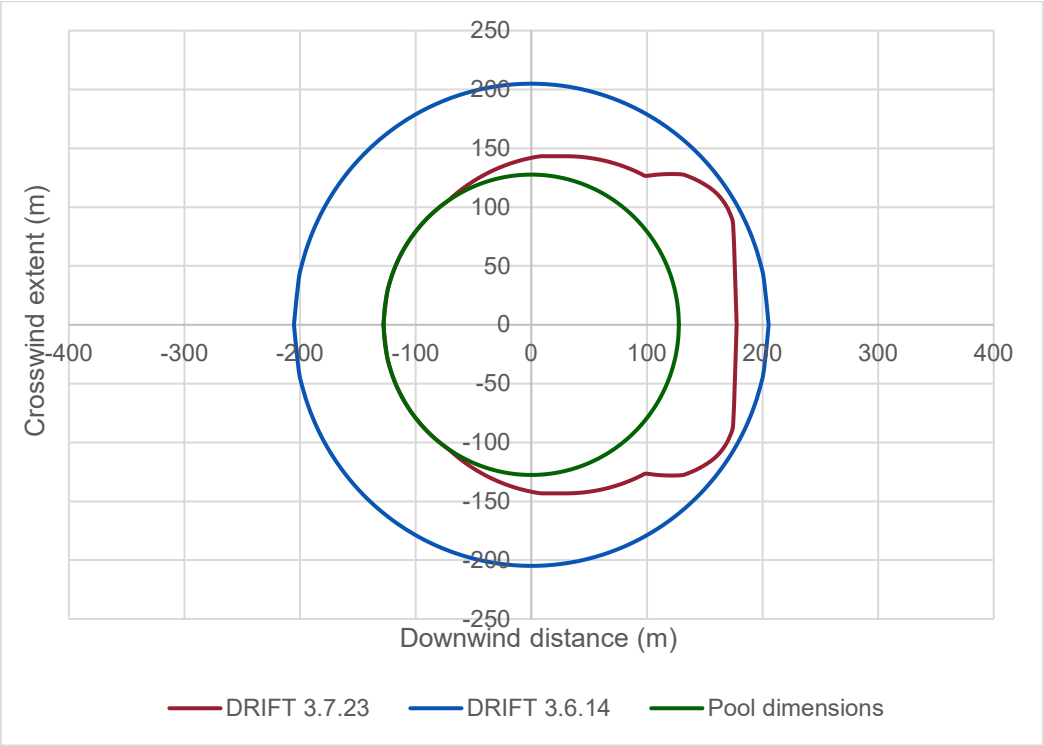


Figure 31 LFL isopleths predicted by DRIFT 3.7.23 and DRIFT 3.6.14 for a major joint failure of the vessel modelled in D4.3 weather conditions with dry soil. The dimensions of the pool source are also shown.

There is much closer agreement in the LFL isopleths predicted by DRIFT 3.7.23 and DRIFT 3.6.14 for the equivalent release on to wet soil. GASP predicts high evaporation rates for LNG pools on wet soil (for a major joint failure of a vessel in D4.3 weather conditions, the evaporation rate is 1629 kg/s on wet soil and 495.1 kg/s on dry soil), so the downwind dispersion distances are greater than those observed in dry conditions and the LFL isopleth dimensions are less sensitive to the source initialisation. The LFL isopleths predicted by DRIFT 3.7.23 and DRIFT 3.6.14 for a major joint failure of the vessel modelled in D4.3 weather conditions with wet soil are shown in Figure 32. For this exemplar scenario, the only significant differences between the DRIFT 3.7.23 and DRIFT 3.6.14 LFL isopleths are in the upwind extent and the width above source.

The same trend is seen across all the LNG scenarios in the exemplar database. Namely, for LNG scenarios where the downwind dispersion of the cloud extends beyond the pool source, the only significant differences between the DRIFT 3.7.23 and DRIFT 3.6.14 LFL isopleths are in the upwind extent and the width above source. Thus, for catastrophic vessel failures there is excellent agreement between the downwind dispersion distances predicted by DRIFT 3.6.14 and DRIFT 3.7.23. Excellent agreement between the two versions of the model is also obtained for all five LNG release scenarios when F2.4 weather conditions are modelled.

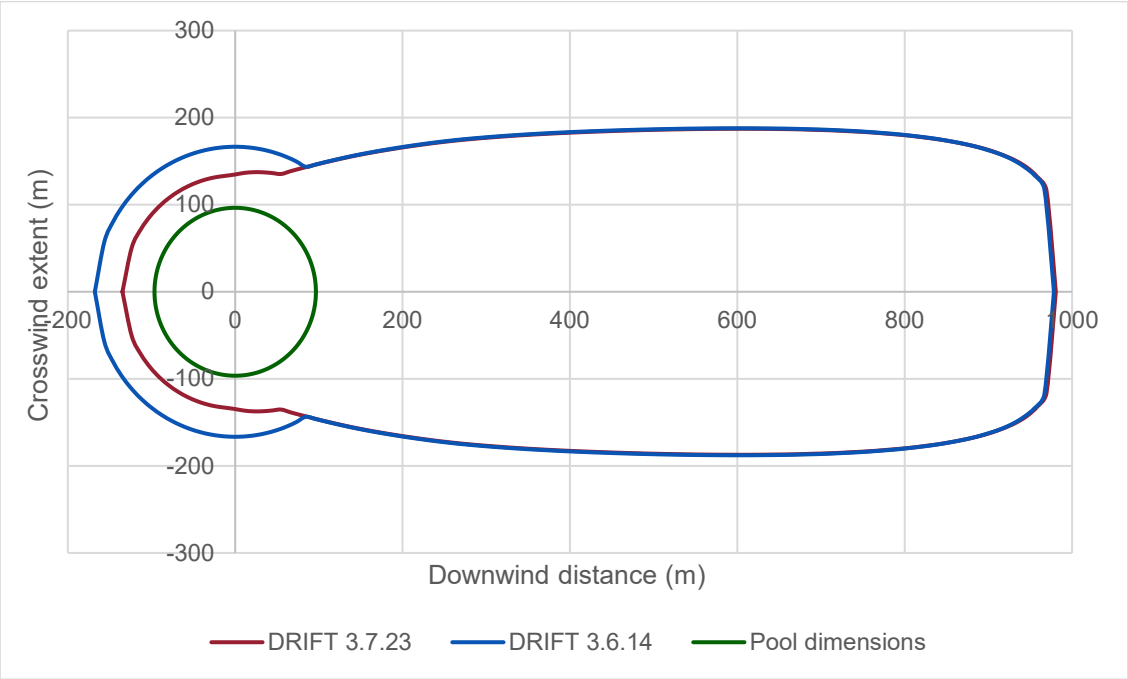


Figure 32 LFL isopleths predicted by DRIFT 3.7.23 and DRIFT 3.6.14 for a major joint failure of the vessel modelled in D4.3 weather conditions with wet soil. The dimensions of the pool source are also shown.

6.2.3.3 Liquefied hydrogen vessel scenarios

For the majority of the liquefied hydrogen vessel scenarios, there is good agreement between the downwind dispersion distances predicted by DRIFT 3.7.23 and DRIFT 3.6.14. However, the releases have a greater propensity for buoyant lift off in DRIFT 3.7.23 than in DRIFT 3.6.14: for example, for a catastrophic failure of a hydrogen vessel in D4.3 weather conditions, the cloud centreline is predicted to reach an elevation of approximately 90 m in DRIFT 3.6.14 and 140 m in DRIFT 3.7.23. Between DRIFT 3.6.14 and DRIFT 3.7.23, the transition between the grounded and elevated models was modified, to improve the fit to the URAHFREP data (Porter and Nussey, 2001; Ott and Jørgensen, 2002). It is this modification that means that a plume is more likely to lift off in DRIFT 3.7.23 than in DRIFT 3.6.14.

The largest difference between the downwind dispersion distances predicted by the two versions of DRIFT is observed for a catastrophic failure of a hydrogen vessel in F2.4 weather conditions. For this scenario, the downwind dispersion distance predicted by DRIFT 3.7.23 is 8% larger than that predicted by DRIFT 3.6.14. In DRIFT 3.7.23, the cloud lifts off and rapidly reaches the top of the boundary layer where elevated passive mixing is small. In DRIFT 3.6.14, the cloud does not significantly lift off and ground-based mixing may dominate, leading to greater dilution of the cloud and a shorter downwind dispersion distance.

For the liquefied hydrogen vessel scenarios, the plume widths predicted by DRIFT 3.7.23 are 10% to 20% smaller than those predicted by DRIFT 3.6.14. Given that the plume rise heights for these scenarios are greater in DRIFT 3.7.23 than in DRIFT 3.6.14, but the downwind dispersion distances are similar, a possible explanation for this observation is

the influence of the wind speed increasing with height. Based on the conservation of contaminant mass, a plume moving at a greater speed must be narrower than a plume of the same concentration moving at a lesser speed.

6.2.3.4 Liquefied hydrogen VCE scenarios

The maximum flammable mass of the cloud predicted by DRIFT 3.6.14 and DRIFT 3.7.23, and the time at which this occurs, are shown in Table 10 for catastrophic failure of 5 tonne and 40 tonne liquefied hydrogen vessels.

Table 10 The flammable mass of the cloud and the time at which this occurs (the 'worst-case' time) for catastrophic failure of 5 tonne and 40 tonne liquefied hydrogen vessels.

Vessel size (tonnes)	Weather	Model	Flammable mass (kg)	Worst-case time (s)
5	D2.4	3.6.14 3.7.23	1436 1433	3.4 3.4
5	D4.3	3.6.14 3.7.23	1365 1330	3.4 3.5
5	D6.7	3.6.14 3.7.23	1290 1282	3.4 3.4
5	F2.4	3.6.14 3.7.23	1922 1911	3.5 3.7
40	D2.4	3.6.14 3.7.23	6185 8189	24.0 23.9
40	D4.3	3.6.14 3.7.23	4720 6436	17.4 26.8
40	D6.7	3.6.14 3.7.23	8073 8567	24.0 24.1
40	F2.4	3.6.14 3.7.23	16,932 15,351	25.3 20.4

For the catastrophic failure of a 5 tonne liquefied hydrogen storage vessel, there is excellent agreement between the flammable cloud masses predicted by DRIFT 3.7.23 and DRIFT 3.6.14. For the catastrophic failure of a 40 tonne vessel, DRIFT 3.7.23 predicts larger flammable masses than DRIFT 3.6.14 in D weather conditions, with the largest differences (approximately 30%) occurring for wind speeds of 2.4 m/s and 4.3 m/s. In F2.4 weather conditions, the flammable mass predicted by DRIFT 3.7.23 for the catastrophic failure of a 40 tonne vessel is approximately 10% smaller than the flammable mass predicted by DRIFT 3.6.14.

For these scenarios, at the time of the maximum flammable mass the cloud is dominated by build-up over the source in both DRIFT 3.6.14 and DRIFT 3.7.23. DRIFT 3.6.14 and

DRIFT 3.7.23 differ in the modelling of build-up over the source: DRIFT 3.7.23 builds up the concentration from a small value and does not transition to a grounded cloud if the cloud is buoyant, whereas DRIFT 3.6.14 starts with a higher cloud concentration and may transition to the ground-based model even for a buoyant release. There are therefore some subtle differences in the cloud dynamics between DRIFT versions over this time period. Differences due to buoyancy effects (such as these) will be greater for larger releases, so larger differences in the DRIFT 3.7.23 and DRIFT 3.6.14 outputs are observed for the 40 tonne release than for the 5 tonne release.

6.3 Flashing instantaneous releases

If a storage vessel containing a pressure-liquefied gas fails, the liquid will flash on release. Some of the released material will be converted directly into vapour, some will be entrained in the vapour as liquid droplets, and the remaining material will rain out to form a pool. The proportion of the release that becomes airborne and the proportion that enters the pool depend on parameters such as the storage conditions, which determine the degree of superheat and therefore the flash fraction.

The initial stages of a flashing instantaneous release from a catastrophic failure of a vessel storing a pressure-liquefied gas are modelled in ACE (Gilham et al., 1999; Shepherd and Deaves, 2000). ACE is a source term model that predicts both the properties of the airborne cloud that is generated and the amount of released material that will form a pool.

The initial airborne component of the release is modelled as an instantaneous two-phase release in DRIFT, using a source term generated by the ACE model. The pool component of the release is modelled as a finite duration gaseous low-momentum area source in DRIFT, using a source term generated by ACE and GASP.

DRIFT 3.7.23 can add the concentration from an initial airborne (direct) source to the concentration from an evaporating pool and generate a single set of isopleths that represents the combined harm from both sources. In this analysis, however, the airborne and pool components are considered separately, to enable a direct comparison with the outputs of DRIFT 3.6.14.

6.3.1 Toxic exemplar scenarios

The exemplar database includes instantaneous releases of toxic pressure-liquefied gases. Chlorine, sulphur dioxide and ammonia release scenarios are considered. The release masses are based on typical vessel sizes at small- and large-scale chlorine facilities and range from 1 tonne to 100 tonnes. Each substance is assumed to be stored at its saturated vapour pressure at ambient temperature. The airborne component of each release has been modelled in D2.4, D4.3, D6.7 and F2.4 weather conditions. For selected scenarios (storage quantities of 1 tonne, 10 tonnes and 100 tonnes in D4.3 and F2.4 weather conditions), the pool component of the release has also been considered. These scenarios are described in more detail in McGillivray and Cruse (2022).

Additional ammonia scenarios have been included in the database to represent releases from refrigerated large-scale ammonia storage, typical of the facilities being proposed to satisfy net-zero applications. 1000 tonne, 10,000 tonne and 100,000 tonne releases from a refrigerated ammonia vessel have been modelled in D2.4, D4.3, D6.7 and F2.4 weather conditions. For all weather conditions, both the airborne and pool components of the release have been considered.

Flashing instantaneous releases of substances that are heated above their normal boiling point temperature in process vessels or reactors are also included in the database. Methyl chloroformate, propionitrile, 2-chloroethanol and acrolein are liquid at standard atmospheric temperature and pressure. To represent process vessel or reactor failures, these substances are assumed to be stored at a temperature that gives a saturation vapour pressure of 4 barg (bar gauge pressure). The scenarios in the database comprise release masses of 1 tonne, 10 tonnes and 100 tonnes modelled in D4.3 and F2.4 weather conditions. For each of these scenarios, both the airborne and the pool components of the release have been considered. These scenarios are described in more detail in McGillivray and Cruse (2022).

The toxic exemplar scenarios for flashing instantaneous releases are summarised in Table 18 in Section B2 of the appendices.

6.3.2 Flammable exemplar scenarios

Instantaneous releases of liquefied flammable gases are represented in the exemplar database by isobutane and propane release scenarios. The isobutane exemplar scenario is catastrophic failure of a 1056 tonne vessel at 5.5 barg and ambient temperature. The propane release is assumed to occur from a 548 tonne vessel at saturated vapour pressure and ambient temperature. For each of these scenarios, both the airborne and the pool components of the release have been considered, in D2.4, D4.3, D6.7 and F2.4 weather conditions.

These scenarios are described in detail in Chaplin and Cruse (2022), and are summarised in Table 19 in Section B2 of the appendices.

6.3.3 Comparison of DRIFT 3.7.23 and DRIFT 3.6.14

6.3.3.1 Chlorine

There is excellent agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for flashing instantaneous releases of chlorine, for both the airborne and pool components. The majority of the physical comparison parameters predicted by DRIFT 3.7.23 are within 1% of the values predicted by DRIFT 3.6.14.

The only significant differences between the outputs of the two models are caused by improvements in the initialisation of the thin ‘pancake’ cloud over an area source that were implemented in DRIFT 3.7.1. As a consequence of these improvements, the upwind spread predicted by DRIFT 3.7.23 for pool scenarios in D4.3 weather is approximately 20% smaller than that predicted by DRIFT 3.6.14. This upwind spread is negligible in comparison to the downwind dispersion distance (for the pool component of a catastrophic

failure of a 100 tonne chlorine tank, the upwind spread to the SLOT DTL is 36 m and the maximum downwind distance to the SLOT DTL is 3170 m).

