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Review of dense-gas dispersion for industrial regulation and emergency preparedness and response

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EXECUTIVE SUMMARY

This work has been undertaken with the goal of providing a high-level review of dense gas dispersion in the context of industrial regulation, emergency preparedness and emergency response. The report begins with a summary of the frameworks for industrial regulation, emergency preparedness and emergency response in the UK, and describes how models are used in that context. In the main body of the report, features of dense gas dispersion are explored through a review of current knowledge on the physics of dense gas dispersion, incidents, models, experiments and mitigation measures.

The review of physics focuses on factors that affect the cloud evolution and on the ingress of dense gases into structures. Causes of the density difference, which result in dense gas dispersion, are summarised. Factors affecting dispersion behaviour are identified as being the source geometry, atmospheric conditions, heat transfer, phase change, deposition, surface conditions, fixed structures and topography. Factors that affect ingress include the type and location of openings, ventilation systems, atmospheric conditions, thermal effects, proximity of structures to the source and the type of structure.

A brief summary of 69 dense gas dispersion incidents is presented, covering a range of hazardous substances and sources. These incidents demonstrate various factors affecting dense gas dispersion behaviour. Where possible, the incidents are used to illustrate the effectiveness of emergency preparedness and response measures.

The review of dense gas dispersion models considers the different types of models available and some of the more common modelling assumptions. Important topics, such as model evaluation, are discussed and existing good practice guidelines are summarised. The features of 64 dispersion models are described, including models for predicting ingress.

A collection of 63 dense gas dispersion experiments are summarised briefly, covering both field trials and wind tunnel studies. For each experiment, details are provided for the substance, location, release conditions and type of measurements, along with references for further information. Where possible, an indication is given of the quality of the dataset and whether it has been used in model evaluation exercises.

Mitigation measures are summarised based on their impact on either the source, on the dense gas dispersion behaviour or on mitigating personal exposure. Where possible, reference is made to the use of mitigation measures in incidents and experiments reviewed earlier in the report.

These six chapters (regulatory/response frameworks, physics, incidents, models, experiments and mitigation) are drawn together into six scenarios illustrating dense gas dispersion in industrial regulation and emergency preparedness and response in the UK.

Looking ahead, future trends and emerging technologies are discussed, along with potential knowledge gaps. A review of previous knowledge gap studies identifies key issues such as:

- Lack of information available from incidents resulting in incomplete knowledge of the scenario, particularly for modelling
- Uncertainties in source emission models. In particular, flashing jets, post-expansion physics, rainout, impaction and uncertainty in behaviour inside the containment vessel
- Uncertainties in transport and dispersion models including chemical removal from the atmosphere due to gravitational settling, dry deposition and chemical reactions
- Uncertainties when buildings and terrain effects are important and need to be resolved in models, including wake effects and the impact on cloud persistence, particularly in light winds

- Impact of low/zero winds on emergency response advice, particularly when terrain and obstacles are present
- Uncertainties in health risk models, i.e. toxicological effects

This review and the knowledge gaps exercises have identified several gaps in existing experimental datasets involving dense gases, including:

- Wind tunnel and full scale dense gas dispersion over topography
- Full scale dense gas dispersion in the industrial/urban environment
- Source uncertainties in measurement and in characterising real-life incidents
- Infiltration and ingress of toxic industrial chemicals (TICs) into structures
- Indoor to outdoor dense gas dispersion
- Dry deposition
- Vertically upwards orientated releases from height
- Congestion (e.g. hedgerows, complex pipework)

Experimental trials in ideal conditions and in a range of atmospheric conditions, including transition from dense to passive dispersion behaviour, would also be useful and, in addition, experimental trials involving changing meteorological conditions, including humidity.

The report concludes with brief summaries addressing questions arising during the course of the review. For example: When is the density difference important? What is the effect of the urban environment? What are the requirements for dispersion models in industrial regulation? Finally, the review discusses current issues in dense gas dispersion modelling for civil emergency response in the UK.

Through the course of this review, the author's discussions with experts at PHE, the Met Office and Dstl have indicated that there appears to be room for improvement in the communication between experts in the UK involved in industrial regulation, emergency preparedness and emergency response on the subject of dispersion of hazardous chemical releases. In the UK, there are a diverse range of organisations involved, including site operators, the Fire and Rescue Service, Local Resilience Forums, PHE, HSE, the devolved environment agencies of England, Scotland and Wales, the Met Office, Defra, Dstl, BEIS, Cabinet Office and CPNI. Relevant parties currently share information via the Resilience Direct website on a need-to-know basis. However, there does not appear to be a forum that brings together all of the relevant parties to discuss recent experience from chemical incidents, to identify knowledge gaps, and to learn about new scientific and technological developments. An annual forum to bring together these organisations and to achieve some harmony/consistency in approaches would be useful. In addition to helping to coordinate UK activities and establish closer links between experts across different organisations, such a forum could also look outward to specialists overseas, to learn how other countries coordinate their activities, to assess the strengths and weaknesses of different approaches and share good practice.

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1 INTRODUCTION

1.1 What is a dense gas?

Atmospheric dispersion of gases can be classified into three categories, each with typical characteristics as follows:

- **Positively buoyant:** the density of the gas cloud is lower than the ambient density and gravitational affects cause the cloud to rise upwards. Positively buoyant releases are sometimes simply referred to as buoyant or lighter than air.
- **Negatively buoyant:** the density of the gas cloud is higher than the ambient density and gravitational effects cause the cloud to sink towards the ground. Initially, the atmospheric turbulence and the mean wind conditions have little effect on cloud dispersion. Negatively buoyant gas clouds are frequently referred to as dense gas clouds or heavier-than-air-gas (HTAG) clouds.
- **Neutrally buoyant:** the dispersion of the gas cloud is dominated by the ambient atmospheric turbulence and the mean wind conditions. For this reason neutrally buoyant releases are often referred to as passive releases. Ultimately, all gas dispersion tends towards neutral buoyancy because as gas clouds are diluted with distance downwind, their density approaches that of the surrounding ambient air.

These are simplistic descriptions of complex physics, particularly in the case of dense gas releases. The characteristics and physics of dense gas clouds are discussed in greater depth in what follows.

Note that the term “dense gas” is used generically here to describe any cloud or plume of substance(s) that has negative buoyancy due to a density difference with the ambient environment, it does not strictly imply gas phase only. Releases of some substances, such as pressure-liquefied ammonia, can behave as a dense gas due to the presence of aerosol droplets in the cloud.

1.2 Background

In 1984 at an industrial site in Bhopal, India, a release valve lifted on a storage tank containing methyl isocyanate and released a cloud of gas which drifted onto nearby housing. 2000 people died, tens of thousands were injured and more than half a million were exposed. Emergency services were overwhelmed, unaware of the gas involved or its effects.

In 1987 at a refinery in Texas City, US a crane dropped its load onto an anhydrous hydrogen fluoride tank, shearing the lines and releasing a large cloud of hydrofluoric acid. Approximately 4000 people were evacuated from residential areas nearby and three area hospitals treated 1037 patients, of which nearly 100 were hospitalised. There was extensive damage to trees and vegetation in the residential area.

In 2011 in the Russian city of Chelyabinsk a dense cloud of bromine wafted out of a switching yard and into a residential district. 10 to 13 gallons of the highly reactive chemical were spilled when they were being transported in glass containers aboard a freight car. The Urals transport authority said there had been a "breach of the regulations on handling, transporting and storing chemical substances¹".

One feature that all of the above incidents have in common is that the released substance formed a negatively buoyant gas cloud at some point in its evolution. Dense gas clouds characteristically hug the ground as they spread. As a consequence, they are particularly

¹ <https://www.bbc.co.uk/news/world-europe-14755874> Accessed 4th March 2020

hazardous to humans and the environment due to both toxicity and flammability via increased likelihood of finding an ignition source in the inhabited environment.

All of the incidents mentioned above also serve to demonstrate the need for regulation of industrial substances that can result in a dense gas hazard and the consequent importance of emergency preparedness and response for dealing with hazardous releases should they occur.

1.3 Industrial regulation and emergency preparedness and response

Industrial regulation is designed to identify and regulate hazards in industry, by assessing the risks and putting systems in place to ensure the safety of industrial personnel, the nearby population and the environment. For example, this might include limits on quantities of a substance stored at a site because the hazard could extend to the nearest town should the storage vessel fail catastrophically. In such scenarios models are used to predict the hazard distances.

By identifying the risks in advance they can be avoided and/or mitigated and plans can be put in place so that both industrial staff and the general population are prepared for emergencies.

Emergency preparedness and response has broader scope than industrial regulation. The emergency preparedness of the population and the environment will comprise emergency planning information compiled from many sources (e.g. several industrial sites around a town) along with scenarios such as accidental/intentional releases, for example, from terrorist attacks. The framework for response must be broad enough to function during any emergency.

In terms of the output from the modelling involved, the predictions required for emergency response are often fairly similar to those required for regulatory purposes, such as hazard distances. One distinction between predictions for industrial regulation, compared with predictions for emergency response, is the timeframes for the modelling. For industrial regulation purposes, including emergency planning, the time frames for obtaining predictions of a release can be relatively long. During an emergency event, emergency responders may require a prediction immediately. This results in different modelling requirements.

1.4 This review

This study comprises a high level review of the dispersion of dense gases. The aim of this document is to provide a comprehensive summary of all aspects of dense gas dispersion knowledge relevant to industrial regulation and emergency preparedness and response.

The objective of this review is to define typical and plausible dense gas release scenarios supported by information required to interpret them. This body of information includes summaries of the physics of dense gas dispersion and past and potential future incidents involving dense gas releases alongside summaries of modelling approaches, experimental tests and mitigation measures.

In conjunction with these objectives, this review seeks to highlight good practices and current gaps in knowledge or data. It is hoped that this will provide an aid for present regulation and emergency planning and also for future trends and emerging technologies.

Finally, this review is intended to encourage consistency across UK Government regulators and emergency responders in their approaches for modelling dense gas dispersion.

1.5 Report structure

This report comprises the following chapters:

Chapter 1 – Introduction**Chapter 2 – Industrial regulation and emergency preparedness and response**

An overview is provided of the past and current framework in the UK for industrial regulation and emergency preparedness and response. This includes reference to governing bodies, competent authorities and their responsibilities in terms of specific regulations or their role in emergency planning.

A brief review of regulatory frameworks in other countries is also included and a high level summary of cross-boundary and worldwide collaboration is provided.

Chapter 3 – Physics of dense gas dispersion

The differences between dense gas and neutrally/positively buoyant gas dispersion are explained including the criteria for when gas releases need to be treated as dense. The evolution of a typical dense gas release is summarised followed by factors that affect this, such as source conditions, meteorology, heat transfer, phase change, humidity, surface roughness, obstacles and topography. The physics of infiltration in the context of dense gases is included.

Relevant flammable or toxic end points (e.g. lower flammability limits, SLOT/SLOD, ERPGs and AEGLs) and exposure durations are discussed.

Chapter 4 – Dense gas dispersion incidents

Incident databases are identified along with some previous reviews of collections of incidents. Selected incidents from the UK and elsewhere around the world involving dense-gas dispersion are summarised. A few semi-confined incidents are also included. The chapter is concluded with a brief analysis summarising the collection of incidents.

Chapter 5 – Modelling dense gas dispersion

This chapter provides a high level summary of models and modelling approaches. The different classes of dense-gas dispersion models are discussed including CFD models, shallow-layer models, integral models and empirical correlations. The review builds on HSE's previous review of dense gas dispersion models in the work of Ivings et al. (2016). The appropriateness of each class of model for different applications is discussed, highlighting strengths and weaknesses and any areas where certain models are not appropriate. Reference is made to models used by regulators and emergency responders, and to existing good practice guidance on model usage.

Specific models of interest have been reviewed briefly, including HPAC, SCIPUFF, SWIFT, QUIC, ALOHA, GASTAR, SLAB, DRIFT, PHAST, TNO-EFFECTS, Shell-FRED, DEGADIS, ADAM, FLACS, CFX/Fluent and FDS. The applicability of models for predicting ingress of dense gases into buildings and structures is discussed.

Chapter 6 – Dense gas dispersion experiments

Experimental datasets are reviewed including field-scale and wind-tunnel tests that are relevant for both outdoor dispersion and infiltration/ingress of dense gas. Also included are summaries of model validation databases and previous reviews of collections of relevant experiments. The chapter concludes with a brief analysis summarising the collection of incidents and discussion of knowledge gaps.

Chapter 7 – Measures for mitigating dense gas releases

Mitigation measures for dense gas releases are summarised including:

- Measures that affect the vapour source, e.g. high expansion foam, thermally insulating concrete, and impounding basins for evaporating liquid spills

- Measures that directly mitigate the dispersion of gas, e.g. vapour fences and water sprays for forced air mixing
- Measures that mitigate exposure, e.g. guidance on sheltering (including ventilation behaviour and choice of shelter room) and use of personal protective equipment

Both on-site and off-site factors have been taken into account and existing best practice guidance or recommendations have been discussed.

Chapter 8 – Dense gas dispersion scenarios

A list of example dense gas release scenarios is compiled. This list covers a range of scenarios chosen to illustrate key aspects of dense gas dispersion that are relevant to risk assessment, emergency response and previous incidents. The list considers previous UK and world events and potential future trends based on emerging technologies, such as the growth of Liquefied Natural Gas (LNG) and carbon capture and sequestration.

Chapter 9 - Discussion

This penultimate chapter discusses potential knowledge or data gaps and identifies potential future work needed in the field of dense gas dispersion.

Chapter 10 – Conclusions

2 INDUSTRIAL REGULATION AND EMERGENCY PREPAREDNESS AND RESPONSE

2.1 Introduction

Analysis of incident data showed that better enforcement of safety legislation led to a general decrease in the number of major industrial accidents since 1997 (Mihailidou et al., 2012). The importance of effective regulation and emergency planning is demonstrated through comparison of developed and developing countries. Developed countries typically have a higher number of industrial accidents, due to high industrial load (but also because accidents are more consistently reported). However, the number of deaths and injuries is considerably less (Mihailidou et al., 2012), which can be attributed to effective enforcement of safety legislation and effective emergency planning and response.

Industrial regulation is designed to identify and regulate hazards in industry, by assessing the risks and putting systems in place to ensure the safety of the nearby population and the environment. Industrial regulation includes putting in place plans for emergencies associated with the hazards of a specific industry.

Emergency preparedness typically involves carrying out risk assessments, business continuity management and emergency planning. The aim of emergency planning is to prevent emergencies occurring and reduce, control or mitigate the effects of the emergency should it occur. It should be a systematic and ongoing process that evolves as lessons are identified and addressed and circumstances change. Emergency response involves the response functions and management when an emergency occurs.

The concepts of emergency preparedness and response have broader scope than industrial regulation. The emergency preparedness of the population and the environment will comprise emergency planning information compiled from multiple known sources linked to scenarios such as accidental/intentional releases during terrorist attacks. The framework for response must be broad enough to function during any emergency eventuality.

Most scenarios involving the dispersion of dense gases arise from loss of containment during industrial incidents at static sites, along pipelines or from transportation.

2.2 Frameworks for industrial regulation in the UK

2.2.1 Static sites

The Seveso Directives are the main EU legislation dealing specifically with the control of on-shore major accident hazards involving dangerous substances². The Seveso III Directive is the latest version and came into force on 1 June 2015, replacing the Seveso II Directive. The Seveso Directive includes requirements for regulations controlling major accident hazards from industrial sites and for land-use planning.

In the UK, these involve duties for site operators, the competent authority, and the local authority, which includes the emergency services. In Great Britain, the competent authority for administering to these tasks comprises jointly HSE and the relevant environment agency: the Environment Agency (EA) in England, Scottish Environment Protection Agency (SEPA) in Scotland and Natural Resources Body for Wales (NRW) in Wales. For nuclear establishments this partnership also includes the Office for Nuclear Regulation (ONR).

² <https://ec.europa.eu/environment/seveso/legislation.htm> Accessed 4th March 2020

HSE's specific roles are to establish the terms of the hazardous substances consent for a site and to provide advice on land-use planning to planning authorities and property developers.

Control of major accident hazards (COMAH³)

The COMAH regulations are in place to implement the majority of the Seveso III Directive in Great Britain. The aim of COMAH is to prevent or mitigate the impact of major accidents from industrial processes that could harm people and/or the environment. Site operators must take all measures necessary to prevent major accidents and to limit their consequences for people and the environment. This is achieved through appropriate plant design, process control, mitigation measures and emergency procedures.

There are two types (tiers) of establishment which are subject to COMAH, known as 'Upper Tier' and 'Lower Tier' depending on the quantity of dangerous substances they hold. Most dangerous substances are categorised by the hazard they pose, e.g. health, physical etc. For each category there is a qualifying quantity for storage of the substance under lower tier requirements and upper tier requirements. Upper Tier establishments have additional requirements placed on them by the Regulations and are required to prepare a Safety Report that demonstrates their understanding of the hazards and the potential consequences of a major accident.

The COMAH reports should contain information on the layout of the site and information about the substances and quantities for both health and safety and environmental purposes. It should include a representative set of major accidents taking into account the probability of occurrence and the magnitude of the consequences, including maps showing surrounding land-use and features within an area that could be affected by major accidents, e.g. hospitals, airports etc. Information should be provided to show that a systematic and comprehensive assessment of the mitigation, rescue and recovery arrangements has been put into place to cope with major accidents. COMAH requires that up to date information is provided to the public and for use by local authorities to feed into emergency response plans for local populations. The site operator must provide appropriate information to people within the public information zone, which is the area where people are liable to be affected by a major accident.

Central to British health and safety regulation is the concept of risks being controlled at a level that is as low as reasonably practicable (ALARP). This concept involves weighing up the risk against the trouble, time and money needed to control it. ALARP allows regulators to set goals for duty holders, rather than being prescriptive. This is a flexible approach that allows duty holders to choose the method that is best for them, which supports original thinking and innovation. It can also be a challenging approach requiring duty holders and the regulator to exercise judgement on whether a risk is ALARP.

Static sites handling dangerous substances but below the limits for the COMAH regulations to apply would still be subject to The Management of Health and Safety at Work Regulations 1999 (the Management Regulations) and various health and safety regulations such as Control of Substances Hazardous to Health (COSHH), Hazardous Area Classification and Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR).

Further information can be found on the HSE website and in the COMAH guidance documentation (HSE, 2015a), which is also available from the HSE website.

³ <http://www.hse.gov.uk/comah/> Accessed on 4th March 2020

Land-Use Planning (LUP)

The aim of LUP legislation is to manage population growth around major hazard sites and help mitigate the consequences of major accidents. In Great Britain, the department for communities and local government (DCLG) and devolved administrations in Scotland and Wales are responsible for this.

Hazardous substance consent must be obtained for sites wanting to hold quantities of hazardous substances at or above limits defined in the hazardous substances planning regulations⁴. HSE is a statutory consultee for these consents and for planning applications around major hazard sites and pipelines.

HSE sets consultation distances around the major hazard site or major accident hazard pipeline, within which a planning authority must consult HSE over relevant developments which are likely to lead to an increased population around the major hazard.

HSE will advise on safety grounds whether or not planning permission should be granted. Account is taken of the size and nature of the proposed development, the inherent vulnerability of the exposed population and the ease of evacuation or other emergency procedures for the type of development proposed. Some categories of development (e.g. schools and hospitals) are regarded as more sensitive than others (e.g. light industrial), and advice is weighed accordingly.



Figure 1 Example of a 3-zone map. Pink lines indicate the facility, red line represents the Inner Zone (IZ), green line represents the Middle Zone (MZ) and blue line represents the Outer Zone (OZ). Image for illustration purposes only.

The consultation distances on which land use planning advice relies are in the form of three-zone maps defined by HSE, for example see Figure 1. The zones are based on the hazard that produces the largest zones at a site when simulated by a set of standard release scenarios. HSE simulates scenarios chosen based on maximum inventory of hazardous substances that an operator is permitted to have onsite by virtue of their hazardous substances consent. Three-zone maps typically remain the same for the duration of the operations on the major hazards site, which can be 20-30 years.

⁴ The Planning (Hazardous Substances) Regulations 2015 <https://www.legislation.gov.uk/uksi/2015/627/schedule/1/made>
Accessed on 4th March 2020

For developments around nuclear sites, ONR provides advice to local planning authorities on any planning applications⁵. The Radiation (Emergency Preparedness and Public Information) Regulations 2019 (REPPiR19) are part of the Government's implementation of the emergency planning requirements of the Basic Safety Standards Directive 2013 made under the Euratom Treaty. REPPiR states that the local authority must put in place off-site emergency planning arrangements to minimise and mitigate the health consequences of any significant radiological release from a nuclear site. ONR is responsible for setting Detailed Emergency Planning Zones (DEPZ) for sites where there could be an off-site radiological release. Local authorities are required to prepare plans for responding to an off-site nuclear emergency, within the DEPZ area. ONR formally assesses the adequacy of arrangements through emergency exercises.

Further information can be found on the HSE website⁶ and ONR website⁷.

2.2.2 Pipelines

In the UK, high-pressure pipelines are used to transport gas and liquid products over long distances. The pipelines traverse through third-party land and are generally located in remote areas and are operated remotely.

The safe carriage of substances via pipelines is regulated in the UK under the Pipeline Safety Regulations 1996 (PSR⁸). PSR applies to pipelines in Great Britain, in territorial waters and the UK Continental Shelf.

PSR does not apply to pipelines such as sewers, drains and most pipelines carrying air or water. They apply to pipelines carrying other fluids and to major accident hazard pipelines (MAHPs) carrying 'dangerous fluids'. These include the high pressure natural gas supply and distribution network, systems transporting oils, chemicals and other gases such as ammonia and ethylene. PSR requires the design, construction, operation and maintenance of any major hazard asset to be in accordance with recognised codes and standards. MAHP operators have special requirements, which include a notifications regime, a major accident prevention document and arrangements for emergency plans.

The construction and agricultural industries are notable causes of pipeline failures. Pipeline operators are required to provide appropriate safety information to those undertaking any form of excavation near their assets. In addition, MAHP operators are required to undertake regular surveillance of their pipelines to assess for any unauthorised excavations.

Further information can be found on the HSE website⁹ and the United Kingdom Onshore Pipeline Operators' Association website¹⁰.

Environmental issues associated with pipelines are covered by the national environment agencies.

2.2.3 Transport

The regulatory framework for the transport of hazardous substances is a combination of regulations specific to Great Britain and those required by the EU. There are different sets of regulations for road, rail, sea and air. In Great Britain, the Department for Transport (DfT) is the competent authority for all transport-related activity except for nuclear and Class 1 explosives, for which the competent authorities are ONR and HSE, respectively. The enforcement of the regulations is shared with regulatory bodies.

⁵ <http://www.onr.org.uk/land-use-planning.htm> Accessed 4th March 2020

⁶ <https://www.hse.gov.uk/landuseplanning/index.htm> Accessed 4th March 2020

⁷ <http://www.onr.org.uk/reppir-2019-update.htm> Accessed 24th April 2020

⁸ https://www.hse.gov.uk/foi/internalops/hid_circs/enforcement/spcenf156.htm Accessed on 4th March 2020

⁹ <https://www.hse.gov.uk/pipelines/index.htm> Accessed 4th March 2020

¹⁰ <https://www.ukopa.co.uk/pipeline-safety/> Accessed 4th March 2020

HSE is one of the enforcement authorities for regulating the carriage of dangerous goods by road, along with the police, the Driver and Vehicle Standards Agency (DVSA) and the DfT. HSE also enforces the regulations relating to dangerous substances in harbour areas (HSE, 2016) but the regulations relating to transport of dangerous goods and marine pollutants are enforced by the Maritime and Coastguard Agency. The Office for Rail and Road are responsible for enforcement of transport of dangerous goods by rail. Enforcement for the transport of goods by air is undertaken by the Civil Aviation Authority (CAA).

For road transport of non-radioactive material, there are several requirements that must be met that contribute significantly to the safety of the public. These include requirements on the integrity of goods packages, tanks, containers etc. and securing the load appropriately; correct documentation held by the relevant people e.g. the delivery driver, haulage company, site etc.; appropriate equipment including fire extinguishers and PPE; driver training; vehicle placarding and orange plate marking; and package marking and labelling. The operational strategy for enforcing these requirements is founded on an inspection regime undertaken by the police, DVSA and HSE and strategic communication designed to influence companies and stakeholders. The regime comprises vehicle checks at the roadside and inspection of compliance with the carriage of dangerous goods regulations during visits to duty holder's premises, which includes checking management systems and vehicles.

Regulations governing the transport of radioactive material in Great Britain are based on standards developed by the International Atomic Energy Agency (IAEA). The IAEA regulations (IAEA, 2018) are prescriptive and apply internationally to enable the safe transport of packages across international borders. ONR enforces the legislation dealing with carriage of radioactive materials. In a similar manner to the transport of non-radioactive goods, regulation is carried out through a programme of targeted, risk-informed inspections and engagement with duty holders which may lead to interventions. Inspections examine the management systems utilised by duty holders, as well as compliance with safety and security legal requirements. In addition, the design of packages used to carry high-hazard radioactive materials requires approval to ensure they meet exacting international safety standards, and the packages are built to robust quality assurance plans, and are correctly used and maintained.

2.2.4 Modelling for industrial regulation

Models are used within COMAH Safety Reports for assessing the magnitudes of consequences of hazardous releases on the site. The choice of model and the modelling undertaken is at the discretion of the duty holder and presented to HSE for assessment as part of the report.

In LUP, simulations to determine the three-zone maps are undertaken by HSE and follow a set policy, which includes specific models. For scenarios requiring dispersion modelling, including dense gases, HSE uses the DRIFT dispersion model. The set of simulations is based on foreseeable and credible release scenarios and might include catastrophic releases and releases from a range of hole sizes, based on a failure frequency model, depending on vessel type. Four weather categories are simulated (D2.4, D4.3, D6.7 and F2.4) and wind directions are assigned probabilities from Met Office weather data relevant to the major hazards site. Obstructions, such as buildings, are modelled as surface roughness. For a medium-sized chemicals facility, the process involves around 700 consequence modelling simulations.

As mentioned previously, three-zone maps typically remain the same for the duration of the operations on the major hazards site, which can be 20-30 years. Therefore, the modelling is designed to stand the test of time. For this reason very specific conditions are not used. Instead, appropriate assumptions are made in order to provide a cautious estimate. It is a

balance between being too cautious, and restricting growth of the surrounding population, and not being cautious enough, and potentially causing mass casualties.

Note that CFD models do not form part of the LUP approach. There are unresolved problems with CFD modelling that need to be addressed before HSE can have confidence in its use for LUP assessments (Gant and Tucker, 2018).

2.3 Frameworks for emergency preparedness and response in the UK

2.3.1 Emergency response structure

The Government provides guidance for emergency preparedness and response in the UK, which falls under the Civil Contingencies Act (CCA¹¹). Detailed information is provided on the Government website¹², a brief summary of which can be found in Cabinet Office (2010a). The responsibility for emergency preparedness and response in the UK is founded at the local level and is split up based on police areas¹³. Under the CCA, each area has to have a Local Resilience Forum made up of the relevant parties required in an emergency. Note that local arrangements in England can differ from devolved administrations in Scotland, Wales and Northern Ireland.