6.3.3.2 Sulphur dioxide

There is very good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for flashing instantaneous releases of sulphur dioxide, for both the airborne and pool components. The majority of the physical comparison parameters predicted by DRIFT 3.7.23 are within 3% of the values predicted by DRIFT 3.6.14.

For the pool component of 15 tonne and 100 tonne releases of sulphur dioxide in F2.4 weather conditions, the upwind spread predicted by DRIFT 3.7.23 is approximately 15% smaller than that predicted by DRIFT 3.6.14. However, in both cases the upwind spread to the SLOT DTL is negligible in comparison to the downwind dispersion distance to the SLOT DTL.

For the airborne component of a catastrophic failure of a 15 tonne tank in D6.7 weather conditions, the maximum width of the SLOT DTL isopleth for an indoor recipient is incorrectly reported in the table of hazard ranges in the DRIFT 3.6.14 GUI. This misreporting is caused by the search algorithm not being allowed sufficient iterations to converge on the downstream distance/travel time at which the maximum cloud width occurs. This convergence difficulty occurs for instantaneous releases in D weather in which the maximum cloud width occurs relatively close to the source. In DRIFT 3.7.23 the maximum number of iterations has been increased, resolving this issue.

As a result of this reporting issue, the width reported in the table of hazard ranges in DRIFT 3.6.14 for the above release (the airborne component of a catastrophic failure of a 15 tonne tank in D6.7 weather conditions) is approximately half that reported by DRIFT 3.7.23. However, the indoor isopleth displayed in the plan view in the DRIFT 3.6.14 GUI has the same width and upwind and downwind extent as the indoor isopleth predicted by DRIFT 3.7.23.

6.3.3.3 Pressure-liquefied ammonia

There is good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for the airborne component of flashing instantaneous releases of ammonia. The majority of the physical comparison parameters predicted by DRIFT 3.7.23 are within 5% of the values predicted by DRIFT 3.6.14 and for many outputs, the agreement is much closer than that.

For some 7.5 tonne, 10 tonne and 15 tonne releases in D weather conditions, a reporting error in the DRIFT 3.6.14 GUI (discussed in Section 6.3.3.2) causes the maximum width of the SLOT DTL isopleth for an outdoor recipient in the DRIFT 3.6.14 table of hazard ranges to be up to 20% smaller than that reported by DRIFT 3.7.23. However, the plan view isopleths reported by DRIFT 3.7.23 and DRIFT 3.6.14 are in good agreement.

For the pool component of flashing instantaneous releases of ammonia, the SLOT DTL isopleth dimensions predicted by DRIFT 3.7.23 in F2.4 weather conditions are significantly smaller than those predicted by DRIFT 3.6.14, as shown in Table 11.

Table 11 Physical comparison parameters for the pool component of flashing instantaneous releases of pressure-liquefied ammonia in F2.4 weather conditions.

Vessel size (tonnes)	Model	Maximum downwind distance to the SLOT DTL (m)	Maximum upwind distance to the SLOT DTL (m)	Maximum width to the SLOT DTL (m)
1	3.6.14 3.7.23	52 14	13 13	28 26
10	3.6.14 3.7.23	188 86	28 27	63 55
100	3.6.14 3.7.23	537 371	54 49	122 103

The change in the interpolation used between ground-based and elevated clouds to improve the fit to the URAHFREP wind-tunnel data could account for the significant differences in predictions between DRIFT 3.7.23 and DRIFT 3.6.14 for ammonia dispersion from pools. DRIFT 3.7 can predict greater lift off than DRIFT 3.6, as illustrated in Figure 2-8 of Tickle (2025a). When the plume becomes elevated, but has not reached the elevated inversion height which caps the atmospheric boundary layer, there is initially greater mixing (since air entrainment can occur at the bottom of the plume, in addition to the sides and top). This can lead to greater dilution and shorter downwind dispersion distances.

In DRIFT, the relative contribution of the ground and elevated models is characterised by the cloud profile parameter. The cloud profile parameter indicates that the fraction of the elevated model in DRIFT 3.7.23 is higher than in DRIFT 3.6.14 for all the scenarios in Table 11.

6.3.3.4 Refrigerated ammonia

As was observed for the releases of pressure-liquefied ammonia, there is good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for the airborne component of refrigerated releases of ammonia. The majority of the physical comparison parameters predicted by DRIFT 3.7.23 are within 5% of the values predicted by DRIFT 3.6.14 and for many outputs, the agreement is much closer than that.

For the pool component of the 1000 tonne release of refrigerated ammonia, there is good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs in D weather conditions. For the 10,000 tonne release, there is good agreement between the model versions in D4.3 and D6.7 weather conditions, whereas for the 100,000 tonne release, there is only good agreement in D6.7 weather conditions. Where there is not good agreement, the downwind dispersion distances predicted by DRIFT 3.7.23 are larger than those predicted by DRIFT 3.6.14. The outputs in F2.4 weather conditions are shown in Table 12. The downwind dispersion distances predicted by DRIFT 3.7.23 are larger than those predicted by DRIFT 3.6.14, and the difference between the outputs of the two models increases with release size.

When simulating a low-momentum area release, DRIFT first runs its instantaneous model to establish steady-state source conditions for the subsequent steady-state dispersion. DRIFT 3.7.23 includes a bug fix, which corrects the touchdown logic for a buoyant cloud to enable subsequent lift off of a touched-down buoyant cloud. For the pool component of a refrigerated ammonia release, this fix leads to a change in the end point of the initial instantaneous run.

In DRIFT 3.7.23, the steady-state source conditions predicted by the instantaneous model correspond to a cloud having a smaller negative Richardson number than is predicted by DRIFT 3.6.14. The smaller negative Richardson number for DRIFT 3.7.23 is in part related to the higher centroid height reached above the source by the instantaneous model (in comparison to DRIFT 3.6.14) and the smaller ambient air density at the higher centroid height.

A smaller negative Richardson number results in less dilution in the subsequent plume, giving rise to the larger downwind dispersion distances in DRIFT 3.7.23. The greatest differences between the outputs of DRIFT 3.6.14 and DRIFT 3.7.23 are seen for the largest release sizes. This is consistent with a dependence on Richardson number – a larger release results in a larger magnitude Richardson number and a greater effect.

Table 12 Physical comparison parameters for the pool component of flashing instantaneous releases of refrigerated ammonia in F2.4 weather conditions.

Vessel size (tonnes)	Model	Maximum downwind distance to the SLOT DTL (m)	Maximum upwind distance to the SLOT DTL (m)	Maximum width to the SLOT DTL (m)
1000	3.6.14 3.7.23	1401 1581	145 142	339 319
10,000	3.6.14 3.7.23	4383 8337	313 259	828 672
100,000	3.6.14 3.7.23	11,132 27,768	683 542	1937 1816

6.3.3.5 2-Chloroethanol, methyl chloroformate, propionitrile and acrolein

There is generally very good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for both the airborne and the pool components of heated releases from process vessels.

For methyl chloroformate, all the physical comparison parameters output by DRIFT 3.7.23 are within 2% of those predicted by DRIFT 3.6.14. For propionitrile, all the physical comparison parameters output by DRIFT 3.7.23 are within 5% of those predicted by DRIFT 3.6.14, and for the vast majority of outputs, the agreement is to within 1%.

For 2-chloroethanol, the majority of the physical comparison parameters output by DRIFT 3.7.23 are within 4% of those predicted by DRIFT 3.6.14. The only exception is the maximum downwind dispersion distance to the SLOT DTL for the pool component of

10 tonne and 100 tonne releases in F2.4 weather conditions. For these scenarios, the downwind distance predicted by DRIFT 3.7.23 is approximately 20% lower than that predicted by DRIFT 3.6.14.

The modification to the interpolation between the grounded and elevated models that has been implemented in DRIFT 3.7 could account for these differences. The cloud profile parameter indicates that the fraction of the elevated model in DRIFT 3.7.23 is higher than in DRIFT 3.6.14 for these scenarios, which leads to increased mixing and shorter downwind dispersion distances.

For acrolein, the majority of the physical comparison parameters predicted by DRIFT 3.7.23 are within 5% of the values predicted by DRIFT 3.6.14 and for most outputs, the agreement is within 1%. The only scenario for which there is a significant difference between the outputs of the two versions of the model is the 100 tonne release in F2.4 weather conditions. For the airborne component of this release, the downwind dispersion distance predicted by DRIFT 3.7.23 is approximately 20% larger than that predicted by DRIFT 3.6.14, for both outdoor and indoor recipients.

6.3.3.6 Isobutane and propane

There is very good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for the airborne components of the isobutane and propane releases. For both substances, almost all the physical comparison parameters output by DRIFT 3.7.23 are within 2% of those predicted by DRIFT 3.6.14, and for many scenarios, the agreement is much closer than that. The only exceptions to this are the downwind distances to the maximum width for propane releases in D2.4 and F2.4 weather conditions, which agree to within 5%.

For the pool components of the isobutane and propane releases, there is excellent agreement between the downwind dispersion distances predicted by DRIFT 3.7.23 and DRIFT 3.6.14 (to within 1%). The upwind spread predicted by DRIFT 3.7.23 is 30% to 40% smaller than that predicted by DRIFT 3.6.14. As was observed for LNG, it is likely that the reduction in the upwind spread in DRIFT 3.7.23 has been caused by improvements in the initialisation of the thin ‘pancake’ cloud over an area source that were implemented in DRIFT 3.7.1. In D4.3 and D6.7 weather conditions, the improvements to the source initialisation also result in a reduction in the maximum isopleth width in DRIFT 3.7.23, in comparison to the DRIFT 3.6.14 predictions.

6.4 Momentum jet releases

A leak in a pressurised storage vessel or pipework will result in a momentum jet release. DRIFT 3 incorporates a jet model and can calculate the initial air entrainment into the jet. DRIFT 3 requires a release rate as input, which is calculated using STREAM (HSE’s in-house suite of programs to calculate outflow from vessels and pipes).

Releases from the vapour space of storage vessels are modelled as finite duration gaseous momentum jets in DRIFT 3, and the release rate is set equal to the flow rate calculated by STREAM.

If a leak occurs in pipework or the liquid space of a storage vessel containing a pressure-liquefied gas, the liquid will flash on release. Some of the released material will be converted directly into vapour, some will be entrained in the vapour as liquid droplets, and the remaining material 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 (the vapour and entrained liquid droplets) and the component that rains out. In the exemplar database, the contributions from the two components are considered separately.

DRIFT 3 does not model rainout itself but can take a rainout fraction as input. The rainout fraction is determined using the HSE model RAIN. RAIN requires the substance, stagnation temperature and ambient temperature as inputs and contains correlations derived from an analysis of CCPS (Center for Chemical Process Safety) measurements of jet releases (Johnson and Woodward, 1999; Tickle, 2015). To model the initial airborne component of a flashing release from below the liquid line of a storage vessel, the flow rate from STREAM is input directly into DRIFT 3, together with the rainout fraction predicted by RAIN. The rainout liquid is assumed to be directly deposited on the ground at the source and does not contribute further to the atmospheric dispersion. The release is modelled in DRIFT 3 as a finite duration momentum jet, using the superheated liquid / two-phase release option.

The spreading and vaporisation of the pool formed by the portion of the release that rains out is modelled using GASP (Webber, 1990). The rate at which material enters the pool is assumed to be equal to the flow rate calculated by STREAM multiplied by the rainout fraction determined using RAIN. The time over which the rained-out liquid enters the pool is assumed to be equal to the release duration for the initial airborne component. However, evaporation from the pool is assumed to continue for 30 minutes, or until all the material in the pool has been vaporised if this occurs sooner. The GASP output is used as a source term for DRIFT 3.

6.4.1 Toxic exemplar scenarios

The exemplar database contains momentum jet releases of chlorine, ammonia and sulphur dioxide. For the purposes of Hazardous Substances Consent assessment, HSE has defined examples of large and small chlorine sites, to allow generic land-use-planning zones for chlorine sites to be calculated. The small chlorine site is assumed to have a single 15 tonne vessel at saturated vapour pressure. The large chlorine site is assumed to have four 100 tonne vessels at a pressure of 6.9 barg (7.9 bara).

The chlorine exemplar scenarios are a subset of the scenarios that would be considered for a full assessment of the large and small chlorine sites. The exemplar scenarios focus on the larger releases that could occur and include vessel holes above and below the liquid line and liquid pipework releases.

For the vessel releases, the release duration is either 30 minutes (1800 s), or the time taken for half the vessel inventory to be released, if shorter. For each pipework release, two scenarios are modelled: one in which an automatic shut-off valve (ASOV) activates after 1 minute, and one in which the ASOV fails, and a manual shut-off valve is closed

after 20 minutes (1200 s). A guillotine failure is modelled for the small chlorine site and a severe split is modelled for the large chlorine site.

The airborne component of each of the chlorine scenarios has been modelled in D2.4, D4.3, D6.7 and F2.4 weather conditions. For selected scenarios (a 50 mm hole in a storage vessel in D4.3 and F2.4 weather conditions), the pool component of the release is also included in the exemplar database.

A release of sulphur dioxide through a 50 mm hole in the liquid space of a 100 tonne storage vessel is included in the exemplar database. It is assumed that the sulphur dioxide is stored at its saturated vapour pressure. For this scenario, both the airborne and the pool components of the release have been considered, in D4.3 and F2.4 weather conditions.

The ammonia scenarios in the exemplar database comprise a release through a 50 mm hole in the liquid space of a 100 tonne storage vessel, a guillotine failure of liquid pipework and a severe split of liquid pipework. It is assumed that the ammonia is stored at its saturated vapour pressure (SVP). For the vessel release, the release duration is the time taken for half the vessel inventory to be released. For each pipework release, two scenarios are modelled: one in which an automatic shut-off valve (ASOV) activates after 1 minute, and one in which the ASOV fails, and a manual shut-off valve is closed after 20 minutes (1200 s). The airborne component of each release has been modelled in D2.4, D4.3, D6.7 and F2.4 weather conditions. The RAIN model predicts that there will be no rainout for these releases.

These scenarios are described in detail in Lamb and Cruse (2022), and are summarised in Table 20 in Section B3 of the appendices.

6.4.2 Flammable exemplar scenarios

The flammable momentum jet scenarios in the exemplar database originate from HSE's 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. Holes and ruptures from the compressor and the pipeline are considered.

In the siting policy, natural gas is modelled as methane and release rates are calculated using PFAF (Pipeline Flowrate And Fireball Model, an in-house HSE model). The compressor is assumed to be at a pressure of 85 barg and a temperature of 5 °C, independent of the ambient temperature. The release scenarios are modelled in D2.4, D4.3, D6.7 and F2.4 weather conditions.

These scenarios are described in detail in Chaplin and Cruse (2022), and are summarised in Table 21 in Section B3 of the appendices.

6.4.3 Comparison of DRIFT 3.7.23 and DRIFT 3.6.14

6.4.3.1 Chlorine

There is excellent agreement between the SLOT DTL isopleths predicted by DRIFT 3.7.23 and DRIFT 3.6.14 for the pool component of the chlorine jet releases. For all the scenarios modelled, the agreement is to within 1%.

For the airborne component of chlorine jet releases, DRIFT 3.7.23 generally predicts shorter, wider SLOT DTL isopleths than predicted by DRIFT 3.6.14. This is illustrated in Figure 33 for a release from a 50 mm hole in liquid pipework in F2.4 weather conditions, with a release duration of 1 minute.