The CCA divides emergency responders into two categories, imposing a different set of duties on each.

- Category 1 responders are organisations at the core of response to most emergencies, i.e. the emergency services, local authorities etc. They are required to assess the risk of emergencies occurring and use this to inform contingency planning, put in place emergency plans, business continuity management arrangements and arrangements to make information available to the public. They are also required to share information and cooperate with other local responders to facilitate coordination and efficiency.
- Category 2 responders are cooperating bodies. These are organisations such as HSE, the Highways Agency and public utility companies. They play a lesser role in the principle emergency planning work but are heavily involved in incidents that affect their own sector. Their primary duties are cooperating and sharing information with other Category 1 and 2 responders.

Most incidents are handled by Category 1 and 2 responders, frequently coordinated by the police or the fire brigade. Under the Military Aid to the Civil Authority (MACA) arrangements, the armed forces can provide personnel or equipment to assist in managing the response to and recovery from emergencies. Incidents can also be escalated to Central Government if required. In such cases, there are pre-determined Lead Government Departments¹⁴ depending on the emergency.

The CCA is split into generic and sector-specific legislation. Generic legislation relates to the fundamental response to any emergency and is operated by Category 1 responders, with the support of Category 2 responders as required. Sector-specific legislation is operated by HSE and relates to preparedness and response to major accident hazards at industrial establishments (COMAH), hazardous pipelines (Pipeline Safety Regulations) and radiation hazards (REPIR).

¹¹ <http://www.legislation.gov.uk/ukpga/2004/36/contents> Accessed on 24th April 2020

¹² <https://www.gov.uk/government/emergency-preparation-reponse-and-recovery> Accessed on 24th April 2020

¹³ <https://www.police.uk/forces/> Accessed 4th March 2020

¹⁴ <https://www.gov.uk/government/publications/list-of-lead-government-departments-responsibilities-for-planning-response-and-recovery-from-emergencies> Accessed 4th March 2020

There is a nationally agreed framework for managing local multi-agency response to and recovery from emergencies. The framework is generic and designed to be flexible to apply to a wide range of emergencies. A brief overview is given below but much more detail can be found on the Government website¹⁵ or the guidance document (Cabinet Office, 2013).

The framework distinguishes between single-agency and multi-agency management in emergency response and recovery. The management of the emergency response and recovery effort is categorised into one or more of three ascending tiers: Operational (bronze), Tactical (silver) and Strategic (gold). It is based on the concepts of command, control and coordination.

Multi agency groups are convened to coordinate the involved agencies activities. Different levels of emergency relate to the region affected and the impact, as shown in Figure 2 and described in Cabinet Office (2010b). Local level emergencies are coordinated by a Strategic Coordinating Group (SCG). As the size and magnitude of the emergency increases, this might involve a regional Government Office (GO) and/or a relevant Lead Government Department (LGD). In a Level 1 emergency, the LGD will lead the response. In the event of a level 2 or 3 emergency, the central response framework would be initiated and would involve the activation of Central Government's crisis management facilities in the form of the Cabinet Office Briefing Rooms (COBR). COBR is a forum of Ministers and senior officials from relevant departments and agencies, brought together to make decisions on an emergency response.

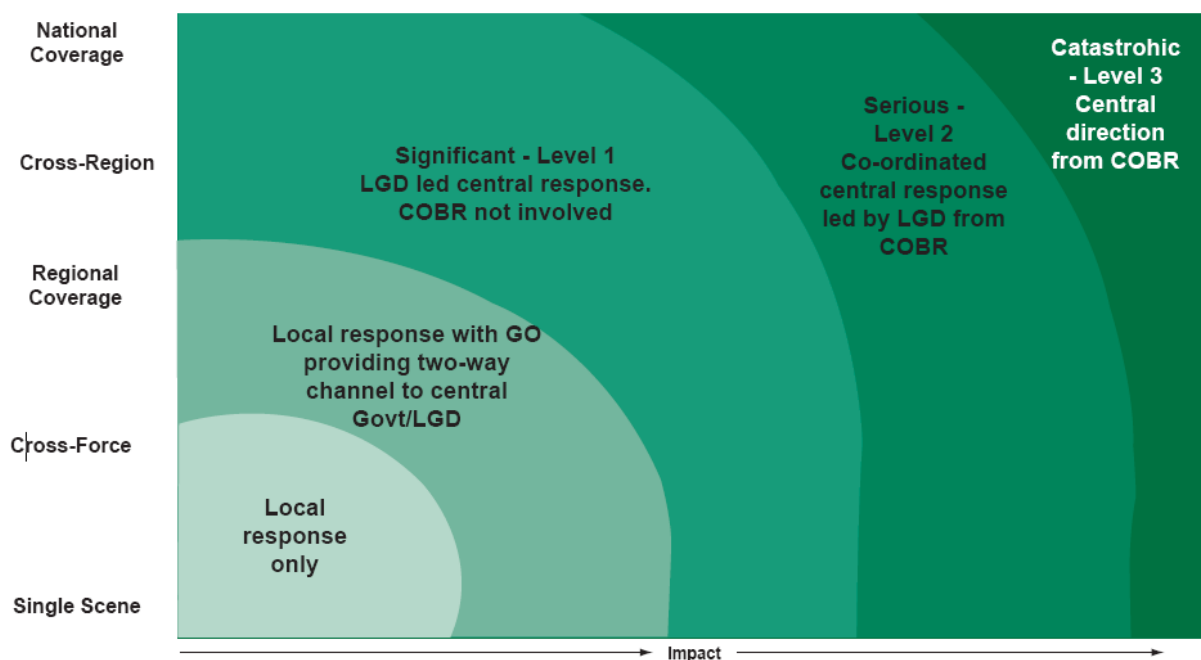


Figure 2 Level of response and coordinating group as a function of scale of emergency and impact. Figure from UK parliament website¹⁶, original from Cabinet Office (2010b).

Some emergencies require access to specialist scientific and technical advice and local responders are advised to establish a Science and Technical Advice Cell (STAC) to provide on-hand advice on relevant scientific and technical issues. Guidance on setting up STACs can be found on the UK Government website¹⁷. STAC members might include site operator technical advisers, EA, HSE, Met Office, DEFRA among other agencies as required. On a

¹⁵ <https://www.gov.uk/guidance/emergency-response-and-recovery> Accessed 4th March 2020

¹⁶ <https://publications.parliament.uk/pa/cm201011/cmselect/cmsctech/498/49806.htm#a9> Accessed on 24th April 2020

¹⁷ <https://www.gov.uk/government/publications/provision-of-scientific-and-technical-advice-in-the-strategic-co-ordination-centre-guidance-to-local-responders> Accessed on 24th April 2020

national level, the scientific and technical advice cell is the Scientific Advisory Group for Emergencies (SAGE).

A significant amount of information on emergency response can be found in the fire and rescue service's National Operational Guidance (NOG), which is managed by the National Fire Chief Council's Central Programme Office (NFCC's CPO). The NOG includes a list of parties¹⁸ that could feasibly be involved in a hazardous materials incident under the provision of specialist advice.

2.3.2 Emergency planning process

An illustration of the general process for emergency planning can be seen in Figure 3, which is reproduced from UK Government emergency preparedness documentation (Cabinet Office, 2011) and can be applied to all areas and sectors. The consultation cycle involves collecting together all of the relevant information and deciding what to do with it and the embedding cycle involves disseminating the information and ensuring that it is effective.

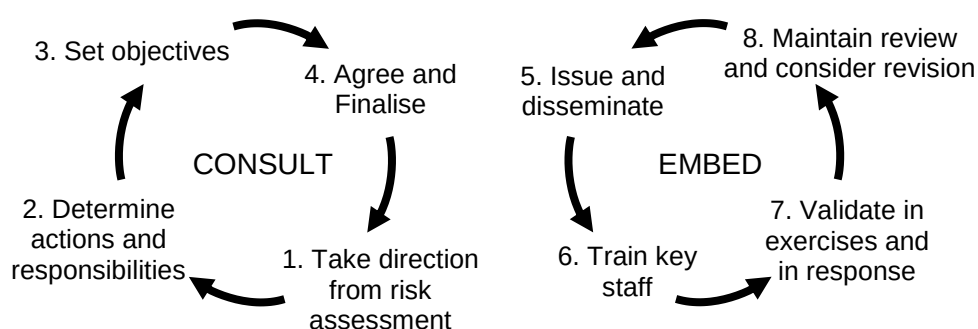


Figure 3 The emergency planning cycle

Emergency planning guidance tailored to the needs of COMAH sites can be found in HSE (1999a). The guidance is aimed at assisting those with responsibilities for emergency planning on and off site. Further guidance can be found in ILO (1993), which is aimed at a wider range of parties involved in emergency planning and response. The concepts in both of these documents are similar to those shown in Figure 3.

One of the key parts of the emergency planning process is exercises. These comprise simulations of events to test the emergency response system. They provide validation of the emergency plan and assist in training of key staff in non-daily activities. Exercises are typically discussion-based, table-top, or live, or a combination of these. General information on planning exercises can be found in the publication from the Cabinet Office (1998).

The difficulty with exercises is the time and resource required to undertake them alongside normal operations.

2.3.3 Modelling for emergency preparedness and response

Predictions from models are used in the consultation cycle as part of risk assessments (1 in Figure 3), for example from COMAH, LUP assessments and REPPiR, as described in as described in Section 2.2. In the embedding cycle, predictions from models are used as part of simulated incident emergency conditions during validation exercises (7 in Figure 3).

During emergency response to a gas release, if it is a release from an industrial site, initially the emergency procedures of the site will be actioned. For a few sites, this may include modelling to predict dispersion. For a gas release that spreads off-site, or for a release that itself takes place off-site (e.g. from a road tanker), the Met Office is frequently one of the first

¹⁸ <https://www.ukfrs.com/guidance/search/specialist-advice-hazardous-materials> Accessed on 4th March 2020

points of contact for the police or fire brigade. The Met Office aims to provide a response within 20 minutes in the form of a CHEMET using the model NAME. The format of a CHEMET is a map showing the approximate release point, direction of dispersion and relative concentration zones. This is accompanied by text of the forecast (typically for the next 8 hours). The response personnel use this information, for example, to apply cordons around restricted areas and to position emergency vehicles and support centres.

If the incident is prolonged and a Science and Technical Advice Cell or Air Quality Cell is set up, then the Met Office and other participants in the cell with modelling capability *may* undertake further modelling to refine the initial estimates. If the atmospheric dispersion modelling requirement is associated with a counter-terrorism emergency, the modelling is undertaken by Dstl using the model HPAC. For radiological and nuclear emergencies, radiative dose modelling is undertaken by PHE to provide potential input for public health advice. Atmospheric dispersion modelling is undertaken with NAME. There are no dense-gas dispersion models in operational use in the UK for real-time modelling during response to a civil emergency.

Recently, the Joint Agency Modelling (JAM) program has been set up to assist in coordinating multi-agency response and to provide assessments to UK Government on the potential impacts and protective actions following a radiological release anywhere in the world. The objective is for JAM to create a single, consolidated viewpoint of the possible and probable scenarios from a nuclear incident. Relevant partners provide the source term, atmospheric dispersion modelling and dose modelling and calculate subsequent health impacts, food impacts and surface water impacts. A dissemination product provides plume maps, high level explanatory text and potential zones for protective actions. JAM provides advice to the UK government, via SAGE, to aid strategic decision-making during an emergency. Further information can be found in the paper by Millington et al. (2019).

The uncertainty is very high in emergency response modelling, primarily because the source is often poorly defined. In the first instance, it can be useful to simply know the direction that the plume will disperse and it is common practice to assume a source of 1 g/s. This provides information on the area at risk from the hazard and if measurement data becomes available from monitors then it can be scaled to provide a more accurate prediction of concentration.

2.4 International frameworks for industrial regulation and emergency preparedness and response

2.4.1 Europe

Regulation

The Seveso Directives¹⁹ are the main EU legislation dealing specifically with the control of on-shore major accident hazards involving dangerous substances, mainly in the chemical and petrochemical industries but also in bulk storage of fuels such as Liquefied Petroleum Gas (LPG) and LNG. There are more than 12,000 industrial establishments in the European Union to which the Directive applies, where dangerous substances are used or stored in large quantities. The Directive requires EC Member States to 'ensure that the objectives of preventing major accidents and limiting the consequences of such accidents were taken into account in their land-use policies and/or other relevant policies'. Towards this end, the framework underlying the Directive is a cycle of prevention, preparation, response and lesson learning, similar concepts to those outlined in Figure 3.

There are requirements on both the operators and the authorities. Operators are required to

- Notify of all concerned establishments

¹⁹ <https://ec.europa.eu/environment/seveso/legislation.htm> Accessed 4th March 2020

- Deploy a major accident prevention policy
- Provide information in case of accidents

With Upper-tier establishments also required to

- Produce a safety report
- Produce internal emergency plans

The authorities are required to

- Produce external emergency plans
- Deploy land-use planning for siting of establishments
- Make relevant information publically available
- Ensure action is taken after an accident, including emergency measures, actions to ensure that the operator takes any necessary remedial measures and informing affected persons
- Report accidents to the European Commission
- Prohibit the unlawful use or operation of establishments
- Conduct inspections

International transport of dangerous goods is not covered by the Seveso Directive. It is governed by standards recommended by the UN Committee of Experts on the Transport of dangerous Goods in the 'Orange Book' (UNECE, 2019). The recommendations are the basis for a series of codes defining the classification, packaging and labelling of dangerous goods for transport by road, rail, sea and air. These codes are the European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR), the Office of International Rail Transport's Regulations Concerning the International Carriage of Dangerous Goods by Rail (RID), the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN), the International Maritime Organization's International Maritime Dangerous Goods Code (IMDG) and the International Civil Aviation Organization's Technical Instructions for Safe Transport of Dangerous Goods by Air (TIS). Individual countries are responsible for implementing the codes by incorporating them into their own legislation.

In an effort to ensure a high level of protection to human health and the environment REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) is an EU regulation requiring manufacturers of hazardous chemicals to provide a comprehensive characterization of the hazards. They are required to communicate this safety information to a central database managed by the European Chemicals Agency (ECHA). REACH also provides guidelines for the decommissioning of chemicals and safer alternatives. Alongside REACH is the Classification, Labeling, and Packaging of Substances and Mixtures (CLP) regulation which is a standardised guideline for characterising and labelling chemicals. In the UK REACH and CLP are regulated by HSE and further information can be found on the HSE website²⁰.

Emergency preparedness and response

Similar to national emergency response, the European response to an incident is initially on a national level but is escalated when there may be trans-boundary impact.

The EU (and additional participating states) has an Emergency Response Coordination Centre (ERCC) that can coordinate provision of assistance to countries in response to disasters. A major disaster can constitute a variety of scenarios including a natural, technological and economical event. The centre operates 24/7 and can help any country

²⁰ <https://www.hse.gov.uk/reach/> and <https://www.hse.gov.uk/chemical-classification/legal/clp-regulation.htm> Accessed on 24th April 2020

inside or outside the EU affected by a major disaster upon request from the national authorities or a UN body. The Emergency Response Coordination Centre (ERCC) replaces and upgrades the functions of the previous Monitoring and Information Centre (MIC).

The International Atomic Energy Agency acts on behalf of its member states to provide guidance for emergency preparedness and response. There is an IAEA safety standards series of which Part 7 is aimed at preparedness and response for nuclear or radiological emergency (IAEA, 2015). The IAEA sets two zones around the relevant installations, a precautionary action zone (PAZ) and an urgent planning zone (UPZ). In the UK ONR administer these standards within REPIR.

2.4.2 US

Regulation

The US has a three-tiered system of federal, state and local government. The local governments are made up of counties, municipalities etc. and directly serve the requirements of the people in their locality. They provide for police and fire protection, health, education, public transport and housing etc. The federal and state governments make the legislation and regulations. A brief breakdown of US legislation and law relating to process safety can be found in Chapter 4 of Mannan (2012). It includes a summary of the regulatory agencies and their jurisdiction and relevant Acts, codes and standards. There are many agencies with the authority to create and enforce the regulations and there is often an overlap between the agencies, for example on regulation of accidental releases. There is also a series of codes and standards that act as regulations (codes) or are frequently incorporated into regulations (standards). These are administered by other bodies such as ASME, ANSI, NFPA and NIOSH.

US legislation covering accidental releases contains four main parts: emergency planning, emergency notification, community right to know and toxic chemical inventory. It is enforced by the EPA. OSHA also imposes a rule which requires a process safety management system to identify, evaluate and control hazards from highly hazardous chemicals.

Emergency preparedness and response

In the US, all incidents are initially dealt with locally by the local authorities in charge, such as police or fire. Many local municipalities have a dedicated office of emergency management with personnel and equipment to support the local government.

Under the Emergency Planning and Community Right-to-Know Act (EPCRA) the local governments are required to set up Local Emergency Planning Committees (LEPCs). In a similar role to the LRFs in the UK, the LEPCs have a responsibility to develop emergency response plans with a focus on hazards presented by the use and storage of hazardous and toxic chemicals. These plans follow the generic description in Figure 3.

If the emergency becomes too much for the local government then responsibility escalates to the state emergency management agency. The lead federal agency for emergency management is Federal Emergency Management Agency (FEMA), which is part of the Department for Homeland Security (DHS). If an event is deemed to be nationally significant, or terror related, the Secretary of Homeland Security can initiate the National Response Framework which allows all emergency agencies from local to federal to work together. There is a National Incident Management System to coordinate the response.

Under the EPCRA, the National Response Team (NRT), made up of 16 federal agencies, is responsible for publishing guidance documents for the preparation and implementation of hazardous substance emergency plans. The Hazardous Materials Emergency Planning

Guide (NRT-1, 2001²¹, "Orange Book") contains guidance on developing state and local emergency response plans.

In addition to the agencies and other official authorities, significant incident response is undertaken by volunteers both affiliated and unaffiliated to organisations. The Citizen Corps is one such organisation, administered locally and coordinated nationally by the DHS. There are also many spontaneous unaffiliated volunteers, often religious organisations and, in recognition of this, there are procedures in place within response agencies to manage and utilise this resource effectively.

Emergency Response Guidebook

In the US, and other continental American countries, emergency responders are issued with the Emergency Response Guidebook (ERG, 2020). The ERG was developed by Transport Canada, US DOT, Secretariat of Communications of Mexico with collaboration from the Centro de Informacion Quimica para Emergencias of Argentina. It is described as:

“a guide to aid first responders in quickly identifying the specific or generic hazards of the material(s) involved in the incident, and protecting themselves and the general public during the initial response phase of the incident.”

The guide provides a three-step look up system based on identifying the substance released, looking up a three digit number associated with the material and looking up the guidance associated with that number. There are various methods for identifying the substance or what to do if this is not possible. There are 62 guides covering a group of materials which possess similar chemical and toxicological characteristics. Each guide comprises two pages containing a brief summary of potential hazards, public safety information and emergency response guidance, and activities for different types of incident and first aid. Dispersion modelling is used to define isolation and protective action distances. The methodology is discussed further in Section 5.7.18. The guide also contains emergency response numbers for participating countries and their agencies.

The guide highlights that it is for first response purposes. Further information about a substance should be sought at the earliest possibility as information provided by appropriate emergency response agencies may be more specific and more accurate. The ERG is relevant for use at incidents occurring on roads, railways and for pipelines, and it may have limited value at static sites.

The ERG is contained in the Wireless Information System for Emergency Responders (WISER²²), which is supplied by the US National Institutes of Health (NIH) and is designed to assist emergency responders during hazardous material incidents.

2.4.3 Global

Regulation

The UNECE Convention on the Transboundary Effects of Industrial Accidents (TEIA²³) “aims to protect human beings and the environment against industrial accidents capable of causing transboundary effects and to promote active international cooperation between contracted parties before, during and after such accidents”²⁴. The Seveso III directive is the main legislative tool implementing the TEIA convention in EU law. The UNECE aims to engender pan-European economic integration but it is not restricted to EC countries, interested UN

²¹ <https://www.epa.gov/emergency-response/nrt-1-hazardous-materials-planning-guide> Accessed on 4th March 2020

²² <https://wiser.nlm.nih.gov/> Accessed 5th March 2020

²³ <https://www.unece.org/env/teia.html> Accessed on 4th March 2020

²⁴ <https://ec.europa.eu/environment/seveso/international.htm> Accessed on 4th March 2020

member states may participate. There are over 40 contracting parties, including the US and the EU.

In the transport sector, there are rules for a Globally Harmonized System of Classification and Labeling of Chemicals (GHS²⁵), which are recognized by the United Nations (UN). This is incorporated into the European CLP.

The majority of shipping of hazardous material by water is governed by the International Maritime Dangerous Goods Code (IMDG Code²⁶) which is produced and maintained by the UN's International Maritime Organization (IMO). The IMDG Code is intended to provide safe transportation of hazardous materials by vessels, to protect crew members, and to prevent marine pollution.

Emergency preparedness and response

The Sendai Framework²⁷ for Disaster Risk Reduction 2015-2030 is a global framework for emergency preparedness and response. It is coordinated by the UN Office for Disaster Risk Reduction and replaces the Hyogo Framework for Action 2005 -2015. The goal of the framework is "to prevent and reduce disaster risk through the implementation of integrated and inclusive economic, structural, legal, social, health, cultural, educational, environmental, technological, political, and institutional measures that prevent and reduce hazard exposure and to disaster, increase preparedness for response and recovery and thus strengthen resilience." The scope and purpose of the framework "will apply to the risk of small-scale and large-scale, frequent and infrequent, sudden and slow-onset disasters, caused by natural or manmade hazards as well as related environmental, technological and biological hazards and risks. It aims to guide the multi-hazard management of disaster risk in development at all levels as well as within and across all sectors."

The World Meteorological Organisation (WMO) has an emergency response function, which can provide worldwide specialised atmospheric transport and dispersion modelling to predict the spread of airborne hazardous substances should an environmental emergency occur. The WMO Information system supports the Global Data-Processing and Forecasting System (GDPFS²⁸) which is a framework for sharing regional and national data related to operational forecasting from meteorological centres. In particular this resource enables developing countries access to cutting edge numerical forecasting.

Global initiatives

The Organisation for Economic Cooperation and Development (OECD) assists countries in developing and implementing policies to make their systems for managing chemicals efficient and robust. The OECD has a dedicated chemical accidents programme working in cooperation with other international organisations to help public authorities, industry, labour and other interested parties within countries to prevent accidents and respond appropriately if one occurs. The scope of the programme is as follows:

- Develop common principles and policy guidance for chemical accident prevention, preparedness and response
- Analyse issues of concern and make best practice recommendations
- Disseminate information and experience

In line with this scope, the OECD Chemical Accidents Programme²⁹ has produced guidance and best practice publications, and it regularly organises workshops on specific issues to

²⁵ http://www.unece.org/trans/danger/publi/ghs/ghs_rev08/08files_e.html Accessed on 24th April 2020

²⁶ <http://www.imo.org/en/Publications/IMDGCode/Pages/Default.aspx> Accessed on 24th April 2020

²⁷ <https://www.preventionweb.net/sendai-framework/sendai-framework-for-drr> Accessed on 4th March 2020

²⁸ <https://public.wmo.int/en/programmes/global-data-processing-and-forecasting-system> Accessed on 4th March 2020

²⁹ <http://www.oecd.org/env/ehs/chemical-accidents/thechemicalaccidentsprogramme.htm> Accessed on 4th March 2020

gather information. The OECD website also provides various sources of information, including links to relevant authorities and resources for some countries³⁰ and other relevant global organisations.

The United Nations Environmental Programme (UNEP) is leading the international 'Flexible Framework Initiative for Addressing Chemical Accident Prevention and Preparedness' (CAPP) which focusses on industrial risk reduction and CAPP in fast growing economies and developing countries.

2.5 Summary

Industrial regulation is aimed at ensuring the safety and health of site personnel during normal operating conditions and during emergencies. It ensures the provision of information to the surrounding population for both land-use planning and emergency planning. In Great Britain, industrial regulation is mainly enforced by HSE, DfT, ONR and the devolved environment agencies, EA, SEPA and NRW.

The emergency planning process is a continual cycle of consultation and collection of information alongside consolidation and embedding of the knowledge in practice. It requires effective collaboration of multiple parties, from multiple disciplines, at various levels. Knowledge of roles and responsibilities, frameworks and structures with effective communication between groups is key to a positive outcome during emergency response.

The modelling requirements for industrial regulation and emergency preparedness are very different to those for emergency response. For industrial regulation there is more time and information available, whereas in emergency response time is very short and information is frequently very uncertain. The common requirement from modelling outputs in industrial regulation and in emergency preparedness and response is clear and appropriate communication of results between all of the parties involved in the process and, in particular, in disseminating appropriate information to the public.

³⁰ <http://www.oecd.org/env/ehs/chemical-accidents/chemical-emergency-preparedness-and-response-othersitesofinterest.htm>
Accessed on 24th April 2020

3 PHYSICS OF DENSE-GAS DISPERSION

3.1 Introduction

This chapter covers the characteristic features of a dense-gas release. The different causes of the density difference are discussed and criteria for when a gas release should be considered as a dense gas. The basic evolution of a dense gas cloud is summarised, followed by factors that affect both the evolution and dispersion of dense gas clouds.

Relevant flammable and toxic end points and exposure durations are discussed. Finally, a summary of sources of substance information is provided.

3.2 Dense gases

3.2.1 What causes the density difference?

In simple terms, a dense gas cloud forms when the density of the released substance is higher than the density of the ambient environment. The higher density can result from one or multiple causes, which can broadly be classified into molecular weight, release temperature, storage pressure, chemical reactions and aerosols and particulates in suspension.

It should be noted that nearly all gases are heavier than air. In fact there are so few that are lighter than air that the NOG provides the two mnemonics³¹ HA HA MICE and 4HMEDIC ANNA:

H	Helium	4H	Hydrogen, Helium, Hydrogen
A	Acetylene		Cyanide, Hydrogen Fluoride
H	Hydrogen	M	Methane
A	Ammonia	E	Ethane and ethylene
M	Methane	D	Diborane
I	Illuminating gases (e.g. neon)	I	Illuminating gases
C	Carbon monoxide	C	Carbon Monoxide
E	Ethane and ethylene	A	Acetylene
		N	Neon
		N	Nitrogen
		A	Ammonia

However, under certain conditions even these substances can be rendered heavier than air and display dense gas characteristics, as discussed below.

Molecular weight

The density difference can result from the released substance having a higher molecular weight than the environment it is released into. Some examples are listed in Table 1. For many of these substances, the density difference is further increased by the storage conditions, as discussed below.

³¹ <https://www.ukfrs.com/foundation-knowledge/foundation-hazardous-materials?bundle=section&id=21804&parent=19547> Accessed on 17th August 2020

Table 1 Examples of common substances that are dense gases by molecular weight at typical UK ambient temperature and pressures

Substance	Molecular weight (g/mol)
Air	28.96
Hydrogen Sulphide	34.10
Chlorine	35.45
Carbon Dioxide	44.01
Propane	44.10
Butane	58.12
Vinyl chloride	62.50
Sulphur Dioxide	64.07

Low temperature

Materials with any molecular weight but released at low temperatures, or cooled due to evaporation processes, can form dense gas clouds. Examples include LNG, chlorine, ammonia, hydrogen and hydrogen fluoride. LNG, which is predominantly made up of positively buoyant methane gas, is denser than air at its boiling point. Even as air is entrained into the dispersing cloud, it will not necessarily result in a positively buoyant lift off of the gas cloud, this is discussed further in Section 3.5.3. Hansen (2020) showed that cryogenic hydrogen releases produce dense gas behaviour, and his analysis indicated that hazard ranges could extend further for liquid hydrogen bunkering than for LNG.