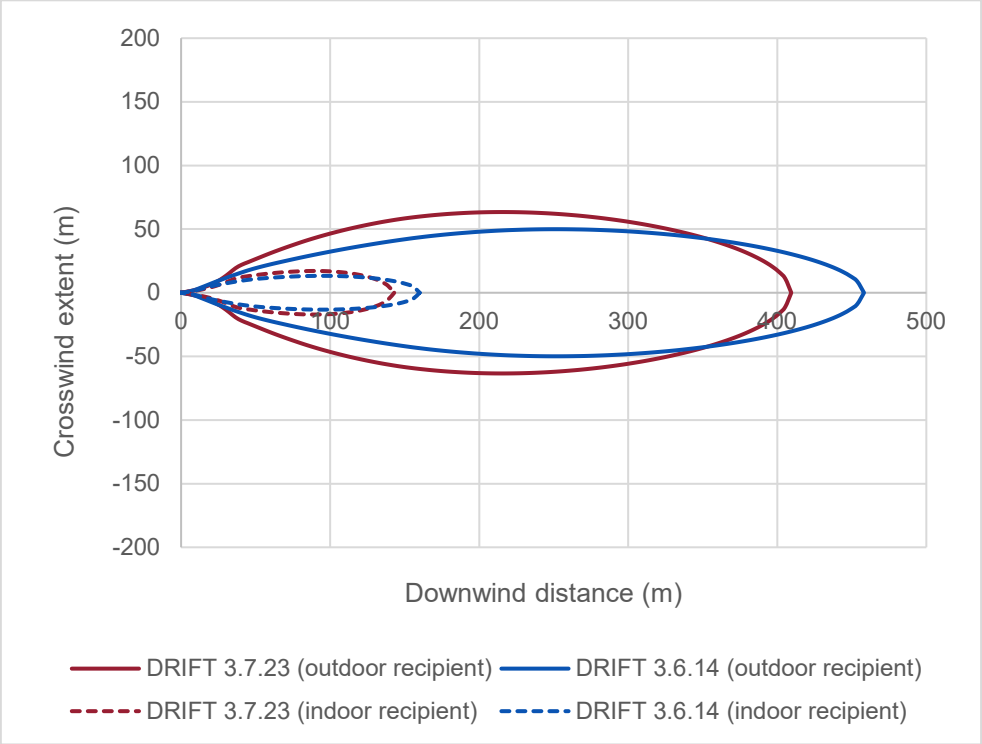


Figure 33 SLOT DTL isopleths obtained for indoor and outdoor recipients for a chlorine release from a 50 mm hole in liquid pipework in F2.4 weather conditions, assuming a release duration of 1 minute. Dispersion of the initial airborne component is shown.

This difference appears to be due in part to a change in the flash expansion modelling in DRIFT 3.7.23. To better align with the gas expansion model, DRIFT 3.7.23 includes allowance for the effect of the discharge coefficient in the momentum balance for the flash expansion region. This leads to a reduction in the predicted expanded source diameter, compared to that predicted by DRIFT 3.6.14, and a consequent reduction in the downwind dispersion distance.

DRIFT 3.7.23 also includes a bug fix to the initialisation of the liquid fraction prior to rainout. In 3.6.14, the airborne liquid fraction after rainout, L_{rainout}, was incorrectly set to

$$L_{\mathrm{rainout}} = (1 - f_{\mathrm{rainout}})L_{\mathrm{flash}}$$

Where L_{flash} is the liquid fraction after flashing and f_{rainout} is the rainout fraction input to DRIFT (defined as the fraction of the liquid release mass that rains out at source). In DRIFT 3.7.23, however, the airborne liquid fraction after rainout is normalised by the fraction of the release remaining airborne

$$L_{\text{rainout}} = \frac{(1 - f_{\text{rainout}})L_{\text{flash}}}{1 - f_{\text{rainout}}L_{\text{flash}}}$$

If the conditions after flash in DRIFT 3.6.14 are adjusted to be the same as those in DRIFT 3.7.23, similar hazard ranges are obtained in the two versions of the model for releases through a 50 mm hole in the liquid space of a storage vessel. This check adjusts for both the factors given above, so it is not possible to determine which has the greater effect. Adjusting the conditions after flash does not significantly improve the agreement between the DRIFT 3.6.14 and DRIFT 3.7.23 outputs for pipework releases. Releases through vessel holes are relatively low velocity as DRIFT assumes metastable liquid flow through the hole. However, pipework releases and above the liquid line releases from vessels have significantly higher velocity due to the presence of vapour, so are likely to be influenced by the changes to the wall jet modelling that have been implemented in DRIFT 3.7.

Tickle (2025c) describes changes that have been implemented in DRIFT 3.7.23 to improve the agreement with experimental data of the lateral spreading rate and dilution in the transition from the airborne jet to the grounded wall jet: in particular, there is now empirical suppression of mixing and spreading during the transition. Tickle (2025c) presents graphs of the centreline velocity (U_c) and lateral and vertical plume dimensions (L_y and L_z), which illustrate the improved agreement between DRIFT 3 and the Davis and Winarto (1980) data for an air wall jet. Selected graphs from Tickle (2025c) have been reproduced here in Figure 34 and Figure 35. h is the release height and D is the release diameter.

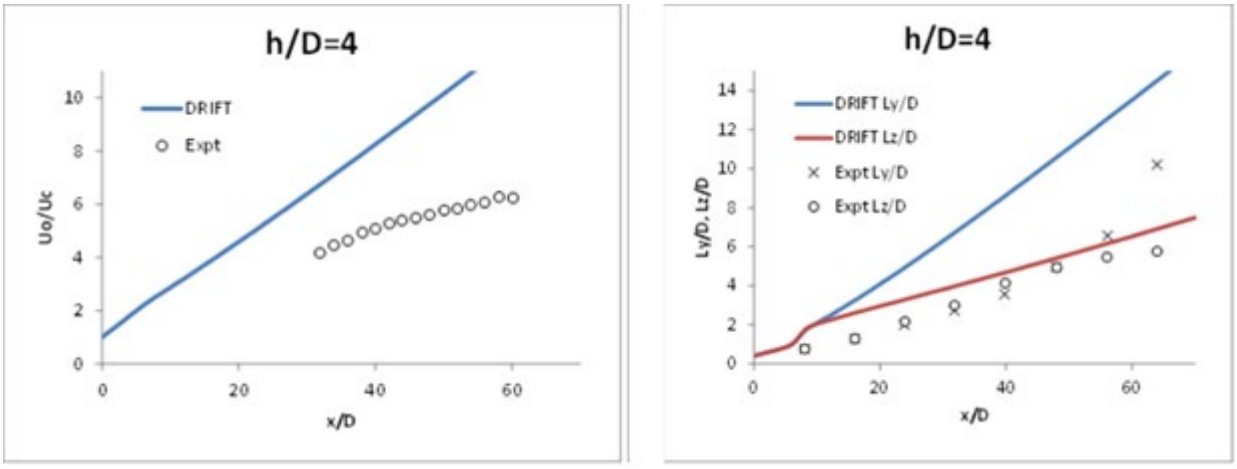


Figure 34 DRIFT 3.6.14 predictions of velocity and plume dimensions for $h/D = 4$ compared with Davis and Winarto (1980) data. Reproduced from Figure 2-5 of Tickle (2025c).

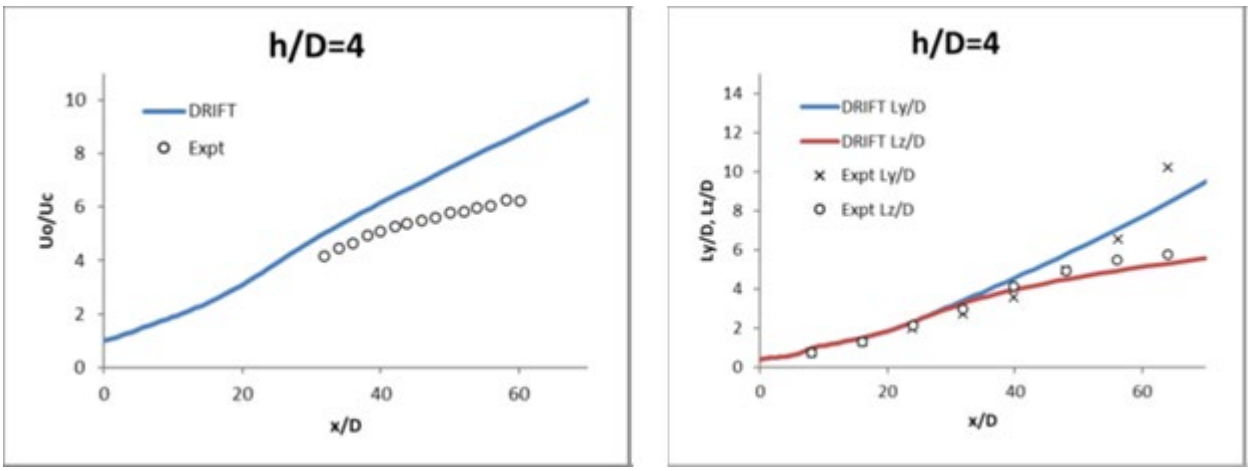


Figure 35 DRIFT 3.7.22 predictions of velocity and plume dimensions for $h/D = 4$ compared with Davis and Winarto (1980) data. Reproduced from Figure 2-9 of Tickle (2025c).

6.4.3.2 Sulphur dioxide

Overall, there is good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for the sulphur dioxide releases through a 50 mm hole in the liquid space of a storage vessel. For the pool component of the releases, the majority of the physical comparison parameters agree to within 1%.

For the airborne component of the releases, the maximum downwind dispersion distances to the SLOT DTL predicted by DRIFT 3.7.23 are within 2% of those predicted by DRIFT 3.6.14. In D4.3 weather conditions, the maximum widths to the SLOT DTL predicted by DRIFT 3.7.23 and DRIFT 3.6.14 agree to within 4%. In F2.4 weather conditions, the SLOT DTL isopleths output by DRIFT 3.7.23 are approximately 15% wider than those output by DRIFT 3.6.14. Adjusting the conditions after flash in DRIFT 3.6.14 to be the same as those in DRIFT 3.7.23 (as described in Section 6.4.3.1 above), significantly improves the agreement between the maximum widths predicted by the two versions of the model.

6.4.3.3 Ammonia

There is no pool component to the ammonia jet releases. For the airborne component of ammonia releases through a 50 mm hole in the liquid space of a storage vessel, DRIFT 3.7.23 generally predicts longer, thinner SLOT DTL isopleths than predicted by DRIFT 3.6.14. In D4.3 weather conditions, the downwind distances and maximum widths output by DRIFT 3.7.23 agree to within 5% of the values output by DRIFT 3.6.14. In F2.4 weather conditions, the differences between the model outputs are slightly larger, but still agree to within 8%. Adjusting the conditions after flash in DRIFT 3.6.14 to be the same as those in DRIFT 3.7.23 (as described in Section 6.4.3.1 above), significantly improves the agreement between the outputs of the two versions of the model for these scenarios.

For the airborne component of ammonia releases from liquid pipework, DRIFT 3.7.23 generally predicts shorter, wider SLOT DTL isopleths than predicted by DRIFT 3.6.14, as was observed for the equivalent chlorine releases. For these higher velocity releases, adjusting the post-flash conditions in DRIFT 3.6.14 does not improve the agreement

between the DRIFT 3.6.14 and DRIFT 3.7.23 outputs. As for the equivalent chlorine releases, it is likely that the differences in the model outputs are caused by the changes to the grounded jet model that have been implemented to improve the agreement with the wall jet data of Davis and Winarto (1980).

6.4.3.4 Methane

For the jet releases from a methane compressor station, the LFL isopleth dimensions predicted by DRIFT 3.7.23 are significantly larger than those predicted by DRIFT 3.6.14, as shown in Table 13. For ruptures, the maximum downwind distance to the LFL predicted by DRIFT 3.7.23 is approximately twice as large as that predicted by DRIFT 3.6.14; for holes the factor is 1.7. The maximum half-width to the LFL predicted by DRIFT 3.7.23 for ruptures is approximately 1.4 times that predicted by DRIFT 3.6.14; for holes the factor is 1.25.

The largest differences are for the highest release rates. These runs involve a significant distance over which the dispersion is as a wall jet and buoyant lift off is only partial towards the end of the hazard range. These releases will therefore be influenced by the changes to the wall jet modelling that have been implemented in DRIFT 3.7, which are described in Section 6.4.3.1 above.

DRIFT 3.7.23 also incorporates a change to the transition from wall jet to passive spreading (Tickle, 2025c). Previous versions of DRIFT could hold on to the wall jet spreading rate far downstream, to a point where the cloud had slowed down to close to the wind speed and could no longer be considered to behave as a momentum jet. This is mainly an issue for very large release rates and could result in too wide a cloud and thus too much mixing and dilution, due to the large top surface area of the cloud. It is likely that the differences in the hazard ranges predicted by DRIFT 3.7.23 and DRIFT 3.6.14 for these large methane releases are caused by the changes to the wall jet modelling that have been implemented in DRIFT 3.7.23.

The changes to the wall jet modelling have less impact on the chlorine, sulphur dioxide and ammonia jet releases in the exemplar database. It is likely that this is because the releases are smaller, and the wall jet region is much smaller for these cases.

Table 13 LFL isopleth dimensions for jet releases from a methane compressor station.

Scenario	Weather	Model	Maximum downwind distance to LFL (m)	Maximum width to LFL (m)
Compressor rupture	D2.4	3.6.14 3.7.23	438 831	123 172
Compressor rupture	D4.3	3.6.14 3.7.23	442 840	121 171
Compressor rupture	D6.7	3.6.14 3.7.23	470 862	118 169
Compressor rupture	F2.4	3.6.14 3.7.23	480 1116	119 166
Compressor hole	D2.4	3.6.14 3.7.23	65 114	17 22
Compressor hole	D4.3	3.6.14 3.7.23	66 114	17 21
Compressor hole	D6.7	3.6.14 3.7.23	67 115	16 20
Compressor hole	F2.4	3.6.14 3.7.23	63 111	17 21
Piping rupture	D2.4	3.6.14 3.7.23	363 692	102 146
Piping rupture	D4.3	3.6.14 3.7.23	366 703	100 144
Piping rupture	D6.7	3.6.14 3.7.23	386 726	97 143
Piping rupture	F2.4	3.6.14 3.7.23	370 787	98 141
Piping hole	D2.4	3.6.14 3.7.23	62 107	16 20
Piping hole	D4.3	3.6.14 3.7.23	62 107	16 19
Piping hole	D6.7	3.6.14 3.7.23	63 108	15 18
Piping hole	F2.4	3.6.14 3.7.23	60 104	16 19

6.5 Pipeline releases

Pipeline releases are modelled as momentum jets in DRIFT 3, using the finite duration sub-model. The DRIFT outputs are used in flash fire calculations.

6.5.1 Exemplar scenarios

The exemplar database contains ethylene and LPG (liquefied petroleum gas) pipeline release scenarios. LPG is modelled as propane in DRIFT 3.

The ethylene pipeline is assumed to have a diameter of 8 inches and a maximum operating pressure of 98.6 barg. The release scenarios in the exemplar database comprise a rupture, a 110 mm hole, a 75 mm hole and a 25 mm hole. Release rates were calculated in PipeTech version 54 (Oke et al., 2003) and are shown in Table 22 in Section B4 of the appendices. The rupture is modelled as a two-phase release in DRIFT 3, and the holes are modelled as gaseous releases.

The LPG pipeline is assumed to have a diameter of 4.5 inches and a maximum operating pressure of 19 barg. Two different wall thicknesses, 6.02 mm and 5.02 mm, are considered. The release scenarios in the exemplar database comprise a rupture, a 100 mm hole, a 75 mm hole and a 25 mm hole. PipeTech was used to generate the release rates for the rupture scenario and HSE's in-house model LOSSESP (Chaplin, 2015) was used to generate release rates for the three hole sizes. The release rates are shown in Table 22 in Section B4 of the appendices. All the LPG releases are modelled as two-phase releases in DRIFT 3.

For the LPG pipeline, the release rates input to DRIFT 3 are calculated 30 seconds after the onset of the release. This delay is to allow time for a steady jet fire to be formed, which is modelled separately in conjunction with the flash fire. The initial release rate for the rupture scenario is high, but decays very quickly. For the holes, the initial release rate is much lower than that predicted for the rupture, but the decay rate is also significantly lower. This leads to flow rates after 30 s that are higher for the 100 mm hole and 75 mm hole release scenarios than for the rupture scenario.

Each of the release scenarios is modelled in D5 and F2 weather conditions, which are the standard weather conditions used by HSE when setting land-use-planning zones in the vicinity of Major Accident Hazard (MAH) pipelines. The scenarios are described in detail in Chaplin and Cruse (2022), and are summarised in Table 22 in Section B4 of the appendices.