Storage pressure

Releases from pressurised storage of gases or liquids of any molecular weight can cause dense gas clouds to form. Flashing of the liquid into vapour on release causes formation of a cloud that is a mixture of aerosols and vapour. Examples include chlorine, ammonia, hydrogen fluoride and LPG (frequently composed of mainly propane or butane). An example of a chlorine release from pressurised storage in the Jack Rabbit experimental trials can be seen in Figure 4.



Figure 4 Chlorine cloud dispersing 5 s (left) and 15 s (right) after release at Dugway Proving Ground during Jack Rabbit trials (Storwald et al., 2011, © UVU copyright)

For pressure-liquefied gases that have a molecular weight lighter than air, such as ammonia, the aerosols are the primary cause of the increased cloud density. Cooling on depressurisation causes ammonia to become an aerosol cloud at its boiling point. Ammonia gas at its boiling point is lighter than typical ambient temperature air but in this case the cloud is dense because of the aerosol content. As air is entrained, the droplets vaporise

cooling the cloud further, until all the droplets are gone and the cloud is a dense mixture of ammonia and air, at a temperature well below the boiling point of ammonia (for example, see Figure 5). It is unlikely that dense gas clouds formed in this manner will lift off, which means that they will likely disperse as negatively buoyant clouds entraining ambient air until they are so dilute as to be effectively neutrally buoyant (Kaiser and Walker, 1978).



Figure 5 Top: Ammonia cloud dispersing 5 s (left) and 15 s (right) after release at Dugway Proving Ground during Jack Rabbit trials (Storwald et al., 2011, © UVU copyright 2011).
Bottom: Ammonia released during large scale field trials undertaken by INERIS (Bouet, 1999, © INERIS copyright)

Chemical reactions

Chemical reactions can cause dense gas clouds to form. Water vapour in the atmosphere (atmospheric humidity) is a common reactant with released substances. An example is hydrogen fluoride, which both oligomerises and forms droplets containing hydrogen fluoride and water (hydrofluoric acid) resulting in a dense fog.

Another example is uranium hexafluoride (UF_6), which reacts exothermically when it comes into contact with water vapour to form hydrogen fluoride and a solid precipitate of fine particulates (UO_2F_2), which remain airborne. Unreacted solid uranium hexafluoride aerosols may also be present. The reaction is very quick. The heat of the reaction can reduce the density of the plume from being very dense to being less dense than air but the presence of the UO_2F_2 particulates contribute to increasing the density of the cloud. The hydrogen fluoride can subsequently react with moisture present as described above.

Titanium tetrachloride is another substance that reacts with water to disperse as a dense gas. The reaction produces corrosive hydrogen chloride vapour and white solid particles of harmful titanium dioxide.

Acids and hypochlorites react with each other to generate chlorine gas and acids and sulphides react with each other to generate hydrogen sulphide.

Sulphur trioxide and oleum react with water and other substances, typically to give off H_2SO_4 aerosol (sulfuric acid) which is initially dense. For further details of work on this topic, see for example Kapias and Griffiths (2000).

Aerosols and particulates in suspension

Aerosols are frequently formed during pressurised releases or chemical reactions and can cause or contribute to the density difference. This has been discussed under the other mechanisms above. Particulates in suspension can also cause the density difference. An example was given for uranium hexafluoride above. Other examples include dust clouds and avalanches, which are not within the scope of this review.

3.2.2 Criteria for when gas releases need to be treated as dense

Whether the released gas disperses with the characteristics of a dense gas is not simply a matter of whether the released substance has higher density than air. For example, if the amount of dense material released is small and environmental velocities are large, the density difference may not be a significant variable and so the dispersion of the released material may be considered to be passive.

For both numerical modelling purposes and for experimental trials, it is important to know when a gas release can be treated as effectively passive. A case in point is the use of sulphur dioxide, a dense gas, as a passive tracer in experiments of neutrally buoyant releases (Barad, 1958).

Ideally, a numerical model needs to be able to account for dense and neutrally buoyant dispersion so that it can model the transition from dense to passive behaviour. In reality, the transition can be complex and require significant modifications to the physics which can be difficult to implement in simpler operational models. Consequently, different models are sometimes used for dense gas releases and neutrally or positively buoyant releases.

There have been several studies to determine criteria for when density effects are important and the transition from dispersion that is characteristic of dense gases to that of neutrally buoyant gases. These criteria are also often used to check for similarity between small scale and full scale experiments. However, they also provide a means for numerical modellers to determine when a release needs to be treated as dense.

Criteria for when a dense gas can be treated as effectively passive are also important in emergency response. However, in such scenarios it is usual for very little information to be available. In the first instance, it may be difficult to even identify what the substance is. Therefore simple criteria, or rules of thumb, indicating if the cloud is likely to show dense or passive dispersion characteristics are valuable to enable provision of appropriate advice to responders.

Richardson number

The Richardson number, Ri , is a measure of cloud stability. It is the ratio of buoyancy forces to inertia forces and is frequently used as an indicator of whether a gas will behave as a dense gas or if it can be treated as a neutrally buoyant release. There are various forms of Richardson number used in the literature. It can be defined using different length and velocity values at different stages of a release and the criteria differ depending on the values chosen and for instantaneous and continuous releases (see section 3.4.1). As such, care should be taken when interpreting and comparing values found in the literature. Some examples are provided below.

Hall and Waters (1983) define a Richardson number based on cloud height and wind speed near the top of the cloud as follows:

$$Ri = \frac{g(\rho_g - \rho_a)}{\rho_a} \frac{L}{u^2}$$

Where g is gravitational acceleration, ρ_g is the cloud density, ρ_a is the ambient air density, L , is the cloud height and u the wind velocity at the top of the cloud. This is effectively a 'bulk' Richardson number.

They provide the following interpretation:

If	$Ri \leq 0.1$	the cloud will show little or no heavy gas effects,
If	$Ri \approx 1$	significant dense gas effects including lateral spreading and reduced vertical dispersion,
If	$Ri \geq 10$	very pronounced dense gas effects including extreme resistance to vertical dispersion and strong upwind and lateral motion.

They add that the highest values of Richardson number result from the largest clouds, the highest density vapours and the lowest wind speeds. This form of the Richardson number could be used on experimental measurements mid-cloud to inform on the anticipated strength of density effects. Hall and Waters (1983) also replace ρ_g with the initial cloud density, ρ_0 , L with a pool source diameter and u with the wind speed at the reference height, u_{ref} , to create a source Richardson number.

Source Richardson numbers have been defined in other variations. Britter and McQuaid (1988) define a source Richardson number with critical values for effective passivity as follows:

$$Ri_0 = \frac{g(\rho_0 - \rho_a)}{\rho_a} \frac{q_0}{Du_{ref}^3} \leq 0.003375 \quad \text{for a continuous release}$$

$$Ri_0 = \frac{g(\rho_0 - \rho_a)}{\rho_a} \frac{L}{u_{ref}^2} \leq 0.04 \quad \text{for an instantaneous release}$$

where q_0 is the initial volume flow rate for the continuous cloud, L is either the height of the initial volume of the instantaneous cloud, or its cube root, D , is the source length scale, and u_{ref} the wind velocity at a reference height (often at a height of $z = 10$ m). Britter and McQuaid (1988) note that if the cloud is initially classified as a dense release, these criteria can be used to determine when the cloud can subsequently be treated as effectively passive. The criteria should be taken as approximate with dense or passive behaviour only dominating completely when the Richardson number is respectively much greater than or less than the quoted value. Otherwise, there will usually be a smooth gradual transition from dense to passive behaviour.

Spicer and Havens (1989) and Havens and Spicer (1990) define a 'release' Richardson number for determining the relative importance of the flow regimes as follows:

$$Ri_0 = \frac{g(\rho_0 - \rho_a)}{\rho_a} \frac{H}{u_*^2}$$

Where H is a characteristic cloud height which can be approximated by $H = q_0/u_{ref}D$ and here D is taken as the source width, u_* is the friction velocity. They interpret this number using the following approximations:

If	$Ri_0 \leq 1$	passive dispersion
If	$1 \leq Ri_0 \leq 30$	stably stratified shear flow

If $Ri_0 \geq 30$ negative buoyancy dominates flow

Note the use of the friction velocity in this form. Hall and Waters (1989) noted that using u_* as the reference velocity is convenient when dealing with a range of plume scales since it avoids difficulties caused by changes in the assumed reference height with changes in the assumed scale³². This is an important consideration in small-scale wind tunnel models. However, they acknowledge that the use of u_* introduces unnecessary variability in measurements since it is coupled to the wind speed by the aerodynamic roughness height.

Hanna et al. (1996) define the source Richardson number similarly using friction velocity, with critical values for effective passivity as follows:

$$Ri_0 = \frac{g(\rho_0 - \rho_a)}{\rho_a} \frac{q_0}{Du_*^3} < 50 \quad \text{for a continuous release}$$

$$Ri_0 = \frac{g(\rho_0 - \rho_a)}{\rho_a} \frac{V}{D^2 u_*^2} < 50 \quad \text{for an instantaneous release}$$

Where V is the instantaneous release volume. They add the comment that the value of 50 is the approximate critical value but experimental data has shown that the dense gas effects become more and more important as Ri_0 increases from 1.0 to 100 so a factor of 2 could be applied to this criterion.

Hanna et al. (1996) also define distinct criteria for elevated releases such as a gas release from a stack or a pipe break (described further in Section 3.4.1). For these cases, two Richardson numbers can be of use. Firstly, the initial cloud length scale, D , in the above equations can be replaced with the initial diameter of the rupture or pipe, D_p , to determine the importance of the dense gas effects at the source. This provides an indication of whether the gas plume will slump to the ground. Secondly, after the plume has touched down again it can be assumed to have a depth approximately the same as the height from which it was released, h_s . Therefore, this value can be used to replace the initial cloud length scale, D , in the above equations.

Hall and Waters (1989) define a plume buoyancy flux parameter, B , in terms of the friction velocity, which they use to describe the stability of the plume, as follows:

$$B = \frac{g(\rho_g - \rho_a)}{\rho_a} \frac{q_0^{0.5}}{u_*^{2.5}}$$

Using this parameter, they define the following classifications for flow over a smooth floor:

If	$0 < B < 10$	essentially neutrally buoyant dispersion
If	$10 < B < 100$	small but noticeable dense gas effects
If	$100 < B < 1000$	gas density controls dispersion
If	$B > 1000$	laminarisation of external flow

Other criteria

In modelling, arbitrary assumptions are commonly used for the transition point between dense and passive dispersion. For example, the TNO Yellow Book (Van den Bosch and Weterings, 2005) suggests effective passivity is attained on the following assumptions:

- The density difference drops below a critical value

³² Note that Hanna et al. (1996) comment that as a rule of thumb, the friction velocity, u_* can be approximated as 5% to 10% of the reference velocity at 10 m.

- The Richardson number drops below a critical value
- The gravity-front velocity decreases to a critical level, usually a fraction of the ambient wind velocity

The NUREG handbook (SAIC, 1998) suggest the following conditions for effective passivity:

- The gravitational slumping must cause a rate of increase of radius not exceeding that to be expected by the atmospheric turbulence alone (with the conceptual assumption that the radius is at the 10 percent edge of a Gaussian profile).
- The rate of growth of plume height predicted by the dense gas dispersion model must exceed that predicted by the traditional Gaussian dispersion model

If both of these are satisfied then the plume transitions to passive. Also, if the density difference, $(\rho_0 - \rho_a)/\rho_a$, is less than 0.001 then it is assumed that the plume becomes passive. But this critical value is fairly arbitrary.

Rauchegger et al. (2015) classify a gas as heavy if both of the following criteria apply:

- Relative density excess at release is greater than 0.16
- Source volume amounts to more than 0.1 m³ (for an instantaneous release), or source volume flow rate is greater than 0.001 m³/s (for a continuous release)

They add that if the dense gas concentration decreases to below 1% of the initial concentration at a distance of only 10-20 m from the source then the dispersion can be treated as neutrally buoyant. This is stated as a pragmatic approach and ideally the Richardson number would be calculated.

Calculation of Richardson numbers and the other criteria presented above require knowledge of the release. During an emergency response situation, the substance and release conditions may not be known, which means that the density may not be known and cloud dimensions may not be immediately obtainable. Therefore, while Richardson numbers are useful indicators of effective density of sources or transition to passivity it is unlikely that they could be calculated quickly enough to be useful during an emergency response situation.

3.3 Evolution of a dense gas cloud

Ignoring for now the conditions surrounding the source of the dense gas cloud, without any other external sources of momentum, gravity affects the density difference between the released dense gas and the ambient environment and causes self-generated flow. The horizontal extent of the resulting cloud is generally increased and the vertical extent is reduced compared to a similar passive release.

Details of the typical evolution of dense gas clouds can be found in references such as van Ulden (1974) and Britter and McQuaid (1988). A brief summary is given below.

Initially, the effects of turbulence and momentum of the ambient flow can be neglected and the dynamics and mixing of the cloud are driven by the negative buoyancy of the cloud due to gravity. The cloud slumps and spreads radially and often a raised edge can be observed at the front of the spread. This front appears sharp and the top of the cloud more diffuse. The concentration distribution within the cloud is typically fairly uniform in the lateral direction. Significant mixing occurs at the interface of the cloud and the ambient atmosphere due to shear flows generated by the gravity-induced spreading. However, within the main body of the dense gas cloud the density is stably stratified in the vertical direction, often well in excess of stability levels normally occurring in the atmosphere, possibly to the point of laminarisation of the flow and making the cloud resistant to the normal dispersion process caused by atmospheric turbulence (Hall and Waters, 1983).

Gravity induced spreading continues to dominate over any horizontal atmospheric diffusion until eventually atmospheric turbulence leads to vertical mixing at a similar or greater rate to the gravity-induced slumping rate. At this stage, advection by the mean wind in the atmosphere starts to occur.

Eventually the cloud becomes diluted so that gravity spreading becomes comparable to horizontal atmospheric diffusion and no longer dominates the flow. The cloud starts to lose definition at its leading edge and appear more diffuse. However, vertical diffusion is still suppressed by the density of the cloud.

Finally, atmospheric turbulence and the mean wind conditions dominate dispersion, density effects can be neglected and the subsequent dispersion continues as for a neutrally buoyant cloud.

In reality, the source conditions cannot be ignored and are a critical factor in the subsequent evolution of the cloud, frequently causing the initial density difference. The release mode, size of the density difference, atmospheric conditions and many other factors influence the dense gas cloud, modifying the typical evolution outlined above. Many of these factors and their impact are discussed in the next section.

3.4 Factors that affect dispersion of dense gases

Note that the impact of many of the factors discussed here on the effective density of the gas cloud can be seen in a general sense through calculation of Richardson numbers if enough information is available.

3.4.1 Source geometry and conditions

Release mode

Source conditions can be broadly categorised into three release types: instantaneous, steady continuous or time varying³³. The mode of release has a significant effect on the formation and subsequent dispersion of a dense gas cloud.

In an instantaneous release, the entire volume of gas is released in a very short, near instantaneous, period of time. An example of an instantaneous release is catastrophic failure/rupture of containment vessels or pressurised tanks causing them to empty within a very few seconds.

A steady continuous release typically has a constant flow rate over a long enough period of time that the gas disperses in a steady state. For example, gas released from a (relatively deep) contained pool or small ruptures in pipes or vessels.

A fully continuous, or time-varying, release may need to take into account time-varying source conditions such as area, temperature, concentration and emission rate. For example gas released from a spreading vaporising pool, larger ruptures in vessels and pipeline ruptures.

The impact of an instantaneous release compared with a continuous release can be significant. An instantaneous release essentially implies that the entire inventory of gas is released all at once instantaneously. In this case, along-wind dispersion of the cloud can be important. On the other hand, a continuous release of the same inventory might only release a very small amount every second. For this reason, an instantaneous release of a gas might need to be treated as dense, while a continuous release of the same quantity of the same

³³ Note that these definitions are in relation to the gas dispersion, not in relation to the source term. For example, catastrophic failure of a tank of LNG constitutes an instantaneous release of liquid, which forms a pool. In terms of gas dispersion the pool is the source and this constitutes a continuous release of gas.

gas but over a prolonged period may be reasonably treated as passive. If enough information is available, the Richardson number criteria can be used to determine whether the release will show dense or passive characteristics (see Section 3.2.2).

It should be noted that a short duration continuous release can sometimes be better described as an instantaneous release for modelling purposes. Britter and McQuaid (1988) provided criteria for deciding which release type is more appropriate, as follows:

$\frac{u_{ref}T_0}{x} \geq 2.5$	Continuous
$\frac{u_{ref}T_0}{x} \leq 0.6$	Instantaneous
$0.6 \leq \frac{u_{ref}T_0}{x} \leq 2.5$	Calculate solutions for both instantaneous and continuous and take the minimum concentration

where T_0 is the release duration, u_{ref} is the reference velocity (wind speed) and x is the distance downwind from the source on, or near, the centreline of the plume.

In some literature instantaneous releases are referred to as a cloud and continuous releases are referred to as a plume. The term “puff” is also used. However, this terminology can be ambiguous as it is sometimes used to describe instantaneous releases and other times used to describe finite duration releases.

The rest of this section discusses several types of instantaneous and continuous release source geometries.

Spills of liquids with boiling point above ambient temperature

When a vessel containing liquid with a boiling point above ambient and at low pressure ruptures, the liquid releases due to pressure from its own weight (static head) and forms a pool (see Figure 6a). The pool may be contained by a dike, bund or other enclosed area, or not contained. Examples of when this type of scenario may occur are ruptures in vessels or pipework when preparing to transfer contents, incidents involving storage vessels containing liquids with high boiling points at industrial facilities.

When a vessel containing liquid with a boiling point above ambient and at high pressure ruptures, the liquid released again forms a pool but in this case aerosols are also formed on release (see Figure 6b). The pool may be contained by a dike, bund or other enclosed area, or not contained. Examples of when this type of scenario may occur are ruptures in pipework while transferring liquid using nitrogen padding, and truck unloading operations.

Dense gas clouds can form in these scenarios due to evaporation of the liquid pool, if the substance has higher molecular weight than air. They are low momentum sources that depend on the evaporation rate from the pool and from the aerosol, which may also rainout into the pool. When the boiling point of the spilled liquid is greater than about 5°C above ambient temperature, the evaporation rate of the pool will be mainly dependent on the wind speed. When the boiling point is within about 5°C of the ambient temperature, the evaporation rate is likely to be dependent on both heat flux into the pool and wind speed (SAIC, 1998; Webber and Jones, 1987).

For releases contained by a bund or dike, pool evaporation rates can be calculated based on a static pool. For releases without containment, it may be important to take into account the effect of pool spreading on the evaporation rate.

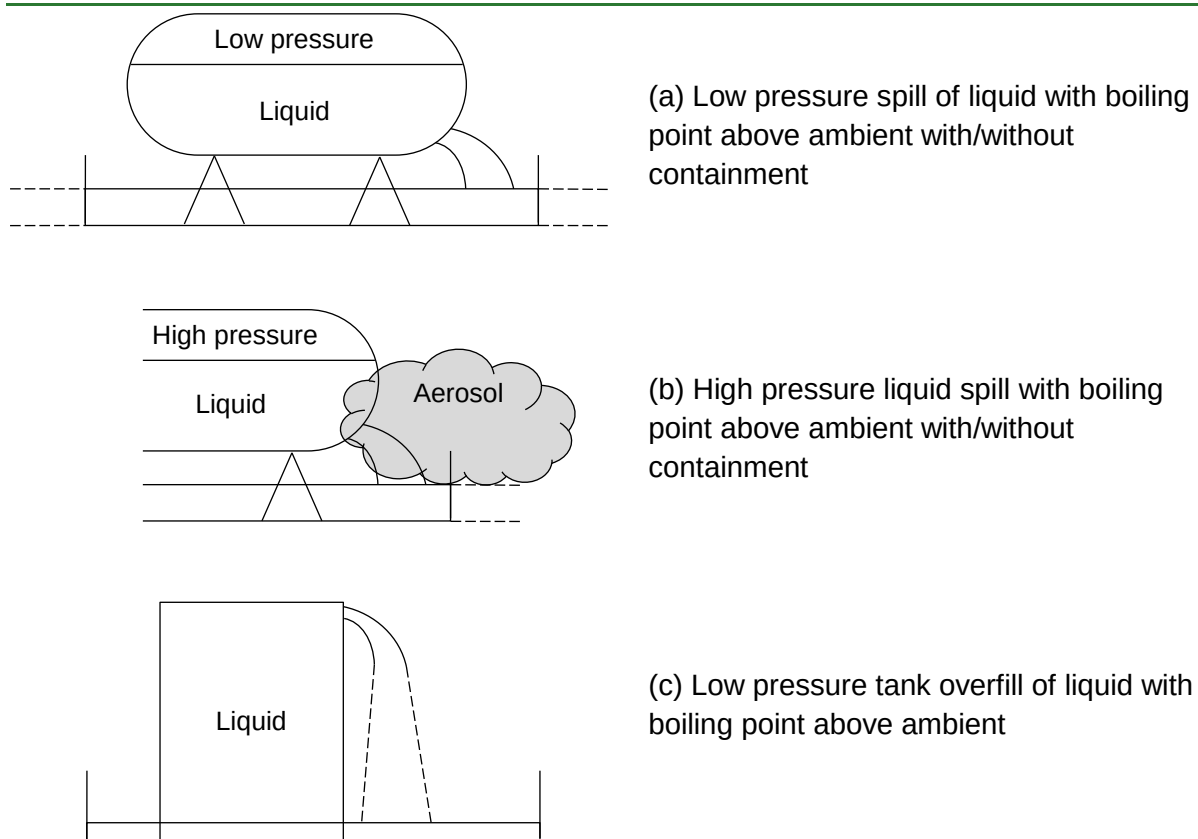


Figure 6 Potential source term configurations for spills of liquid with boiling point above ambient temperature³⁴

Liquids with a boiling point above ambient temperature released from height from low pressure containment can also form droplets. Examples are over-filling of a fuel storage tank such as occurred in the Buncefield incident (see Section 4.4.5) or ruptures of high level pipework (see Figure 6c). As the liquid falls from height, some of it breaks up into a cascade of droplets. A proportion of the liquid and droplets will form a pool on the ground. Evaporation of the more volatile fractions in the cascade lowers the temperatures in the surrounding vapour phase (to below 0 °C and perhaps as low as -10 °C, Atkinson and Gant, 2012) resulting in a gas cloud at much lower temperatures than the ambient temperature, i.e. a dense gas cloud. Depending on the level of humidity of the ambient air, the sudden drop in temperature causes condensation of moisture in the air to form fog rendering the cloud visible. Atkinson and Coldrick (2012) include a workbook for analysis of vapour cloud formation and hazard ranges, which was extended by Atkinson and Pursell (2013).

Spills of refrigerated liquids

Many gases are stored and transported in refrigerated or pressurised liquid form and in some cases a combination of both pressurised and refrigerated storage is used. In similar scenarios to those for liquids with boiling points above ambient temperature, the liquid may spill to form a pool (see Figure 7). However, in these cases the dominant contribution to evaporation is heat flux into the pool, particularly from the ground. Again, the pool may be contained by a bund wall. Examples of when this type of scenario may occur are ruptures in vessels during storage or while transferring refrigerated liquids.

³⁴ Figure 6 to Figure 8 and Figure 11 and Figure 12 **Figure 12** are based on Fryer and Kaiser (1979) and SAIC (1998)

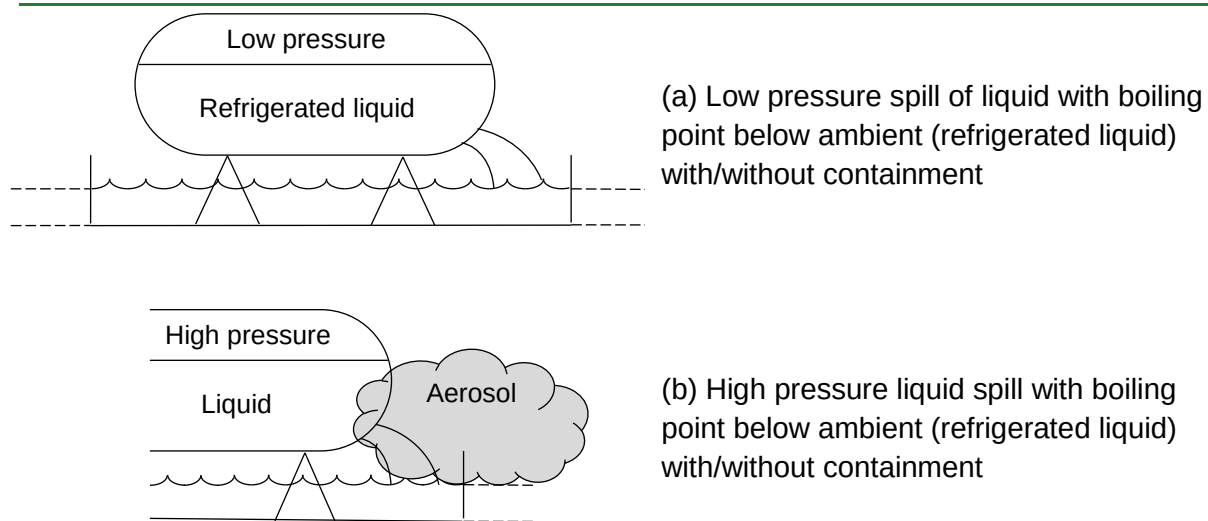


Figure 7 Potential source term configurations for spills of liquid with boiling point below ambient temperature (refrigerated liquids)

As mentioned in Section 3.2.1, dense gas clouds form in these scenarios due to the temperature of the gas being lower than the ambient temperature, e.g. spills of cold, temperature-liquefied LNG. They are low momentum sources with the extent of the gas cloud depending on the evaporation rate. Containment may have significant impact on evaporation rates for refrigerated releases because the heat flux from the ground will decrease with time as the ground cools.

Releases of pressure-liquefied gases

As mentioned above, many gases are stored and transported as pressure-liquefied gases. There are several conceivable release mechanisms should containment fail. This subsection considers releases from the liquid space, shown in Figure 8 and the next subsection considers releases from the vapour space, shown in Figure 11.

Figure 8 (a) shows a puncture or rupture below the liquid level in the wall of a vessel containing a pressure-liquefied gas. This could also happen should a short pipe in a vessel wall rupture.

The rate of release of the liquid will be driven by the high pressure of the containment. Flashing will occur resulting in aerosol and vapour formation at the rupture point. The fraction of liquid that flashes to vapour can be calculated using the following expression (AIChE, 1989):

$$F_v = c_{p,liquid}(T_0 - T_b)/H_{liquid}$$

Where F_v is the fraction of liquid vaporised, $c_{p,liquid}$ is the heat capacity of the liquid averaged over the temperature range T_0 to T_b (J/kgK), T_0 is the initial temperature of the liquid (K), T_b is the atmospheric boiling point of the liquid (K) and H_{liquid} is the latent heat of vaporisation of the liquid (J/kg).