6.5.2 Comparison of DRIFT 3.7.23 and DRIFT 3.6.14

For the ethylene pipeline releases, the LFL isopleth dimensions predicted by DRIFT 3.7.23 in F2 weather conditions are significantly larger than those predicted by DRIFT 3.6.14, as shown in Table 14. For holes, the maximum downwind distance and maximum width to the LFL predicted by DRIFT 3.7.23 are approximately twice as large as those predicted by DRIFT 3.6.14; for ruptures the factor is slightly smaller.

Table 14 LFL isopleth dimensions for releases from an ethylene pipeline of diameter 8 inches and wall thickness 7.04 mm.

Scenario	Weather	Model	Maximum downwind distance to LFL (m)	Maximum width to LFL (m)
Rupture	D5	3.6.14 3.7.23	373 472	71 124
Rupture	F2	3.6.14 3.7.23	328 489	73 121
110 mm hole	D5	3.6.14 3.7.23	178 322	41 92
110 mm hole	F2	3.6.14 3.7.23	167 324	42 87
75 mm hole	D5	3.6.14 3.7.23	155 280	36 80
75 mm hole	F2	3.6.14 3.7.23	145 291	37 78
25 mm hole	D5	3.6.14 3.7.23	64 111	15 31
25 mm hole	F2	3.6.14 3.7.23	60 136	15 36

Similar trends are observed for the LPG pipeline releases, as shown in Table 15. For holes, the maximum downwind distance and maximum width to the LFL predicted by DRIFT 3.7.23 are approximately 1.3 times larger than the values predicted by DRIFT 3.6.14; for ruptures the factor is smaller in D5 weather but larger in F2 weather.

As for the methane compressor releases described in Section 6.4.3.4, it is likely that the differences in the hazard ranges predicted by DRIFT 3.7.23 and DRIFT 3.6.14 for these releases are caused by the changes to the wall jet modelling that have been implemented in DRIFT 3.7.

Table 15 LFL isopleth dimensions for releases from an LPG pipeline of diameter 4.5 inches and wall thickness 6.02 mm.

Scenario	Weather	Model	Maximum downwind distance to LFL (m)	Maximum width to LFL (m)
Rupture	D5	3.6.14 3.7.23	122 132	25 36
Rupture	F2	3.6.14 3.7.23	136 240	29 54
100 mm hole	D5	3.6.14 3.7.23	66 87	16 22
100 mm hole	F2	3.6.14 3.7.23	63 79	16 21
75 mm hole	D5	3.6.14 3.7.23	50 65	13 17
75 mm hole	F2	3.6.14 3.7.23	48 61	12 16
25 mm hole	D5	3.6.14 3.7.23	17 23	4 6
25 mm hole	F2	3.6.14 3.7.23	17 22	4 6

6.6 Conclusions

The outputs of DRIFT 3.7.23 and DRIFT 3.6.14 have been compared for a set of exemplar scenarios. The exemplar scenarios have been chosen to cover the full range of scenarios modelled by HSE for Hazardous Substances Consent assessments.

For the majority of the scenarios modelled, there is good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs. In cases where there is a significant difference between the outputs of the two versions of DRIFT, the reason for the difference has been explained, with reference to changes in the model physics.

The largest differences between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs are seen for the pool component of releases of refrigerated ammonia from large scale storage. For these releases, the maximum downwind dispersion distances to the SLOT DTL predicted by DRIFT 3.7.23 are significantly larger than those predicted by DRIFT 3.6.14. A probable cause of these differences is a bug fix incorporated in DRIFT 3.7.23, which corrects the touchdown logic for a buoyant cloud to enable subsequent lift off of a touched-down buoyant cloud.

Large differences between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs are also observed for jet releases from a methane compressor station and releases from ethylene and LPG

pipelines. For these scenarios, the LFL isopleth dimensions predicted by DRIFT 3.7.23 are significantly larger than those predicted by DRIFT 3.6.14. It is likely that these differences are caused by the improvements to the wall jet modelling that have been implemented in DRIFT 3.7. The transition from the airborne jet to the grounded wall jet has been modified to improve the agreement with experimental measurements of the lateral spreading rate and dilution presented by Davis and Winarto (1980). Improvements have also been made to the transition from wall jet to passive spreading (Tickle, 2025c).

Between DRIFT 3.6.14 and DRIFT 3.7.23, separate changes to the transition between the grounded and elevated models were made to improve the fit to the URAHFREP data (Porter and Nussey, 2001; Ott and Jørgensen, 2002). As a result of this modification, plumes have a greater propensity for buoyant lift off in DRIFT 3.7.23 than in DRIFT 3.6.14. This modification explains the observed differences in the DRIFT 3.7.23 and DRIFT 3.6.14 outputs for pool releases from hydrogen tankers.

For the airborne component of chlorine jet releases, DRIFT 3.7.23 generally predicts shorter, wider SLOT DTL isopleths than predicted by DRIFT 3.6.14. For releases through vessel holes, this difference appears to be due in part to a change in the flash expansion modelling in DRIFT 3.7.23 to better align with the gas expansion model. These releases may also be affected by a bug fix to the initialisation of the liquid fraction prior to rainout.

There is a known issue with the initialisation of low-momentum area sources in DRIFT 3.6.14, which has been fixed in DRIFT 3.7.23. As a consequence of this, differences are observed between DRIFT 3.7.23 and DRIFT 3.6.14 outputs for pool scenarios in which the vapour evolved from the pool is not predicted to disperse far downwind, such as LNG vessel or pipework releases onto dry soil in higher wind speeds.

7 Conclusions

DRIFT 3.7.23 has been evaluated against a Model Evaluation Protocol designed specifically for DRIFT. The DRIFT Model Evaluation Protocol (Cruse et al., 2026) comprises five parts: scientific assessment, verification, validation, a user-oriented assessment and testing of the model against a set of exemplar scenarios. The DRIFT MEP extends the LNG MEP protocol developed by Ivings et al. (2016) in several areas. Namely, the scientific assessment is broadened to cover buoyant lift off and buoyant rise, and other model capabilities relevant to HSE's regulatory work. The validation database is also expanded to include data from experiments that consider passive releases and a larger range of release substances and release types.

The evaluation of DRIFT 3.7.23 against each element of the DRIFT MEP is summarised in the following subsections. The overall outcome of the evaluation is that DRIFT 3.7.23 is fit for purpose and is suitable for use in HSE's regulatory work, including Hazardous Substances Consent assessments. Furthermore, DRIFT 3.7.23 incorporates a significant number of enhancements and bug fixes, and is better able to model wall jets and buoyant lift off than DRIFT 3.6.14 and earlier versions of DRIFT.

7.1 Scientific assessment

The aim of the scientific assessment is to demonstrate that the underlying mathematical model in DRIFT 3.7.23 has a sound scientific basis.

The physical, mathematical and numerical basis of DRIFT 3.7.23 has been reviewed, using information provided in reports and papers describing the DRIFT 3 mathematical model. To facilitate this review, a specially-designed questionnaire was completed.

DRIFT 3.7.23 was also assessed against a set of qualitative criteria, which have been chosen to provide a high-level summary of its capabilities. DRIFT 3.7.23 was found to satisfy all of these criteria.

DRIFT 3.7.23 incorporates a number of model enhancements. These include modifications to the grounded-jet model and to the transition from jet to wind-blown spreading, to better match experimental data, and changes to the transition between the elevated and grounded models, to better model ground-level concentrations under buoyant lift off. Where applicable, improvements to DRIFT have been tested by the model developer and shown to give improved performance (Tickle, 2025a,b,c).

7.2 Verification

Verification is the process of checking that the computer implementation of a model matches its mathematical basis.

Evidence of verification has been obtained from the developer and documentation. This evidence indicates that sufficient verification has been carried out by ESR Technology to give confidence that the equations in DRIFT 3.7.23 have been programmed correctly.

7.3 Validation

Validation is the process of showing that the model predicts measured quantities to satisfactory accuracy, across a given range of applicability.

A database of experimental datasets has been compiled to test the performance of DRIFT. The DRIFT validation database includes dense gas releases from the LNG database (Stewart et al., 2016), plus data from the Jack Rabbit II, CO2PIPETRANS, Hanford, Prairie Grass, Desert Tortoise, FLADIS, Goldfish and URAHFREP experiments. It includes pool sources, area sources and jet sources and a range of release substances, including flammable and toxic substances.

For each trial in the DRIFT validation database, the DRIFT 3.7.23 predictions for the concentration and cloud width were compared to the experimentally measured values. The performance of DRIFT 3.7.23 was assessed using the Statistical Performance Measures (SPM) and associated acceptance criteria recommended by Ivings et al. (2016).

For the field-scale experiments in the DRIFT validation database, all five SPM are within the acceptability range for both concentration and cloud width data.

For the wind-tunnel scale experiments, DRIFT tends to underpredict the measured concentrations. Underprediction of wind-tunnel concentration measurements has been observed for previous versions of DRIFT (Coldrick and Webber, 2017; Cruse and Coldrick, 2022) and for other models (Stewart et al., 2016). However, all SPM for the wind-tunnel scale experiments are within their acceptability ranges, apart from $\mathrm{FAC2}$ for the concentration data. This takes a value of 0.49, slightly outside the acceptability range of $\mathrm{FAC2} > 0.5$.

There are several features of the wind-tunnel trials that differ from the field-scale trials. These include: lower Reynolds numbers (i.e. conditions closer to laminar flow) and a lack of wind meandering in the wind-tunnel trials, idealised source conditions, and the presence geometrical features in some of the wind-tunnel trials (such as roughness elements and walls). These features may explain the underprediction of wind-tunnel concentration measurements in DRIFT 3.7.23.

The overall results from the model validation exercise demonstrate that DRIFT 3.7.23 is fit for purpose.

7.4 User-oriented aspects of model

In the DRIFT Model Evaluation Protocol (Cruse et al., 2026), user-oriented aspects of the model are assessed through completion of the model questionnaire.

Users can interact with DRIFT 3.7.23 using either the GUI or the COM interface. The GUI is intuitive to use and includes an inbuilt user manual.

For HSE users, two substance property databases are available within DRIFT 3.7.23: the ESR substance database and HSE's substance property database. HSE's substance property database is used for regulatory purposes.

A large number of outputs are available in graphical or tabular form via both the GUI and the COM interface. For all types of release, the DRIFT outputs include all the information required for HSE's current regulatory purposes.

7.5 Exemplar testing

The aim of the exemplar testing is to assess the effect of changes to the model on its predictions for the types of release scenarios typically modelled by HSE for Hazardous Substances Consent assessments. The DRIFT 3.7.23 outputs have been compared to the outputs from the version of DRIFT currently used by HSE for regulatory purposes, i.e. to DRIFT 3.6.14 outputs.

For the majority of the scenarios modelled, there is good agreement between the DRIFT 3.7.23 and DRIFT 3.6.14 outputs. In cases where there is a significant difference between the outputs of the two versions of DRIFT, the reason for the difference can be explained with reference to changes in the model physics.

The model enhancements that have had the largest impact on the model outputs are the improvements to the wall jet modelling and the changes to the transition between the grounded and elevated models. The latter of these results in plumes having a greater propensity for buoyant lift off in DRIFT 3.7.23 than in DRIFT 3.6.14.

7.6 Future work

The COM interface guide (Walton, 2011) would benefit from being revised and expanded to provide more detailed guidance for HSE users.

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Appendix A
Model Evaluation Questionnaire

A1 Introduction

This appendix presents the scientific assessment of DRIFT 3.7.23, carried out according to the DRIFT Model Evaluation Protocol (Cruse, Coldrick and Ivings, 2026).

A1.1 Key to summary information

In Sections A3 to A5, summary information is provided on many aspects of the model. This is organised as follows:

a. Where there is a mutually exclusive choice of options, the relevant choice is denoted by a circle containing a dot ◉, while the remaining choices are accompanied by an empty circle ○.

b. A square box containing a tick ☑ denotes that a feature is present, or an option applies to the model; if the box remains empty ☐, this indicates that the feature is not present or that the option does not apply.

c. A character between square brackets can convey one of the following meanings:

[U] denotes that the user can specify the details of the feature.

[M] denotes that the model specifies the details of the feature.

[ ] denotes that the feature is absent or not considered.

[✓] denotes that the feature is present.

[?] denotes that the status of the feature is uncertain.

[n] denotes that the item has the value *n*.

A2 Evaluation information

A2.1 Protocol

This scientific assessment was carried out using the DRIFT Model Evaluation Protocol (Cruse et al., 2026). The DRIFT Model Evaluation Protocol is derived from the LNG Model Evaluation Protocol (Ivings et al., 2016) and the SMEDIS Model Evaluation Protocol, Version 2.0 (7 December 2000) (Carissimo et al., 2001; Daish et al., 2000). Version 1 of the DRIFT Model Evaluation Report template (May 2024) was used.

A2.2 Evaluator

The scientific assessment was carried out by:

- Simon Coldrick (HSE)
- Helen Cruse (HSE)

Where appropriate, information provided in the scientific assessment of DRIFT 3.6.4 (Coldrick and Webber, 2017) has been incorporated into this assessment. Feedback from the model developer (Gemma Tickle of ESR Technology) has also been included in this assessment.

A2.3 Date

The scientific assessment of DRIFT 3.7.23 was completed on 16 October 2025.

A2.4 Documentation

A2.4.1 DRIFT references

The following references describe the DRIFT mathematical model, together with its verification and validation, and were used to inform the scientific assessment of DRIFT 3.7.23 and previous versions of DRIFT.

A2.4.1.1 Primary model specification

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A2.4.1.3 User manual

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A2.4.1.4 Verification, validation, and background material

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A2.4.3 Comments on documentation supplied

The latest version of the DRIFT mathematical model report describes DRIFT 3.7.3 (Tickle and Carlisle, 2015). Improvements implemented in DRIFT versions 3.7.19, 3.7.21 and 3.7.22 are described in the corresponding verification reports (Tickle, 2025a,b,c). The minor changes that were implemented in DRIFT 3.7.23 are documented in the version log.

A2.4.4 Major omissions and uncertainties arising

A large quantity of output variables is available from the graphical user interface and via the COM interface. There is no single source containing a description of each variable.

There is no documentation that explains what averaging is applied to each variable in the COM interface.

A3 General model description

A3.1 Name, version number and release date

Name: DRIFT

Version number: 3.7.23

Release date: June 2025

A3.2 Short description of model

DRIFT (Dispersion of Releases Involving Flammables or Toxics) is an integral gas dispersion model. It can model instantaneous releases, steady continuous releases, steady releases of finite duration and time-varying releases. DRIFT can model dense, passive or buoyant clouds and can account for buoyant lift-off. It has been generalised to include multicomponent mixtures.

A3.3 Model developer

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A3.4 History of model

DRIFT was developed by the Safety and Reliability Directorate (SRD) of the United Kingdom Atomic Energy Authority (UKAEA) on behalf of the Health and Safety Executive (HSE) in the late 1980s and early 1990s. By the time of privatisation of parts of UKAEA into AEA Technology in 1996 (who became responsible for the code), the original version of the code was complete, and it had acquired some enhancements (such as the ability to handle obstacles) as a result of research done as part of various projects sponsored by the CEC (Coordinating European Council). Later, part of AEA Technology became ESR Technology, and that company is currently responsible for the code.

In 2010, ESR Technology reissued the code as DRIFT 3, incorporating a number of modifications that allow a wider range of scenarios to be modelled. These modifications are summarised in the document describing the DRIFT 3.7.3 mathematical model (Tickle

and Carlisle, 2015). They include the extension of the model to treat buoyant lift-off and rise and its generalisation to include multicomponent releases.

A full scientific assessment was carried out on DRIFT 3.6.4 (Coldrick and Webber, 2017). In their assessment of DRIFT 3.6.14, Cruse and Coldrick (2022) reviewed the changes to the model that were implemented between DRIFT 3.6.4 and DRIFT 3.6.14.