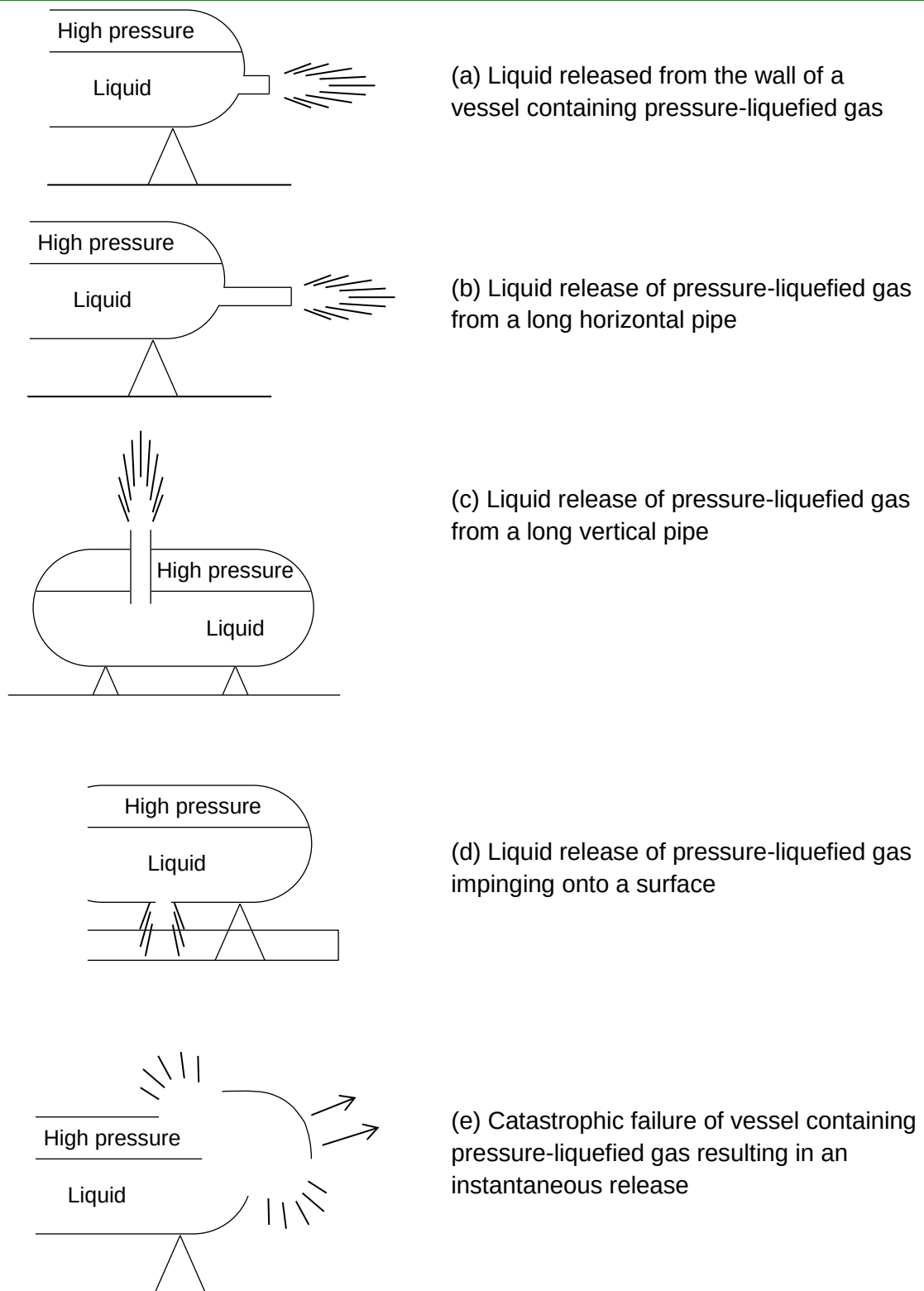


Figure 8 Potential source term configurations for spills of pressure-liquefied gases from the liquid space

Any remaining liquid aerosolises or falls to the ground and evaporates. Complete aerosolisation can be assumed if the temperature of the liquid is more than 10°C above its boiling point (SAIC, 1998). Substances such as ammonia and hydrogen fluoride are often

stored under pressure at ambient temperature. Ammonia has a boiling point of -33°C and ambient temperatures are typically $0^{\circ}\text{C} - 30^{\circ}\text{C}$, therefore a release will most likely result in total aerosolisation. Hydrogen fluoride has a boiling point of 20°C , within the range of typical ambient temperatures and therefore is less likely to undergo total aerosolisation, although it could be possible on a hot day.

When flashing occurs it will nearly always result in a dense gas cloud due to the decrease in temperature resulting from the pressure drop. Aerosols entrained in the vapour can increase the density and additional cooling occurs as the aerosols evaporate. The density effect may be very short-lived, particularly for substances that also undergo exothermic reactions which will reduce the cooling effect. Experiments have determined that as a rule of thumb flashing results in almost instantaneous mixing with approximately ten times by mass of air (Kaiser, 1979). If the air is warm it can evaporate the aerosols but the cooling resulting from the evaporation means that once thermodynamic equilibrium is achieved it may still be colder than the ambient air and therefore behave as a dense cloud. The humidity in the air also provides a source of moisture for water reactive substances.

Figure 8 (b) and (c) show a rupture of a long pipe fitted below the liquid level leading from a tank containing pressure-liquefied gas. In this case, some of the liquid flashes in the pipe and then flashing occurs again on release so that a two-phase mixture of aerosol and vapour is emitted. This is similar for horizontal or vertical releases, except that vertical releases of dense gases result in short term plume rise, due to the momentum of the source. The plume subsequently arcs in line with the wind direction before touching down and spreading along the ground, as illustrated in Figure 9 (a) and shown experimentally in Figure 9 (b). Note that in these cases, the high density of the gas causes the plume to sink and touch down but the entrainment that occurs during this process can mean that the density difference can be so reduced that the grounded cloud is effectively passive. It is useful to calculate two Richardson numbers in this scenario, one to assess the density effects at the source and one for the touched down plume (Hanna et al., 1996, see Section 3.2.2).

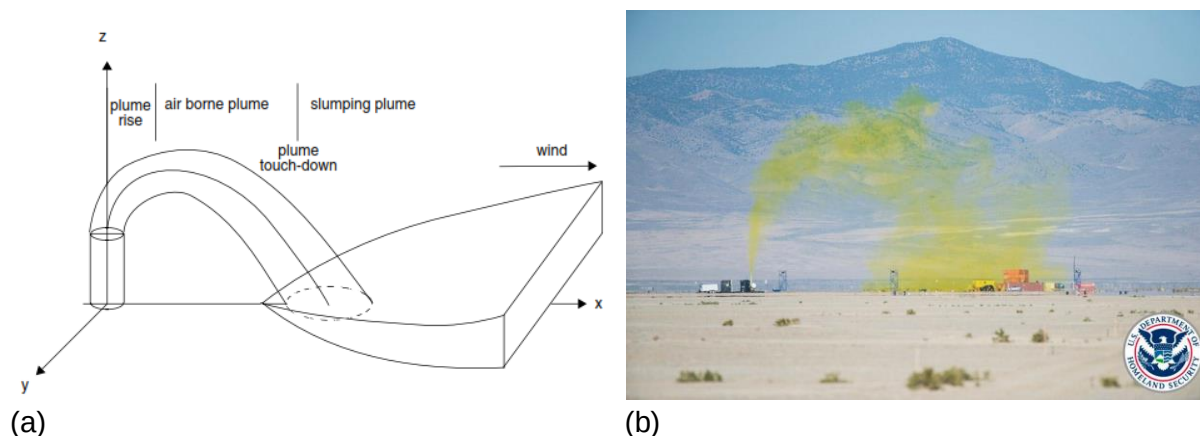


Figure 9 Evolution of a vertical plume of dense gas from an elevated source. The plume is ejected upwards from the orifice before sinking, touching down and spreading along the ground. (a) Illustration from Van den Bosch and Weterings (2005, © TNO copyright) (b) Vertical plume of chlorine released in JR II Trial 8 (© UVU copyright)³⁵

The plume is influenced by the atmospheric conditions. An illustration of jet and plume dispersion from a variety of orientations and wind conditions is shown in Figure 10 and broadly illustrates the differences between neutrally buoyant, positively buoyant and negatively buoyant releases (Mannan, 2012, Chapter 15).

³⁵ Image from <https://www.uvu.edu/es/jack-rabbit/> Accessed 4th March 2020

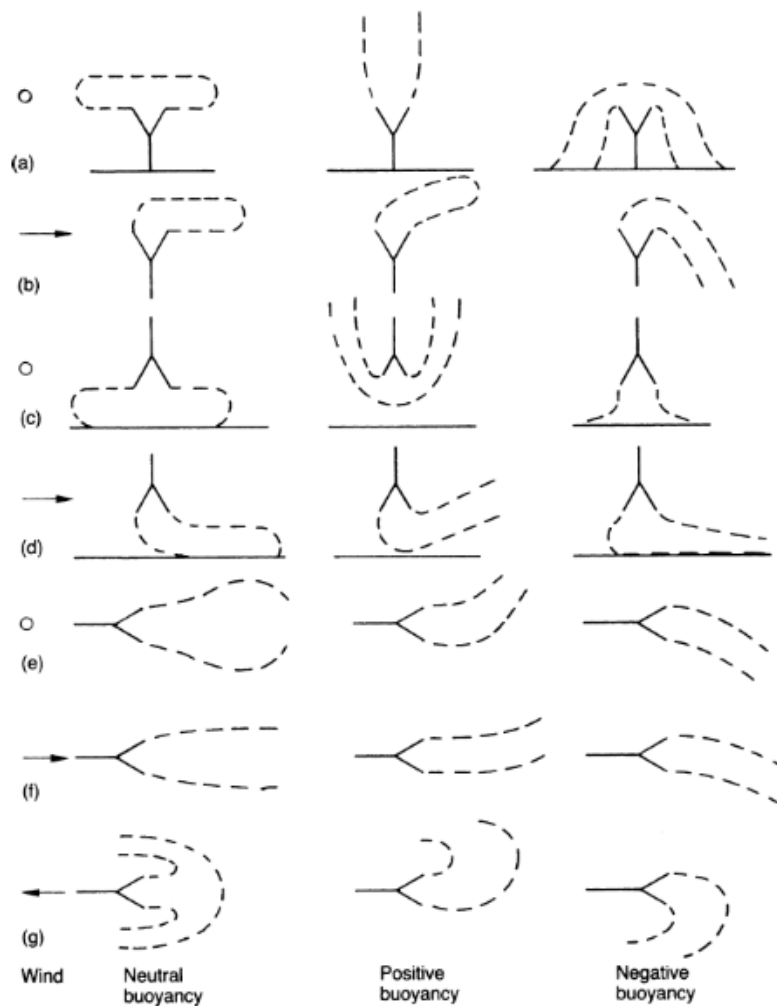


Figure 10 Jet and plume dispersion for (a) an upward-pointing vertical release in nil wind, (b) an upward-pointing vertical release in a crosswind, (c) a downward-pointing vertical release in nil wind, (d) a downward-pointing vertical release in a crosswind, (e) a horizontal release in nil wind, (f) a horizontal release with wind in direction of release and (g) a horizontal release with wind opposed to release. Scenarios shown for neutral buoyancy (left), positive buoyancy (centre), negative buoyancy (right) (Mannan, 2012)

The height of the release orifice is important. Elevated sources result in increased entrainment. As the source height increases, the length of the dense gas cloud at ground level decreases and there is a critical source height, z_c , beyond which a dense gas cloud can no longer form at ground level. This has been proposed as follows (Rauchegger et al. 2015):

$$z_c = 16.5 \left[\frac{\rho_a}{g(\rho_0 - \rho_a)} q_0^2 \right]^{\frac{1}{5}}$$

If a vessel ruptures below the liquid level of a pressure-liquefied containment vessel, the orientation of the rupture may be such that the flashing release impinges on a surface, as shown in Figure 8 (d). This results in droplets collecting on the obstruction (droplet recovery), which can form a pool while vapour and other droplets remain airborne. The subsequent pool evaporation may contribute to the dense gas cloud along with the vapour/aerosols from the flashed liquid, resulting in a complex source. Experiments on ammonia showed that the amount of liquid recovered can be up to 75% (Resplandy, 1969).

Catastrophic failure of a pressure-liquefied gas vessel will cause the entire contents to boil forming vapour and aerosol. The resultant expansion is highly turbulent and entrains air (about ten times by mass, as mentioned above). This constitutes an instantaneous release likely composed of aerosol, vapour and air.