Changes and enhancements to the model that have been implemented since DRIFT 3.6.14 include:

- the inclusion of a pool re-evaporation option to add the concentration from a direct source to the concentration from an evaporating pool
- changes to the grounded jet model to suppress initial spreading, for better agreement with the wall jet data of Davis and Winarto (1980) – this was achieved using empirical suppression functions for wall jet entrainment and lateral spread
- modifications to the transition from jet to wind-blown spreading and to the entrainment to better match the Desert Tortoise trials (Goldwire et al., 1985) and comparisons with other models
- a change to the interpolation between the elevated and grounded models, to better model ground-level concentrations under buoyant lift-off
- changes to the elevated jet entrainment, to better match experimental data
- modifications to improve the modelling of jets in cross-flows, including suppression of the initial cross-flow entrainment and change to the constraints used for axisymmetry for elevated releases
- improvements to the initialisation of the thin 'pancake' cloud over an area source to rectify the unphysically large initial contour sizes sometimes observed for very short duration releases in earlier versions of DRIFT
- the inclusion of binary interaction parameters for the hydrogen peroxide-water system
- a switch to using a fit to the Tillner-Roth (Tillner-Roth and Friend, 1998) correlation for the ammonia-water interaction coefficients – the Tillner-Roth correlation is based on a wider set of conditions than the Wheatley correlation (Wheatley, 1987) that was used previously
- modifications to the vapour deposition model to include new user inputs of surface resistance and a fixed vapour deposition velocity
- the addition of atmospheric pressure as a model input – this parameter defaults to 101325 Pa
- the facility to specify parameters that change the atmospheric turbulence via the COM interface

A3.4.1 Model Ancestors

DRIFT version 2.31 (Webber et al. 1992 a,b) is an immediate ancestor of DRIFT 3. The integral models DENZ (for instantaneous releases) and CRUNCH (for steady continuous releases) are also precursors to DRIFT 3. DENZ (Fryer and Kaiser, 1979) and CRUNCH (Jagger, 1983) were developed at SRD for HSE in the late 1970s and early 1980s and DRIFT's specification was defined so that it would handle those two geometries in a similar

way, but also do a lot more, and, in light of expanding empirical knowledge of gas clouds, do it more accurately.

A3.4.2 Features Inherited

The model equations from DRIFT 2 for dense and passive ground-based clouds have been maintained and extended to cover buoyant lift-off, the integration of a momentum jet model, finite duration and time-varying releases and multi-component thermodynamics.

DRIFT 3.7.23 contains the same underlying scientific model as DRIFT 3.6.14, the most recently evaluated version of DRIFT (Cruse and Coldrick, 2022). The changes to the model that have been implemented since DRIFT 3.6.14 are summarised in Section A3.4 above.

A3.5 Quality assurance standards adopted

DRIFT 2 was developed according to the Model Evaluation Group (MEG) guidelines. S. J. Jones, one of the DRIFT development team, was also a member of the MEG, and was actively involved in the development of the MEG guidelines.

The development of DRIFT 2 predated AEA Technology's certification to ISO 9000. However, software verification (as defined by the MEG) was an important element in its development.

DRIFT 3 was developed by ESR Technology, which operates a Quality Management System that complies with the requirements of ISO 9001:2015.

A3.6 Relationship with other models

The pool spread and vaporisation source term code GASP (Webber, 1990) has an option to generate a .din file (a legacy DRIFT input file, compatible with both DRIFT 2 and DRIFT 3), from which DRIFT can then be used straightforwardly to generate dispersion predictions. DRIFT is also able to directly import .gasp files.

ACE (Gilham et al, 1999; Shepherd and Deaves, 2000), a model used by HSE to generate source terms for flashing instantaneous releases, also produces .din and .drift files, which can then be run through the DRIFT GUI or the COM interface.

The DRIFT output is used by RISKAT (Nussey, 1994), HSE's in-house risk calculation model, which is used to calculate land use planning zones around major hazards sites handling or storing toxic substances. RISKAT calls and runs DRIFT files through the COM interface.

The DRIFT output is also used by HSE's in-house flash fire model, FLIC (FLash fire Ignition Calculator). FLIC does not rerun DRIFT files but extracts the required information from DRIFT files that have been previously run in either the GUI or the COM interface.

A3.7 Current model usage within HSE

DRIFT is used by HSE for both regulatory and research purposes.

HSE uses DRIFT in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazards sites, to fulfil its role as a statutory consultee on all Hazardous Substances Consent applications (MHCLG, 2019). The outputs of these assessments are also used to set Land Use Planning (LUP) zones around major hazards sites (HSE, 2025).

DRIFT is being used across various projects to support the planning and execution of experiments, particularly in scoping release and dispersion behaviour. In the Jack Rabbit III[2] and ARISE[3] experiments (both ammonia releases) DRIFT has played a key role in experimental design and will continue to do so. Similarly, in the Skylark CO_2 project[4], DRIFT will guide experimentalists on aspects such as sensor placement.

Beyond its application in experimental planning, DRIFT is also a valuable research tool. For example, it has been used to investigate the effects of atmospheric conditions such as ambient humidity and temperature (Hetherington et al., 2024).

A3.8 Software requirements

Operating system: Windows 10 or Windows 11.

The COM interface is offered in either 32-bit or 64-bit installations of DRIFT. The bitness of the DRIFT installation must match the bitness of the product that calls it. This is usually Microsoft Excel (as part of Office) but could also be the Python development environment if the COM interface is to be called from Python.

[2] https://admlc.com/jriii/ (accessed November 2025)

[3] https://www.arise-partnership.org/ (accessed November 2025)

[4] https://www.dnv.com/group/joint-industry-projects/skylark-pioneering-excellence-in-co2-pipeline-safety/ (accessed November 2025)

A4 Scientific basis of model

A4.1 Model type

DRIFT is a one-dimensional integral model. It assumes self-similar profiles, allowing integration of the three-dimensional conservation equations (which otherwise would require solution of partial differential equations) to one-dimensional conservation equations, which require solution of ordinary differential equations. The one-dimension refers to the downstream distance (in the continuous plume model) or travel time (in the instantaneous puff model) over which the cloud evolves and not the dimensionality of its trajectory or spreading, which can be three-dimensional.

A4.2 Specification of the source

A4.2.1 Primary origin for the source

A4.2.1.1 Types of release conditions available directly to dispersion model

Release models available

☑ Gaseous jet ☑ Liquid jet ☑ Two-phase jet ☐ Catastrophic release

☐ Liquid pool ☐ Other

DRIFT incorporates a jet model that can account for gaseous, liquid and two-phase jets. However, DRIFT cannot calculate source terms for catastrophic and pool releases. Separate source term models must be used in conjunction with DRIFT to model such releases.

A4.2.1.2 Directionality of jet sources

☑Model accounts for jet directionality

☑ Jet into crossflow permitted ☑ Jet into wind permitted

☑ Non-horizontal jet permitted

The initial release direction for a momentum jet is set by specifying two angles:

Angle from Horizontal
The angle in degrees between the initial jet direction and the horizontal plane. A positive angle represents a jet initially tilted upwards from the horizontal, a negative angle an initially downward tilted jet and zero an initially horizontal jet. Valid range: +90º to -90º.

Angle from North
The bearing angle (in degrees) clockwise from the north (y-axis) in which the momentum jet is initially pointing. The default, 90º, corresponds to a release directed along the x-axis. Valid range: 0º to 360º.

The modelling of momentum jets directed into the wind can be problematic because DRIFT does not account for any re-entrainment of material when cross-sections of the plume overlap and also the contouring algorithm may fail to find a solution when the plume segments overlap due to strong bending/reversal of the jet centreline.

A4.2.1.3 Source geometry handled by the dispersion model for liquid pools

Pool plan view

☑ Circular ☐ Long trench ☐ Other

Liquid containment

☐ No dike ☐ Dike ☐ High collar bund ☐ Other

A4.2.2 Fluid dynamic properties of source

A4.2.2.1 Instantaneous releases

☑ Instantaneous releases

[U] Spatial dimensions	**[U]** Symmetry	**[U]** Velocity	**[M]** Volume
[M] Density	**[U]** Mass	**[ ]** Multiple sources	**[ ]** Elevation
[U] Other	**[U]** Entrained air		

Instantaneous releases are assumed to occur at ground level.

A4.2.2.2 Continuous releases

☑ Continuous releases

[U] Spatial dimensions	**[U]** Orientation	**[M]** Symmetry	**[U]** Velocity
[M] Volume flow rate	**[M]** Density	**[U]** Mass flow rate	
[ ] Multiple sources	**[U]** Elevation	**[U]** Other	
[U] Entrained air	**[M]** Model can recalculate source dimensions		

The elevation can only be specified for momentum jets. Low-momentum area sources are considered to be at ground level.

A finite duration model is available based on the same equations as the steady continuous model but allowing for longitudinal diffusion.

A4.2.2.3 Time-varying releases

☑ Time-varying releases

[U] Spatial dimensions	**[U]** Orientation	**[U]** Symmetry	
[M] Volume flow rate	**[M]** Density	**[U]** Mass flow rate	
[ ] Multiple sources	**[U]** Elevation	**[U]** Time variation	**[U]** Other
[U] Entrained air	**[M]** Model can recalculate source dimensions		

The elevation can only be specified for momentum jets. Low-momentum area sources are considered to be at ground level.

A4.2.2.4 Other aspects of release types

☑ Guidance provided on choice of dispersion source type

☑ Instantaneous ☑ Continuous ☑ Time-varying ☑ Other

A finite duration model is available based on the same equations as the steady continuous model but allowing for longitudinal diffusion.

A4.2.3 Thermodynamic properties of source

☑ Temperature ☐ Isothermal ☐ Other

A4.2.4 Material nature of source

☑ Pre-defined substances ☑ User-defined substances

☑ Mixtures

[U] True mixtures **[ ]** Effective single-component mixtures **[ ]** Passive tracer **[ ]** Other

In a 'true mixture' model, the composition of the mixture can change, for example due to different vaporisation rates of different components. 'Effective single-component mixture' models treat the mixture as a single component with single component properties derived from those of the mixture at a particular composition.

DRIFT offers 'true' multi-component mixture modelling capability. It models the evolution of the individual components of an aerosol mixture based on either an assumption of immiscibility (components behave independently), an ideal solution (vapour pressure follows Raoult's Law) or a non-ideal solution. For non-ideal solutions, such as HF-water and ammonia-water solutions, the modelling is based on a parametrisation of activity coefficients.

☑ Chemically reactive substances

☐ Reaction with H_2O ☐ Specific reactions ☑ Oligomerisation ☑ Other

Oligomerisation is considered for hydrogen fluoride.

DRIFT does not directly model the reaction of substances with water. However, for ammonia, hydrogen fluoride and hydrogen peroxide dispersing in moist air, DRIFT accounts for the heat of mixing and the non-ideality of the solution.

☐ Radioactive substances

☑ Dependence of physical properties

[M] Temperature **[ ]** Pressure **[M]** Composition **[ ]** Other

The temperature dependence of physical properties is based on information in the selected substance property database (ESR database or HSE SPI files – see Sections A5.4 and A5.5 for further details).

Generally, molar specific quantities are calculated from the mole fractions, as for an ideal mixture.

For example, for a liquid mixture:

Liquid molar mass, $M_{\mathrm{m}} = \sum_{i=1}^{N_{\mathrm{comp}}} x_i M_{\mathrm{m},i}$, where N_{comp} is the number of components in the mixture, x_i is the mole fraction of component i in the liquid phase and $M_{\mathrm{m},i}$ is the molar mass of component i.

Liquid molar volume, $V_{\mathrm{m}} = \sum_{i=1}^{N_{\mathrm{comp}}} x_i V_{\mathrm{m},i}$, where $V_{\mathrm{m},i}$ is the liquid molar volume of component i.

Liquid density, $\rho = M_{\mathrm{m}}/V_{\mathrm{m}}$

Exceptions are:

Vapour pressure for a non-ideal mixture, $P_{\mathrm{vap}} = \sum_{i=1}^{N_{\mathrm{comp}}} x_i \gamma_i(\boldsymbol{x}) P_{\mathrm{vap},i}(T)$, where $\gamma_i(\boldsymbol{x})$ are the mixture activity coefficients and $P_{\mathrm{vap},i}(T)$ is the vapour pressure of pure component i at temperature T.

Molar enthalpy for a non-ideal mixture, $h_{\mathrm{m}} = \sum_{i=1}^{N_{\mathrm{comp}}} x_i h_{\mathrm{m},i} + \Delta h_{\mathrm{mix}}(\boldsymbol{x})$, where $h_{\mathrm{m},i}$ is the molar enthalpy of component i and $\Delta h_{\mathrm{mix}}(\boldsymbol{x})$ is the heat of mixing, which depends on the composition.

DRIFT 3.7.23 includes a new atmospheric pressure input, P_{a}, which affects vapour volumes through the ideal gas law and the vapour-liquid equilibria:

$$y_i = x_i \gamma_i(\boldsymbol{x}) P_{\mathrm{vap},i}(T)/P_{\mathrm{a}}$$

where y_i is the mole fraction of component i in the vapour phase. Boiling temperatures are evaluated at the new input atmospheric pressure. However, other substance properties taken from the ESR database or HSE SPI files are assumed to be unchanged from their values at standard atmospheric pressure.

A4.3 Specification of the environment

A4.3.1 Frame of reference

A4.3.1.1 Coordinate system

☑ Cartesian ☐ Cylindrical polar ☐ Spherical polar ☐ Other

A4.3.1.2 Relation to environment

☑ Origin at source ☑ x-axis downwind ☑ Other

By default in DRIFT, the source is at the (x,y) origin, the ground is the z=0 plane and the x-axis is downwind. However, the user may specify a different source location (subject to the

constraint that low-momentum area sources must be at ground level), and a different wind direction relative to North, where North is in the +y direction.

A4.3.2 Atmosphere

A4.3.2.1 Mean wind field

☑ Mean wind parameterised

[M] Vertical profile **[ ]** Horizontal field **[ ]** Time-varying **[M]** Stratification
[ ] Other

☑ Vertical velocity profiles used

☑ Logarithmic ☑ Other **[U]** Velocity at reference height
[M] Friction velocity specified

☐ Mean wind modelled

[ ] Vertical profile **[ ]** Horizontal field **[ ]** Time variation **[ ]** Other

☐ Zero wind allowed

In the DRIFT GUI, the minimum wind speed that can be entered is 0.1 m/s. This limit is in place to prevent users from attempting to model a low momentum area source in zero wind. In such cases, DRIFT's gas blanket model would never reach steady state and the cloud would never transition to a plume advecting with the wind, instead remaining as a transient pancake-like cloud. The gas blanket model treats this transient pancake-like cloud as an area average with gravity spreading at the edge and may not give a good representation of the radial variation for a maintained source spreading in zero wind.

In principle some of DRIFT's release options, such as a momentum jet or an instantaneous release, could model dispersion in zero wind.

A4.3.2.2 Turbulence

☑ Turbulence parameterised ☐ Turbulence modelled

A4.3.2.3 Stratification

☑ Stability ranges

☑ Neutral ☑ Stable ☑ Unstable

☑ Stratification parameterised

☐ Vertical density profile ☐ Time-varying
☑ Pasquill-Gifford stability categories used ☑ Monin-Obukhov length used
☑ Monin-Obukhov ↔ Pasquill-Gifford conversion

☐ Stratification modelled

[ ] Vertical density profile **[ ]** Time-varying **[ ]** Other

If a Pasquill-Gifford scheme is used it is converted internally to Monin-Obukhov. The Holtslag method may also be used. This is also converted internally to Monin-Obukhov.

A4.3.2.4 Use of meteorological data

☑ Meteorological data used

☑ Temperature ☑ Humidity ☑ Cloud cover ☑ Date/time

☑ Latitude/longitude ☑ Other

The meteorological data used depends on the selected weather scheme.

'Other' has been selected because DRIFT accounts for wind speed (see Section A4.3.2.1) and atmospheric stability (see Section A4.3.2.3).

A4.3.3 Terrain

A4.3.3.1 Terrain types available

☐ Non-flat terrain

[ ] Single slope **[ ]** Slope segments (#) **[ ]** General 2-D **[ ]** Other

A4.3.3.2 Wind orientation for non-flat terrain

☐ Downslope ☐ Upslope ☐ General ☐ Other

A4.3.3.3 Surface characteristics

☑ Roughness length

☐ Pre-defined surface types ☑ User-defined values

[ ] Temperature **[ ]** Other

A4.3.4 Obstacles

A4.3.4.1 Obstacle types available

☑ Obstacle types available

☑ 2-D fence ☐ Cylindrical building/tank ☑ Cuboidal building

☐ General shape ☐ 1-sided canyon ☐ 2-sided canyon ☐ Other

A4.3.4.2 Obstacle distribution

☑ Distribution of obstacles

☑ Maximum number (10 buildings and 10 fences)

[U] Positions **[U]** Orientations **[ ]** Other

A4.3.4.3 Obstacle characteristics

☑ Dimensions

[U] Horizontal **[U]** Vertical **[ ]** Other

☐ Structural characteristics

[ ] Porous **[ ]** Other

A4.4 Model physics and formulation

A4.4.1 Fundamental equations, initial conditions and boundary conditions

A4.4.1.1 Equations used/set up

☐ Volume	☐ Mass	☑ Momentum	☑Width/radius
☐ Energy	☑ Enthalpy	☑ Temperature	
☐ Concentration	☐ Species concentration		
☐ Contaminant mass fraction	☐ Species mass fraction	☑ Other	

For instantaneous releases, the primary variables relating to cloud mass, volume and content are the number of moles of contaminant gas, contaminant liquid, dry air, water vapour and water liquid in the cloud. For continuous releases the fluxes of those quantities are the primary variables.

The DRIFT mathematical model report (Tickle and Carlisle, 2015) provides detailed information on the differential equations, algebraic constraint equations and partitioning between the primary variables and secondary (dependent) variables which are solved for in the model.

A4.4.1.2 Dependent variables

☑ H	☐ W	☐ R	☑ ρ	
☑ U_{ad}	☑ u	☑ v	☑ w	
☑ E	☐ h	☐ T		
☑ c	☑ $\{c_i\}$	☑ m	☑ $\{m_i\}$	☑ Other

H = depth; W = width; R = radius; ρ = density; U_{ad} = advection velocity; (u, v, w) = velocity components; E = energy; h = enthalpy; T = temperature; c = concentration; c_i = concentration of species i; m = contaminant mass fraction; m_i = mass fraction of species i

W, R and h are not checked because they are primary variables. There are differential equations that directly govern the evolution of these variables in the model.

T is not checked because a constraint equation links T to h.

A4.4.1.3 Independent variables

☑ Spatial ☑ Time ☑ Other

Refer to the DRIFT mathematical model report (Tickle and Carlisle, 2015) for further details.

A4.4.1.4 Model-type-dependent features of equation formulation

☑ Use of similarity profiles in setting up equations

☑ Dependent variables

☑ Concentration ☑ Velocity ☑ Temperature ☑ Other

☑ Profile shapes used

☐ Uniform ☐ Gaussian ☑ Other

Profiles evolve smoothly from the heavy gas region into the passive dispersion region.

A4.4.1.5 Initial conditions

☑ Initial conditions specified

[U] Source **[U]** Atmosphere **[ ]** Terrain **[U]** Obstacles **[ ]** Other

A4.4.2 Dispersion: advection

☑ Advection velocity derived from wind profile

☐ Average over cloud height ☑ Wind speed at fraction of cloud height

☐ Other

☑ Acceleration of stationary cloud from rest calculated

☐ Advection modelled directly

The advection speed is asymptotic to the wind speed at the centroid height.

A4.4.3 Dispersion: gravity spreading

☑ Gravity spreading parameterised

☑ Gravity spreading locations

☑ Plume sides ☑ Puff edge ☑ Cloud boundary ☐ Other

☑ Gravity spreading characterisation

[M] Constant Froude number ☐ Other

☑ Upstream/lateral spreading of vapour blanket (continuous releases)

☑ Upstream spreading ☑ Lateral spreading ☐ Other

☐ Gravity spreading modelled directly

Lateral spreading is a combination of gravitational and dispersive effects with a smooth transition from the regime where one dominates to the regime where the other dominates.

A4.4.4 Dispersion: dilution

A4.4.4.1 Dispersion modelling in the dense gas regime

☐ Turbulent diffusion ☑ Top entrainment ☑ Edge entrainment

☑ Gaussian or similar parameterisation ☐ Other

The self-similar parameterisation admits entrainment velocities.

A4.4.4.2 Dispersion modelling in the passive regime

☑ Turbulent diffusion ☑ Top entrainment ☑ Edge entrainment
☑ Gaussian or similar parameterisation ☐ Other

These concepts are all related by the model. See for example Wheatley (1986a).

A4.4.5 Dispersion: concentration fluctuations

☑ Concentration fluctuations considered

Concentration fluctuations are considered indirectly. Horizontal plume meander is accounted for in post processing by applying an averaging time correlation to the concentration profiles, following the approach of Nielsen et al. (2002). The effect of vertical plume meander on the average concentration of a buoyant plume in unstable atmospheric conditions is accounted for following the approach of Weil, Corio and Brower (1997).

Within the GUI, only the output displayed in the toxic and general results windows includes the effect of time averaging. Flammable results are based on short (near-instantaneous) average values.

A4.4.5.1 Fluctuation calculations

☑ Derived from data ☐ Modelled directly ☐ Other

A4.4.6 Dispersion – concentration profiles

☑ Concentration profiles considered

A4.4.6.1 Types of concentration profiles used for dense gas dispersion region

☑ Vertical profile
☐ Uniform ☐ Gaussian ☐ Exponential decay ☑ Other

☑ Lateral profile
☐ Uniform ☐ Gaussian ☐ Uniform core with erf edges ☑ Other

☑ Radial profile
☐ Uniform ☐ Gaussian ☐ Uniform core with erf edges ☑ Other

DRIFT's profiles are more general functions than the options listed above. In certain limits the DRIFT profiles can be approximately uniform or Gaussian. Definitions of DRIFT's profiles are given in the DRIFT mathematical model report (Tickle and Carlisle, 2015).

A4.4.6.2 Types of concentration profiles used for passive dispersion region

☑ Concentration profiles applied
☐ Uniform ☐ Gaussian ☑ Exponential decay ☑ Other

In neutral conditions, the vertical profile is exponential. In non-neutral conditions, the vertical profile is more general than the listed options: it involves a modified Bessel

function of the first kind. Definitions of DRIFT's profiles are given in the DRIFT mathematical model report (Tickle and Carlisle, 2015).

A4.4.7 Thermodynamics

☑ Thermodynamics considered

A4.4.7.1 Sources of heat gain/loss for cloud

[M] Ambient air **[M]** Ground: forced convection **[M]** Ground: free convection
[U] Insolation **[M]** Chemical reactions **[M]** Phase changes **[M]** Other

Solar insolation is only modelled in the Holtslag weather scheme, in which it is used to determine the Monin-Obukhov length, a measure of the sensible heat flux from/to the ground.

'Chemical reactions' has been selected because DRIFT accounts for heat gain and loss from the heat of solution for non-ideal mixtures (liquid solutions of ammonia, hydrogen fluoride and hydrogen peroxide with condensed water are accounted for in DRIFT 3.7.23).

'Other' has also been selected to reflect the inclusion of oligomerisation of hydrogen fluoride in the vapour phase which represents another heat source/sink for the cloud.

A4.4.7.2 Relations used for thermodynamic properties

☑ Perfect gas law ☑ Antoine correlation ☑ Other

'Other' covers relations such as the calculation of enthalpy from temperature dependent specific heats and the calculation of latent heat.

DRIFT calculates temperature dependent substance properties by reading the coefficients from the HSE SPI file or ESR substance database and using these in temperature dependent correlations that are coded as part of DRIFT.

A4.4.8 Mass transfer mechanisms

☑ Mass transfer mechanisms considered

A4.4.8.1 Sources of vapour mass loss from cloud

[U] Dry deposition **[ ]** Wet deposition **[ ]** Other

By default in DRIFT, dry deposition is turned off. However, when enabled, a deposition velocity can either be specified by the user as a fixed constant, or calculated by DRIFT. If it is to be calculated, DRIFT uses a resistance model with user inputs (such as surface resistance and leaf area index). Deposition is represented as a material sink term through the ground, which is coupled to the cloud dynamics.

There is currently no option within DRIFT to specify saturation of the surface. However, a method has been developed to incorporate saturation effects in a post-processing step by using results from DRIFT simulations without deposition (Tickle, 2024). With this post-processing method there is no coupling between deposition and the cloud dynamics.

A4.4.9 Chemical reactions

☑ Chemical reactions considered

DRIFT does not directly model chemical reactions. However, for ammonia, hydrogen fluoride and hydrogen peroxide dispersing in moist air, DRIFT accounts for the heat of mixing and the non-ideality of the solution.

Oligomerisation is considered for hydrogen fluoride.

A4.4.9.1 Substances considered

☑ NH_3 ☑ HF ☑ H_2O_2 ☐ N_2O_4 ☐ UF_6 ☐ Other

A4.4.9.2 Effects of chemical reactions on cloud

☑ Heat source/sink ☑ Species (composition) ☐ Other

The heat source/sink option is checked to indicate inclusion of the heat of solution for non-ideal mixtures (ammonia, hydrogen fluoride and hydrogen peroxide) and inclusion of the enthalpy of oligomerisation for hydrogen fluoride in the vapour phase. The species (composition) option is checked to indicate the modelling of the changes in the vapour phase of hydrogen fluoride between different oligomerisation states.

A4.4.9.3 Level of detail in modelling

Reactants
[M] Vapour phase **[M]** Liquid phase

Reaction types modelled
[ ] Finite rate **[M]** Reversible **[ ]** Turbulence-controlled **[ ]** Other

'Vapour phase' is selected under 'Reactants' to account for the inclusion of oligomerisation of hydrogen fluoride in the vapour phase. 'Liquid phase' is selected because DRIFT accounts for the heat of mixing for solutions of ammonia, hydrogen fluoride and hydrogen peroxide with condensed water.

A4.4.9.4 Radioactivity

[ ] Radioactive decay modelled

A4.4.10 Transition to passive dispersion

A4.4.10.1 Criteria for transition to passive dispersion

☑ Richardson number small ☐ Density difference small
☐ Rate of lateral spreading small ☐ Other

There is no discrete transition: the model moves smoothly from the primarily gravitational regime to the primarily passive regime in a way which is guided by the Richardson number.

A4.4.10.2 Treatment of passive dispersion

☐ Dispersion parameters (σ's) used ☑ Other

Dispersion parameter dependencies
☐ Downwind distance ☑ Roughness length ☑ Atmospheric stability ☐ Other

DRIFT does not use simple functional forms for the growth of the standard deviations of the concentration profiles (σ_y and σ_z) with downwind distance. Instead, the passive spread is calculated from an approximate solution of the diffusion equation in an atmospheric boundary layer, based on standard deviations of velocity fluctuations about the mean, σ_u and σ_v, and the cloud travel time.

A4.4.11 Buoyant lift off and buoyant rise

☑ Provision for lift off of a grounded plume
☑ Option to model elevated passive plumes

A4.4.11.1 Criterion for lift off

☐ Richardson number ☑ Other

DRIFT does not use a Richardson number criterion for determining lift-off. It models lift-off based on the vertical buoyancy force on the cloud and an interpolation of model parameters between those for a ground-based cloud and those for an elevated cloud.

A4.4.12 Complex effects: aerosols

☑ Aerosols considered

A4.4.12.1 Sources of mass loss from two-phase clouds

[U] Rainout (two-phase) **[M]** Other

Other mass losses are included if ground deposition options are selected. These include loss of contaminant vapour by dry deposition and loss of liquid by gravitational settling of aerosol droplets, based on a user-specified initial droplet size and subsequent shrinkage calculated from the evaporation of liquid aerosol using DRIFT's homogenous equilibrium model.

A4.4.12.2 Type of model

☑ Homogeneous equilibrium ☐ Explicit droplet ☐ Other

A4.4.12.3 Effects incorporated in aerosol model

☑ Mass transfer between phases ☑ Heat transfer between phases
☑ Interaction with atmospheric water ☐ Other

A4.4.12.4 Cloud variables affected by aerosol

☑ Temperature ☑ Density ☑ Velocity ☑ Concentration ☑ Other

A4.4.12.5 Rainout and other effects considered

Mass loss

☑ Rainout ☐ Obstacle impact ☐ Other

Re-evaporation

☑ Initial rainout ☐ Deposition

DRIFT 3.7.23 includes an option for combining the initial airborne component of a release (consisting of vapour and entrained liquid droplets) and the component that rains out to form a pool. This can be used for any of the release options. DRIFT models the 'direct' release and the 'secondary' release from the pool vaporisation separately and adds together the resulting concentration predictions.

Droplet behaviour

☐ Coalescence ☐ Break-up ☐ Other

Droplet behaviour is only considered within the deposition model, in which a droplet deposition velocity is calculated based on droplet size.

A4.4.13 Complex effects: terrain

☐ Terrain considered

A4.4.13.1 Cloud variables affected by terrain

☐ Depth ☐ Width ☐ Velocity ☐ Concentration ☐ Other

A4.4.13.2 Physical processes modified in formulation of terrain effects

☐ Advection ☐ Entrainment ☐ Gravity spreading ☐ Other

A4.4.13.3 Modification of ambient flow by terrain

☐ Mean flow ☐ Turbulence ☐ Other

A4.4.14 Complex effects: obstacles

☑ Obstacles considered

A4.4.14.1 Level of detail

☑ Net effect ☐ Local detail ☐ Other

A4.4.14.2 Cloud variables affected directly by obstacles

☑ Depth ☑ Width ☑ Velocity ☐ Puff time-of-arrival
☑ Concentration ☑ Other

A4.4.14.3 Physical processes modified in formulation of obstacles

☑ Advection ☑ Entrainment ☑ Gravity spreading ☑ Other

A4.4.14.4 Modification of ambient flow by obstacles

☐ Mean flow ☐ Turbulence ☐ Other

A4.5 Solution technique

A4.5.1 Equation types

A4.5.1.1 Type of main equations

☑ Algebraic ☑ Ordinary differential ☐ Partial differential ☐ Other

A4.5.2 Analytical solution methods

☑ Significant analytical solution methods used

☐ Methods developed as part of model ☑ Existing methods used ☐ Other

A4.5.3 Numerical solution methods

☑ Significant numerical solution methods used

☐ Methods developed as part of model ☑ Existing methods used ☐ Other

DRIFT employs the DDRIV3 solver from CMLIB.

A4.5.3.1 Computational grid

☐ Structured ☐ Unstructured ☑ Adaptive ☐ Multi-block ☐ Other

[ ] Grid size/arrangement ☐ Advice provided

DRIFT employs a variable step ODE (ordinary differential equation) solver.

A4.5.3.2 Discretisation methods

☑ Temporal discretisation of governing equations

☐ Explicit ☑ Implicit ☐ Other

☑ Spatial discretisation of governing equations

☐ Finite difference ☐ Finite volume ☐ Finite element ☑ Other

A variable step ODE solver is used solving a mixed set of both first-order differential equations and purely algebraic equations. Temporal steps are used for instantaneous releases; spatial steps are used for steady continuous releases.

'Other' is selected for 'spatial discretisation of governing equations' because the implicit method used by the solver does not rely on approximating the derivatives by a simple finite difference method, but solves an implicit equation to obtain the state at the next step. DRIFT does not discretise the spatial field. The solver decides on the step size to achieve solution accuracy at the requested numerical tolerance.

A4.5.3.3 Solution of discrete system

Solution methods used

☐ Segregated solver ☑ Coupled solver

Convergence

☐ Convergence criteria ☐ Features to enhance convergence ☑ Other

Accuracy

☑ Desired accuracy specified ☐ Other

DRIFT requests a solution from DDRIV3 with a specified tolerance (relative accuracy in all solution components). For well-behaved model equations the numerical method is convergent and it is not a requirement for DRIFT itself to check for numerical convergence. In the circumstance that the solver cannot find a solution, likely due to some poorly-behaved aspect of the model equations, then it will report an error which is passed on by DRIFT as a warning or error message.

A4.6 Results or output available from model

A4.6.1 Concentration-related output for steady situations

A4.6.1.1 Plume centreline

☑ Plume centreline trajectory

A4.6.1.2 Pointwise concentration output

☑ Pointwise concentration distributions

☑ Centreline ☑ Longitudinal ☑ Lateral ☑ Vertical ☑ All points

☐ Other

Pointwise concentration output can be obtained by using the COM interface to interrogate the cloud.

A4.6.1.3 Derived concentration data

☑ Derived concentration information

☑ Contours ☑ Flammable inventory

☑ Lateral distance to given concentration

☑ Longitudinal distance to given concentration

☑ Indoor concentration ☐ Other

☑ Dose calculated based on prescribed exposure duration

☑ Contours

☑ Lateral distance to given dose

☑ Longitudinal distance to given dose

☑ Dose received by an indoor recipient ☐ Other

A4.6.1.4 Concentration fluctuations

☑ Concentration fluctuations

☑ Averaging time ☐ Probability density function ☐ Other

Horizontal plume meander is accounted for in post processing by applying an averaging time correlation to the concentration profiles, following the approach of Nielsen et al. (2002). The effect of vertical fluctuations for buoyant plumes in unstable conditions is accounted for using the approach of Weil et al. (1997). The averaging time is limited by the release duration. If the user inputs an averaging time that exceeds the release duration, DRIFT sets the averaging time equal to the release duration.

Within the GUI, only the output displayed in the toxic and general results windows includes the effect of time averaging. Flammable results are based on short (near-instantaneous) average values. All custom plots and tables are also based on short (near-instantaneous) average values.

Methods that directly ask for concentration/dose results via the COM interface are time-averaged according to the toxic averaging time. Methods that contain the word Flammable are based on the short (near-instantaneous) average values. All other variables, including output variables at each output step, are not time averaged (i.e. they correspond to short time (near-instantaneous) average values.

A4.6.2 Concentration-related output for non-steady situations

This section describes the concentration-related output that is available when modelling instantaneous, finite duration or time varying releases.

A4.6.2.1 Cloud position

☑ Position of cloud

☑ Centroid ☑ Time-of-arrival ☑ Other

A4.6.2.2 Pointwise concentration output

☑ Concentration time history at a point

☑ Coordinate origin for distributions

☑ Cloud centroid ☑ Fixed origin ☐ Other

☑ Distributions relative to origin

☑ Centreline ☑ Longitudinal ☑ Lateral ☑ Vertical ☑ All points

☐ Other

Pointwise concentration output can be obtained by using the COM interface to interrogate the cloud.

A4.6.2.3 Derived concentration data

☑ Derived concentration information

☑ Contours ☑ Flammable inventory
☑ Lateral distance to given concentration
☑ Longitudinal distance to given concentration
☑ Concentration time history at a point
☑ Maximum concentrations over time
☑ Indoor concentration ☐ Other

☑ Dose calculated based on prescribed exposure duration

☑ Contours
☑ Lateral distance to given dose
☑ Longitudinal distance to given dose
☑ Dose received by an indoor recipient ☐ Other

A4.6.2.4 Concentration fluctuations

☑ Concentration fluctuations

☑ Averaging time ☐ PDF ☐ Other

For finite duration and time varying releases, plume meander is accounted for in post processing using the same approach as is used for continuous releases. An averaging time correlation is applied to the concentration profiles, following the approach of Nielsen et al. (2002). The effect of vertical fluctuations for buoyant plumes in unstable conditions is accounted for using the approach of Weil et al. (1997). For finite duration and time varying releases, the averaging time is limited by the release duration. If the user inputs an averaging time that exceeds the release duration, DRIFT sets the averaging time equal to the release duration.

Concentration fluctuations are not considered for instantaneous releases. This is because the variations in wind direction that cause a plume to meander (and which average out as an increased plume width) are expected to simply displace the centroid of an instantaneous release such that it might take a more circuitous path than a straight line. This would amount to a dilution for an ensemble average of many repeated instantaneous releases, but for a single instantaneous release DRIFT assumes no addition dilution due to these fluctuations and simply treats the path of the centroid as following the mean wind direction. This treatment of concentration fluctuations is idealised and in reality, if a puff release is large and takes some time to pass an observer it might really behave more like a (time-varying) plume in terms of the effect of time-averaging.

See Section A4.6.1.4 for a description of which outputs include the effects of time averaging.

A4.6.3 Other information available

A4.6.3.1 Temperature

☑ Mean temperature ☐ Fluctuations

A4.6.3.2 Further variables

☑ Other variables available in output

☑ Radius/width	☑ Height/depth	☑ Density
☑ Velocity magnitude	☑ Velocity vector	☐ Pressure
☐ Turbulent kinetic energy	☐ Turbulent dissipation	☑ Other

A4.7 Sources of model uncertainty

A4.7.1 Stochastic processes

Stochastic processes are always a source of uncertainty and dispersion is a stochastic process. The uncertainty is reduced as much as possible by predicting averaged concentrations.

A4.7.2 Modelling assumptions

There may be some uncertainty in very stable atmospheric conditions where little data are available for validation. The same is true for low wind speeds.

The models for transient and unsteady releases add some new ideas and assumptions and some uncertainty exists in the specification of these models. However, in relation to other modelling assumptions, the influence of these uncertainties is likely to be small.

The following are other areas of model uncertainty. Not all of these sources of uncertainly are unique to DRIFT and represent uncertainties that would be expected to arise in integral modelling approaches in general.

Time-averaging
The increase in the lateral spread due to plume meander is based on the model of Nielsen et al. (2002), which was developed under the EU COFIN project using lidar data. However, the EU COFIN datasets showed significant variation.

Time-varying model
DRIFT's treatment of time-varying releases is sensitive to its segmentation of the cloud and can produce unphysical spikes in concentration from overlapping segments.

Rainout and deposition
DRIFT does not calculate rainout but relies on a user-input rainout fraction which can be very uncertain. DRIFT's default is to ignore deposition. DRIFT's deposition models rely on user input of surface resistance and initial droplet size which are uncertain. DRIFT does not account for saturation effects limiting deposition, although this may be applied approximately in post-processing.

Interface with pool vaporisation model
DRIFT includes an option for combining the initial airborne component of a release (consisting of vapour and entrained liquid droplets) and the component that rains out to form a pool. DRIFT treats the dispersion from the direct (initial airborne) release and from

the vaporising pool as separate, adding together the predicted concentration fields. In reality, overlapping clouds are expected to merge and not disperse independently.

Heat transfer
DRIFT's heat transfer model assumes a constant ground temperature, whereas in reality the ground may cool over time reducing heat transfer. By default, DRIFT ignores heat transfer to the cloud from the ground.

Expansion modelling
DRIFT uses the model of Birch et al. (1987) for calculating the pseudo-source conditions at ambient pressure for sonic gaseous jets. This assumes ideal gas behaviour which adds to uncertainty for releases that choke at very high pressure.

Jet impingement
DRIFT has a simplified model for impingement which is only expected to apply at shallow angles of impingement.

Dilution over the source
The approach used to calculate the initial dilution over the source for a low momentum area source lacks validation.

Atmosphere
The assumption that the cloud remains trapped below an elevated inversion may not be appropriate for very buoyant releases and the model lacks validation for cases when the cloud extends fully over the depth of the boundary layer.

The assumption of constant meteorological conditions may not apply when validating the model against some datasets or when considering very long-range dispersion.

A4.7.3 Numerical method

There is low uncertainty in the numerical method. The solver is a commercial package designed using advanced concepts of numerical mathematics to control errors.

A4.7.4 Sensitivity to input

Any sensitivity to input is expected to reflect real sensitivity to initial conditions.

A4.8 Limits of applicability

A4.8.1 Sources

A4.8.1.1 Primary origin

The source must be specified as a heavy, passive or buoyant gas, aerosol cloud or momentum jet. It may be instantaneous, continuous, finite duration, or time varying. Low momentum area sources must be ground based.

A4.8.1.2 Release type

Pools, jet sources and flashing instantaneous releases are routinely considered with the program.

The pool model GASP produces an input file for DRIFT which converts what is a non-instantaneous, non-steady release into a form which DRIFT can cope with explicitly. GASP files can be imported directly.

A4.8.1.3 Thermodynamic properties

DRIFT can model the dispersion of a gas or aerosol cloud consisting of a mixture of contaminant gas, contaminant liquid, dry air, water vapour and water liquid. Any appropriate temperature may be input. The thermal effects of vaporisation and condensation are included.

For ammonia, hydrogen fluoride and hydrogen peroxide, the heat of solution is modelled; for hydrogen fluoride, oligomerisation is modelled.

A4.8.1.4 Chemical properties

DRIFT does not directly model chemical reactions. However, for ammonia, hydrogen fluoride and hydrogen peroxide dispersing in moist air, DRIFT accounts for the heat of mixing and the non-ideality of the solution.

Oligomerisation is considered for hydrogen fluoride.

A4.8.2 Environments

A4.8.2.1 Atmosphere

Wind speed and atmospheric stability are accounted for. The minimum wind speed that can be input in the GUI is 0.1 m/s.

The primary parameters are friction velocity, roughness length and Monin-Obukhov length. The Monin-Obukhov length can be input direct or estimated internally from Pasquill or Holtslag schemes.

A4.8.2.2 Terrain

DRIFT can only model flat terrain.

A4.8.2.3 Obstacles

Multiple buildings and fences can be modelled. Any buildings or fences are assumed to be cuboidal.

A4.8.3 Targets/output

A4.8.3.1 General situations

A large amount of output is available in graphical or tabular form.

A4.8.3.2 Steady situations

A large amount of output is available in graphical or tabular form. For steady continuous releases, the user can generate custom tables that can include any global or component variables output by DRIFT.

A4.8.3.3 Time-dependent situations

A large amount of output is available in graphical or tabular form. For instantaneous and finite duration releases, the user can generate custom tables that can include any global or component variables output by DRIFT. This facility is not available for time-varying releases or when a GASP file has been imported.

A4.9 Special features

A4.9.1 Capabilities

DRIFT has the ability to handle fence and building obstacles. These sub-models were produced and validated as a result of extensive Coordinating European Council (CEC) research programmes, which demonstrated how they could be included quite generally in almost any integral model.

DRIFT has the ability to model jets in a crosswind. It can also model jets tilted away from the horizontal, at any angle from initially vertically upwards to initially vertically downwards.

DRIFT contains a sophisticated model for calculating the toxic dose to which outdoor and indoor recipients are exposed. The exposure duration is limited by either the cloud passage time or the maximum exposure duration specified by the user.

A4.9.2 Formulation

The variety of optional output variables is unusually large. This makes it fairly straightforward to get an overall idea of the dispersion predictions – much more so, for example, than when simply predicting concentrations at given points.

A4.9.3 Mathematical aspects

N/A

A4.10 Planned scientific developments

Validation work related to ammonia is envisaged as part of Jack Rabbit III and possibly also in parallel with proposed European experiments on ammonia spills in water. There is general interest as to how best to use DRIFT to model dispersion from ammonia spills into water. In addition, the increased interest in using semi-refrigerated ammonia will make it more important to be able to characterise the likely rainout under these conditions.

With the increased focus on hydrogen for future clean energy, the model developers propose to address the modelling uncertainty resulting from using the ideal gas law in

DRIFT to model under-expanded hydrogen jet dispersion by adopting a more applicable equation of state.

Further development of the time-varying model is planned, to improve the segmentation of releases and remove unphysical spikes in the concentration predictions, particularly when modelling dispersion from vaporising pools. The current limitations to the time-varying model prevent it from being applied more widely.

A5 User-oriented aspects of model

A5.1 User-oriented documentation and help

A5.1.1 Written documentation

☑ User manual ☑ Other

A user manual (ESR, 2022) and COM interface guide (Walton, 2011) are provided, together with a guide to the DRIFT mathematical model (Tickle and Carlisle, 2015).

A5.1.2 On-screen help and documentation

☑ Context-sensitive help ☑ User manual online ☐ Other

A5.2 Installation procedures

DRIFT 3.7.23 is available as an internet download.

The files should be copied to the desired location before running the installation programme. Guidance on installation is available in an accompanying text file.

Previous versions of DRIFT need to be uninstalled before installation of a new version of DRIFT.

A5.3 Description of the user interface

A5.3.1 General properties

☑ Interactive ☑ Batch ☑ Graphical
☑ Text file-based input/output system ☑ Other

Users can interact with DRIFT using either the GUI or the COM interface. The COM interface provides a programmatic means of inputting data, running the model and extracting output.

Text files are not intended for general users to edit.

A5.3.2 Provision of input

☑ Edit files directly ☑ Guided input ☑ Enter data on graphical forms
☑ Edit existing files ☑ Edit default input ☑ Other

The user also has the option of inputting data via the COM interface.

A5.3.3 Information when model running

☐ Numerical values ☑ Error/warning messages ☑ Status of calculation
☐ Other

A5.3.4 Examining output

A5.3.4.1 Graphical display of output

☑ Integral graphical display facilities ☐ Separate graphical display program
☑ Interactive selection ☐ Other

Interactive selection: the user can plot graphs or tables of any combination of DRIFT outputs. This facility is not available for time-varying releases or when a GASP file has been imported.

A5.3.4.2 Examining numerical values

☑ Integral numerical display facilities ☑ Separate numerical display facility
☐ Output files ☐ Other

Numerical outputs can be examined in the GUI or extracted to a spreadsheet via the COM interface or via copy-paste.

A5.4 Internal databases

☑ Internal databases available

A5.4.1 Databases available

☑ Material properties ☐ Scenarios ☐ Other

The ESR substance database contains the substance property information required by DRIFT for 54 substances. The database includes a range of toxic and flammable substances, air and water. It contains the LFL (lower flammable limit) and UFL (upper flammable limit) for flammable substances but does not contain toxicity levels for toxic substances.

A5.4.2 Access by user

☑ Access from model ☑ Access outside model ☐ Other

The data and correlations in the ESR substance database are based on substance property information contained in the SRD DATABANK (Prince, 1990).

The ESR substance database can be opened using Microsoft Access or accessed using database queries. However, it was not intended that the ESR substance database should be changed by the general user.

A5.4.3 Modification

☐ General users ☐ Administrators only ☑ No users ☐ Other

General users can specify a user-defined substance, but this is not saved in the database (even locally). A user-defined substance can only be used in the DRIFT file in which it is created.

No user guide is provided for editing existing data or adding new data and this approach is not recommended.

A5.5 External databases

☑ Model can link to external databases

A5.5.1 Databases available

☑ Material properties ☐ Scenarios ☐ Other

DRIFT has the facility to read in data from HSE's substance property database, which is in the form of SPI (Substance Property Information) files (Macbeth, 2004). 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.

For DRIFT to initialise correctly when the Substance Properties Data Source is set to 'SPI files', a propane SPI file must be present.

SPI files are not available for use outside HSE.

A5.5.2 Access by user

☐ Access from model ☑ Access outside model ☐ Other

The SPI file data can be read directly from the text files or via a spreadsheet viewer developed for use within HSE.

A5.5.3 Modification

☐ General users ☐ Administrators only ☑ No users ☐ Other

Users should not modify SPI files. Requests for updates or corrections to SPI files should be sent to the relevant team within HSE.

A5.6 Guidance in selecting model options

A5.6.1 Main choices required

☐ Primary origin details
☑ Source configuration
☑ Substance release
☐ Properties of substance released
☑ Atmospheric conditions
☐ Terrain
☑ Obstacles
☐ Boundary conditions
☑ Initial conditions
☐ Computational grid
☑ Output required
☐ Other

The roughness length can be input but no other terrain details are required.

A5.6.2 Guidance in choices available

A5.6.2.1 Sources

☑ User documentation ☑ Within interface ☐ Pre-existing input files ☐ Other

A5.6.2.2 Type

☐ Worked examples ☑ Explicit advice ☐ Pre-set lists of values
☐ Defaults ☐ Other

DRIFT defaults to propane on opening. The defaults are applicable to propane but not necessarily to other substances.

A5.7 Assistance in the inputting of data

A5.7.1 Facilities available

A5.7.1.1 Checks

☑ Valid range ☑ Valid type ☐ Entry has been made ☐ Other

DRIFT prepopulates an entry in every field.

A5.7.1.2 Filing system

☑ Choose input file location ☑ Choose input file name.

A5.8 Error messages and checks on use of model beyond its scope

A5.8.1 Facilities to trap inappropriate use

☑ Facilities available
☑ Checks on intermediate results ☑ Warning messages given
☑ Other action taken

DRIFT terminates if it encounters conditions that it cannot explicitly cope with.

A5.8.2 Error/warning Messages

A5.8.2.1 Occurrence

☑ During input ☑ During model run ☑ During output examination ☐ Other

A5.8.2.2 Type

☑ Self-explanatory ☐ Look up online ☑ Look up in documentation ☐ Other

A5.9 Computational aspects

A5.9.1 Programming languages

A5.9.1.1 Mathematical model

The DRIFT mathematical model is written in C++.

A5.9.1.2 Interface

The GUI is written in C++ and uses Qt libraries. The COM interface is written in C#.

A5.9.2 User programming

No user programming of the model itself is possible. However, the user can interact with the model through the COM interface and gain access to an increased range of output.

A5.9.3 Execution times for specified problems

◉ Seconds ○ Minutes ○ Hours ○ Days

A5.10 Clarity and flexibility of output results

A5.10.1 Summary of model output

Model output is displayed in the GUI in graphical and tabular format and can also be extracted using the COM interface.

A5.10.2 Facilities for display of results

☑ Graphical formats

☑ Line ('x-y') plots ☑ Contour plots ☐ Vector plots
☐ Display on GIS ☐ Animated display ☐ Virtual reality ☐ Other

☑ Numerical formats

☑ Tabulated output ☑ User interrogation ☐ Other

For instantaneous, steady continuous and finite duration releases, the user can generate custom tables that can include any global or component variables output by DRIFT. This facility is not available for time-varying releases or when a GASP file has been imported.

☑ Hard copy facilities available directly from program

☑ Numerical output ☑ Graphical output ☐ Other

☐ Additional software may be required

◉ Necessary ○ Optional

Required for:

☐ Line ('x-y') plots ☐ Contour plots ☐ Vector plots
☐ Display on GIS ☐ Animated display ☐ Virtual reality
☐ All ☐ Other

A DRIFT report containing all user inputs and key model outputs can be printed from the GUI. Individual graphs can also be printed out.

Table contents can be copy-pasted into other applications such as Excel.

A5.11 Suitability to users and usage

A5.11.1 Suitability with respect to type of user

A5.11.1.1 Background

☑ Engineer ☑ Consultant ☑ Regulator ☑ Academic ☐ Other

A5.11.1.2 Type of experience

☑ Dispersion ☐ Fluid dynamics ☐ Thermodynamics ☐ Numerical methods
☐ Statistics ☐ Programming ☑ Consequence modelling ☐ Risk analysis

Other experience (e.g. fluid dynamics, thermodynamics) will allow users to interact with the model in greater depth but is not required for routine usage.

A5.11.1.3 Length of experience

○ Hours ○ Days ◉ Weeks ○ Months ○ Years

A5.11.2 Suitability with respect to type of usage

A5.11.2.1 Type of assessment

☑ Specific incidents ☑ Hazard assessment ☑ Risk assessment ☐ Other

DRIFT does not carry out risk calculations but can be used as part of a risk assessment.

A5.11.2.2 Range of problems

○ Narrow ○ Medium ◉ Wide

A5.12 Possible improvements

☑ Written documentation ☐ Online help and documentation ☐ Installation
☐ User interface ☐ Selection/entry of input data
☐ Information and checks while running ☐ Output results

The finite duration and time-varying models would benefit from further explanation in the documentation.

The current COM interface guide (Walton, 2011) does not document all the available functions. An improved explanation of the variables in the COM interface would also be beneficial to users.

A5.13 Planned user-oriented developments

Discussions have taken place on improving the documentation of DRIFT's COM interface. The COM interface was originally designed as a testing tool for model developers, but in recent years, the number of HSE users running DRIFT via the COM interface has increased. The COM interface guide would benefit from being revised and expanded to provide more detailed guidance for these users.

The updated guidance could:

- provide a comprehensive list of the functions available within the COM interface
- provide an improved explanation of the variables available in the COM interface and document what averaging is applied to each variable

A6 Evaluation against MEP qualitative assessment criteria

A6.1 Scientific criteria

- ☑ Key details of the model available for scientific assessment
- ☑ Model based on accepted/published science
- ☑ Model accepts a credible source term, including pool sources (low momentum area), jet sources (vapour and two-phase) and instantaneous sources (vapour and two-phase)
- ☑ Model accounts for the effects of wind speed
- ☑ Model accounts for the effects of humidity
- ☑ Model accounts for the effects of surface roughness
- ☑ Model accounts for the effects of atmospheric stability
- ☑ Model accounts for passive dispersion
- ☑ Model accounts for gravity-driven spreading
- ☑ Model accounts for the effects of buoyancy on dilution
- ☑ Model accounts for buoyant lift off and buoyant rise
- ☑ Numerical methods are based on accepted/published good practice

A6.2 Input and output criteria

- ☑ Model produces output suitable for assessment against MEP statistical performance measures
- ☑ Model can access data from HSE's SPI (Substance Property Information) files
- ☑ Model can calculate the dose received by outdoor and indoor recipients
- ☑ Model can calculate dose isopleths
- ☑ Model exports data in a format suitable for use in HSE's risk calculation model
- ☑ Model can be run in batch mode (through the COM interface)

Appendix B

Exemplar scenarios

B1 Pool releases

The pool release scenarios in the DRIFT exemplar database are summarised in Table 16 and Table 17.

Table 16 Summary of the pool releases of toxic substances in the DRIFT exemplar database.

Substance	Storage quantity (tonnes)	Failure type	Release	Bund	Substrate	Weather conditions
Methyl iodide	65.5	Catastrophic failure	65.5 tonnes	Fails	Concrete	D2.4, D4.3, D6.7, F2.4
Methyl iodide	65.5	250 mm hole	462 kg/s for 364 s	Remains intact	Concrete	D2.4, D4.3, D6.7, F2.4
Ethylene oxide	90	Catastrophic failure	90 tonnes	Remains intact	Concrete	D2.4, D4.3, D6.7, F2.4
Ethylene oxide	90	50 mm hole	37.4 kg/s for 1203 s	Remains intact	Concrete	D2.4, D4.3, D6.7, F2.4

Table 17 Summary of the pool releases of flammable substances in the DRIFT exemplar database.

Substance	Storage quantity (tonnes)	Failure type	Release	Bund	Substrate	Weather conditions
Liquid hydrogen	3.5	Catastrophic failure	3.5 tonnes	None	Concrete	D2.4, D4.3, D6.7, D10, D15, F2.4
Liquid hydrogen	3.5	50 mm hole	14.3 kg/s for 245 s	None	Concrete	D2.4, D4.3, D6.7, D10, D15, F2.4

Substance	Storage quantity (tonnes)	Failure type	Release	Bund	Substrate	Weather conditions
Liquid hydrogen	5	Catastrophic failure	5 tonnes	None	Concrete	D2.4, D4.3, D6.7, F2.4
Liquid hydrogen	40	Catastrophic failure	40 tonnes	None	Concrete	D2.4, D4.3, D6.7, F2.4
LNG (liquefied natural gas)	21,000	Catastrophic failure	21,000 tonnes	Fails	Wet soil, dry soil	D2.4, D4.3, D6.7, F2.4
LNG	21,000	Catastrophic failure	1,888 tonnes	Remains intact	Wet soil, dry soil	D2.4, D4.3, D6.7, F2.4
LNG	21,000	1000 mm hole	3970 kg/s for 1800 s	Fails	Wet soil, dry soil	D2.4, D4.3, D6.7, F2.4
LNG	21,000	300 mm hole	327 kg/s for 1800 s	Fails	Wet soil, dry soil	D2.4, D4.3, D6.7, F2.4
LNG	21,000	200 mm liquid pipe guillotine	61 kg/s for 1800 s	Remains intact	Wet soil, dry soil	D2.4, D4.3, D6.7, F2.4

B2 Instantaneous flashing releases

The instantaneous flashing release scenarios in the DRIFT exemplar database are summarised in Table 18 and **Table** 19.

Table 18 Summary of the instantaneous flashing releases of toxic substances in the DRIFT exemplar database.

Substance	Storage quantity (tonnes)	Vessel temperature (°C)	Failure type	Weather conditions
Chlorine	1, 7.5, 10, 15, 50, 100	Ambient	Catastrophic failure	D2.4, D4.3, D6.7, F2.4
Sulphur dioxide	1, 7.5, 10, 15, 50, 100	Ambient	Catastrophic failure	D2.4, D4.3, D6.7, F2.4
Ammonia	1, 7.5, 10, 15, 50, 100	Ambient	Catastrophic failure	D2.4, D4.3, D6.7, F2.4
Ammonia	1000, 10,000, 100,000	-33.34	Catastrophic failure	D2.4, D4.3, D6.7, F2.4
Acrolein	1, 10, 100	109	Catastrophic failure	D4.3, F2.4
2-chloroethanol	1, 10, 100	185	Catastrophic failure	D4.3, F2.4
Methyl chloroformate	1, 10, 100	125	Catastrophic failure	D4.3, F2.4
Propionitrile	1, 10, 100	161	Catastrophic failure	D4.3, F2.4

Table 19 Summary of the instantaneous flashing releases of flammable substances in the DRIFT exemplar database.

Substance	Storage quantity (tonnes)	Vessel temperature (°C)	Failure type	Weather conditions
Isobutane	1056	Ambient	Catastrophic failure	D5, F2
Propane	548.4	1	Catastrophic failure	D5, F2

B3 Momentum jet releases

The momentum jet release scenarios in the DRIFT exemplar database are summarised in Table 20 and Table 21. For each chlorine pipework release, two scenarios are modelled: one in which an automatic shut-off valve (ASOV) activates after 1 minute, and one in which the ASOV fails, and a manual shut-off valve is closed after 20 minutes.

Table 20 Summary of the momentum jet releases of toxic substances in the DRIFT exemplar database.

Substance	Storage quantity (tonnes)	Storage temp. (°C)	Failure type	Release rate	Weather conditions
Ammonia	100 (at SVP (saturated vapour pressure))	15	50 mm hole in vessel liquid space	33.8 kg/s for 1480 s	D2.4, D4.3, D6.7
Ammonia	100 (at SVP)	5	50 mm hole in vessel liquid space	27.8 kg/s for 1800 s	F2.4
Chlorine	15 (at SVP)	15	50 mm hole in vessel liquid space	44.3 kg/s for 169 s	D2.4, D4.3, D6.7
Chlorine	15 (at SVP)	5	50 mm hole in vessel liquid space	37.1 kg/s for 202 s	F2.4
Chlorine	15 (at SVP)	15	50 mm hole in vessel vapour space	1.32 kg/s for 1800 s	D2.4, D4.3, D6.7
Chlorine	15 (at SVP)	5	50 mm hole in vessel vapour space	1.06 kg/s for 1800 s	F2.4
Chlorine	15 (at SVP)	15	50 mm hole in liquid pipework (ASOV)	2.59 kg/s for 60 s	D2.4, D4.3, D6.7
Chlorine	15 (at SVP)	5	50 mm hole in liquid pipework (ASOV)	2.23 kg/s for 60 s	F2.4
Chlorine	15 (at SVP)	15	50 mm hole in liquid pipework (manual)	2.59 kg/s for 1200 s	D2.4, D4.3, D6.7
Chlorine	15 (at SVP)	5	50 mm hole in liquid pipework (manual)	2.23 kg/s for 1200 s	F2.4
Chlorine	100 (at 6.9 barg)	15	50 mm hole in vessel liquid space	53.1 kg/s for 941 s	D2.4, D4.3, D6.7
Chlorine	100 (at 6.9 barg)	5	50 mm hole in vessel liquid space	53.7 kg/s for 930 s	F2.4

Substance	Storage quantity (tonnes)	Storage temp. (°C)	Failure type	Release rate	Weather conditions
Chlorine	100 (at 6.9 barg)	15	50 mm hole in vessel vapour space	2.78 kg/s for 1800 s	D2.4, D4.3, D6.7
Chlorine	100 (at 6.9 barg)	5	50 mm hole in vessel vapour space	2.15 kg/s for 1800 s	F2.4
Chlorine	100 (at 6.9 barg)	15	Severe split of liquid pipework (ASOV)	7.85 kg/s for 60 s	D2.4, D4.3, D6.7
Chlorine	100 (at 6.9 barg)	5	Severe split of liquid pipework (ASOV)	10.0 kg/s for 60 s	F2.4
Chlorine	100 (at 6.9 barg)	15	Severe split of liquid pipework (manual)	7.85 kg/s for 1200 s	D2.4, D4.3, D6.7
Chlorine	100 (at 6.9 barg)	5	Severe split of liquid pipework (manual)	10.0 kg/s for 1200 s	F2.4
Sulphur dioxide	100 (at SVP)	15	50 mm hole in vessel liquid space	26.6 kg/s for 1800 s	D4.3
Sulphur dioxide	100 (at SVP)	5	50 mm hole in vessel liquid space	19.1 kg/s for 1800 s	F2.4

Table 21 Summary of the momentum jet releases of flammable substances in the DRIFT exemplar database.

Substance	Failure type	Release rate	Weather conditions
Methane	Compressor rupture	9742 kg/s for 1800 s	D5, F2
Methane	Compressor 110 mm hole	126 kg/s for 1800 s	D5, F2
Methane	Piping rupture	6331 kg/s for 1800 s	D5, F2
Methane	Piping 100 mm hole	110 kg/s for 1800 s	D5, F2

B4 Flammable pipeline releases

The ethylene and LPG (liquefied petroleum gas) pipeline release scenarios in the DRIFT exemplar database are summarised in Table 22.

Table 22 Summary of the pipeline releases of flammable substances in the DRIFT exemplar database.

Substance	Pipeline diameter (inches)	Pipeline wall thickness (mm)	Failure type	Release rate	Weather conditions
Ethylene	8	7.04	Rupture	323.77 kg/s for 120 s	D5, F2
Ethylene	8	7.04	110 mm hole	225.68 kg/s for 120 s	D5, F2
Ethylene	8	7.04	75 mm hole	166.63 kg/s for 120 s	D5, F2
Ethylene	8	7.04	25 mm hole	25.05 kg/s for 120 s	D5, F2
LPG	4.5	6.02	Rupture	30.34 kg/s for 1800 s	D5, F2
LPG	4.5	5.02	Rupture	33.14 kg/s for 1800 s	D5, F2
LPG	4.5	6.02	100 mm hole	80.28 kg/s for 1800 s	D5, F2
LPG	4.5	5.02	100 mm hole	86.69 kg/s for 1800 s	D5, F2
LPG	4.5	6.02	75 mm hole	85.98 kg/s for 1800 s	D5, F2
LPG	4.5	5.02	75 mm hole	88.29 kg/s for 1800 s	D5, F2
LPG	4.5	6.02	25 mm hole	13.19 kg/s for 1800 s	D5, F2
LPG	4.5	5.02	25 mm hole	13.20 kg/s for 1800 s	D5, F2

HSE uses the gas dispersion model DRIFT 3 in its assessment of the hazards and risks posed by toxic and flammable substances stored at major hazard sites. The development of DRIFT 3 is ongoing, motivated by the need for HSE's statutory advice to be based on an up-to-date dispersion model.

To ensure that DRIFT 3 remains fit for purpose it is important to continue to evaluate it and to assess the effect of changes to the model on its predictions. This report describes the evaluation of DRIFT 3.7.23 against a Model Evaluation Protocol (MEP) designed specifically for DRIFT, which contains scientific assessment, verification, validation and a user-oriented assessment. The DRIFT MEP also includes the testing of the model against a set of exemplar scenarios, representative of the types of scenarios typically modelled by HSE for the purposes of Hazardous Substances Consent assessment. Based on the evaluation of DRIFT 3.7.23 against the DRIFT MEP, DRIFT 3.7.23 is judged to be fit for purpose and suitable for use in HSE's regulatory work.

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

Published by the Health and Safety Executive 08/26