Releases of pressurised vapours

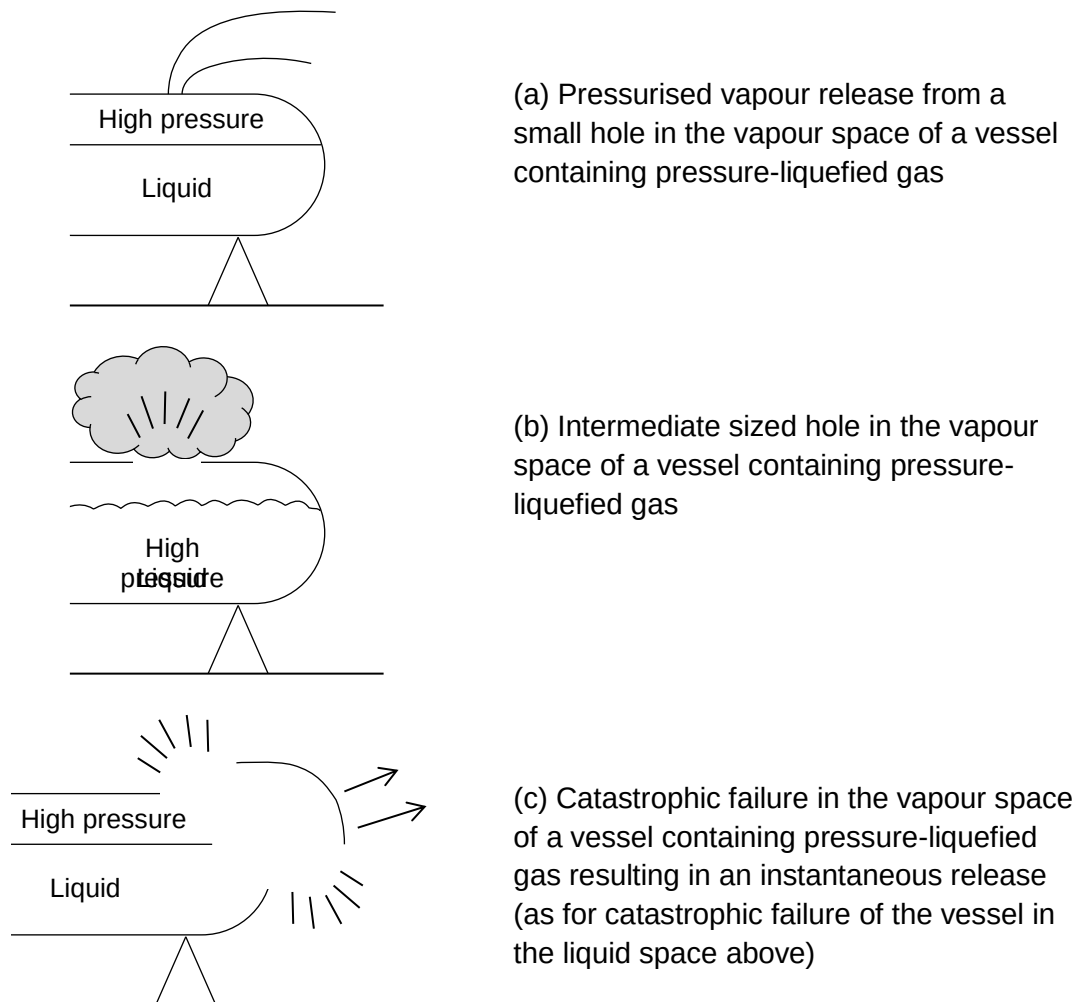


Figure 11 Potential source term configurations for spills of pressure-liquefied gases from the vapour space

As shown in Figure 11, when gases are contained in a vessel in a pressure-liquefied state, a proportion of the space remains as pressurised gas. When a small hole occurs in the vapour space of a pressure-liquefied vessel (Figure 11a), the vapour is driven out under high pressure. A small hole can be defined by the ratio of the hole area, a , to the surface area of the liquid within the tank, A , being much smaller than one ($a/A \ll 1$). Examples of this scenario are a small rupture in the vapour space of a tank during transfer operations, leaks in pipes, relief valve discharges and lower velocity releases from stacks. For many storage vessels a sheared off valve would lead to a ratio much smaller than one. Any gas releases where the substance has a molecular weight greater than air will behave as a dense gas cloud, although this may not extend far from the source.

The above is for a small hole. When an intermediate sized hole occurs in the vapour space of a vessel containing pressure-liquefied gas, the release is far more complex (Figure 11b).

The surface of the liquid within the vessel will foam or froth and the discharge from the hole can transition through up to four flow regimes depending on vapour flux and fluid characteristics (SAIC, 1998), as follows:

- Pure vapour flow as for a small hole
- Bubbly flow – continuous liquid phase with bubbles
- Churning turbulent flow – continuous liquid phase with coalesced vapour regions of increasing size
- Droplet flow – continuous vapour phase with liquid droplets

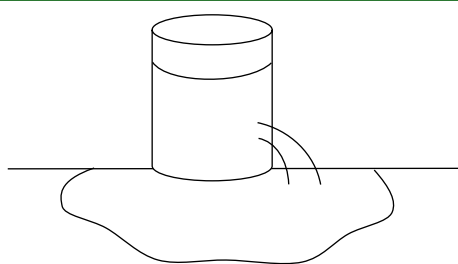
In such cases it can be difficult to characterise the source in order to understand the subsequent dispersion.

A very large hole in the vapour space of a pressure-liquefied gas vessel (Figure 11c) essentially constitutes catastrophic failure of a pressure-liquefied gas vessel, which has been discussed previously.

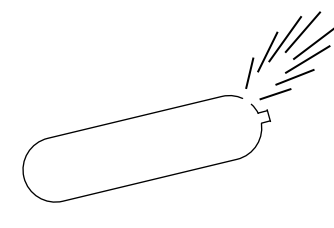
Releases from drums and cylinders

Some substances are stored and transported in much smaller vessels. Liquids with a boiling point above ambient temperature and vapour pressure below 100 kPa can be stored in drums. A puncture would cause the contents to spill onto the ground and form a small evaporating pool (Figure 12a). Pressure-liquefied gases are stored in cylinders in which a puncture would result in a flashing liquid jet (Figure 12b).

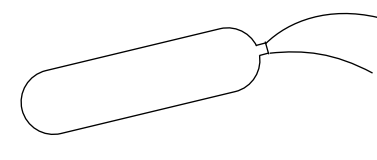
Some gases are stored and transported as compressed gases and remain in the gas phase. These are typically contained in smaller quantities in cylinders. A puncture of a compressed gas cylinder would result in a vapour jet (Figure 12c). Catastrophic failure of a cylinder, for example if it was dropped, would result in a small instantaneous gas release (Figure 12d).



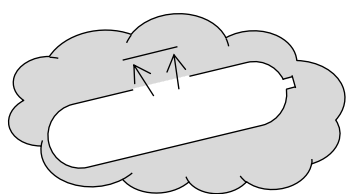
(a) Release of liquid from a drum due to a puncture



(b) Release due to a puncture in a cylinder containing pressure-liquefied gas



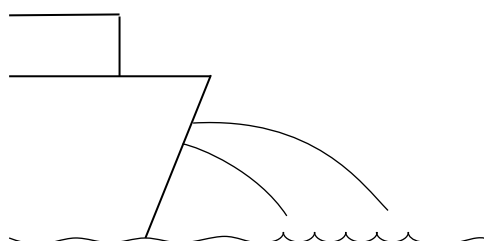
(c) Release due to a puncture in a cylinder containing compressed gas



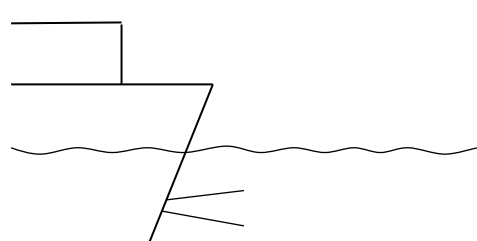
(d) Catastrophic rupture of a cylinder

Figure 12 Potential source term configurations for small scale vessels

Spills onto water



(a)



(b)

Figure 13 Potential source term configuration: (a) spill from a ship onto water (b) spill from a ship from a hole below the water line

Water bodies have potential impact on source conditions of a spill. As implied in Figure 13 (a) and (b) any hazardous substances are transported by ship and industrial sites or pipelines might be located next to waterways. Containment bunds may contain a volume of water, particularly if fire-fighting is in progress. The impact of water is greatest on spills of refrigerated liquids, where the heat flux from the substrate directly influences the evaporation

rate, and on spills of water-reactive substances. The impact of water is discussed further in Section 3.4.4.

Complex sources

Note that in several of the above source scenarios, there are multiple sources of the dense gas. Liquid pools can frequently form concurrently with jet releases so that both the jet and the vaporising pool act as dual sources, for example as shown in Figure 7b. Multiple sources can make it difficult to characterise a release and to determine important metrics such as concentration peaks, duration of release and persistence of the gas cloud. For example, Bouet (1999) found that the persistence of the ammonia cloud was modified when a pool formed alongside the jet. In the Jack Rabbit II trials, the dispersing cloud was ‘mushroom shaped’ where the cloud from the initial short duration release was advected by the wind while a plume of chlorine continued to be emitted from evaporating pools of liquid around the release point (see Figure 14).



Figure 14 Mushroom-shaped cloud resulting from release of pressure-liquefied chlorine in the Jack Rabbit II Trial 7 (Byrnes et al., 2017, © UVU copyright)

Other factors such as surface conditions can also add to source complexity, particularly for evaporating, spreading pools. For example, in the Jack Rabbit I trials chlorine that had penetrated into the ground continued to off-gas for up to 90 minutes (National Fire Academy, 2016).

3.4.2 Atmospheric conditions

Wind speed and atmospheric stability

As described in Section 3.3, in the initial stages of release, or near to the source, stability effects within the dense cloud typically dominate those in the atmosphere, regardless of the atmospheric stability. For example in the Jack Rabbit II experiments, chlorine gas was observed to travel upwind over 35 m and up to about 100 m in wind speeds of over 2 m/s

(see Section 6.5.37 and Figure 15). However, once the cloud is more dilute the dominance of the cloud density decreases and the importance of wind effects and atmospheric stability increase. The relative importance of the density effects compared with the atmospheric conditions are indicated by the Richardson number criteria, as discussed in Section 3.2.2.



Figure 15 Chlorine release point slightly right of centre and wind direction is from right to left³⁶ (© UVU copyright).

Significant differences in far field concentrations of ammonia for discharges of identical flow rate but under different atmospheric stability conditions have been recorded in experimental trials (Bouet, 1999). In many of the experimental trials, wind effects on the dense gas dispersion can be observed in the measurement data. For example, in Maplin sands (see Section 6.5.45), the wind caused the plume to narrow so significantly that it passed between many of the measurement stations. Wind meander frequently causes the dispersing dense gas plumes to move in and out of range of measurement devices over the duration of a trial.

During very stable atmospheric conditions (usually during the night or early morning) the wind is typically very low (< 2 m/s) and the wind direction can be very uncertain. There will be virtually no mixing of a dense gas plume into the surrounding air and high concentrations of gas may persist near the source for a long time. Britter and McQuaid (1988) suggest that the downwind distance to a given concentration for a dense gas released into a stably stratified atmosphere will increase compared with a release into a neutral atmosphere i.e. stable atmospheric conditions result in higher toxic concentrations and larger flammable gas clouds. This also applies to passive releases but the effect is more pronounced for dense gas releases, resulting in a greater hazard.

In one of the Burro experimental trials (see Section 6.5.10), the dense gas cloud displaced the atmospheric flow. The velocity measured within the gas cloud was almost zero and the wind was able to flow over the cloud like a solid object. This resulted from the stable stratification within the dense gas cloud dampening the turbulent mixing. These observations were made in slightly stable low wind conditions and the cloud was lower and wider than for any of the other trials in that series, undertaken at higher wind speeds. The cloud also persisted for longer. There have been many incidents where the lack of wind has had

³⁶ Image from <https://www.uvu.edu/es/jack-rabbit/> Accessed 4th March 2020

significant impact, in particular as a contributory factor in several large vapour cloud explosions (VCEs) such as Buncefield (Atkinson et al., 2017).

However, it is not necessarily the case that low winds lead to the worst case. In very low wind conditions, the chlorine cloud shown in Figure 14 is unlikely to travel as far. The presence of the wind causes the plume to travel further downwind. Higher wind can extend plumes very long distances with concentrations that are still of concern. A positive aspect of these cases is that the plume duration and width are significantly reduced nearer to the source.

A criterion for what constitutes a “low” wind speed was presented by Lines et al. (2000) in their Appendix A. Their criterion, based on Richardson number, implies that a wind speed classified as ‘low’ for a slightly dense cloud must be lower than for a very dense cloud. For a passive gas jet, a low wind speed is one much smaller than the jet velocity. For a dense gas jet, a low wind speed will have to be low in terms of generating a large Richardson number and much smaller than the jet speed. The conclusion is that ‘low’ does not translate into a fixed velocity in m/s, but rather is defined in any given release by its physical effect.

Low winds can cause issues for modelling because many models depend on the specification of a non-zero wind speed and the wind direction is highly variable. This is discussed in Chapter 5.

Atmospheric conditions can also affect dense gas cloud dispersion in a localised way. This is particularly the case when terrain or obstructions are present, as discussed further in Sections 3.4.4 to 3.4.7. Urbanisation affects the atmospheric boundary layer through the ‘urban heat island’ and increased surface roughness and may affect dispersing dense gases depending on the scale of the cloud relative to the urbanised area.

Local effects of convection currents were the proposed cause of some of the phenomena observed at the Amuay refinery incident (see Section 4.5.53). In this incident, the dense gas cloud spread away from the refinery off-site and did not spread further into the refinery from the source. Atkinson et al. (2017) suggested that this was due to flow induced by local convection currents caused by the heat produced in the refinery site. The currents caused local airflows towards the heat source, increasing flow speeds with increasing proximity to the source. As a result, the vapour cloud flow on the refinery side of the site was diluted and prevented from accumulating and spreading further in that direction. Conversely, dense vapour released on the side further from the refinery was not be as affected by the local convective airflow and the gravity current caused the cloud to continue spreading at dangerous concentrations in that direction.

In another example of the effects of local convection currents, in Mississauga, Ontario (see Section 4.5.21) over 70 tonnes of chlorine was released through a 3 ft diameter hole in a railcar. It is thought that the chlorine release was less serious than it might have been because there was a large fire which caused the gas to rise in the thermal currents, inhibiting the spread of dense gas along the ground.

Atmospheric humidity

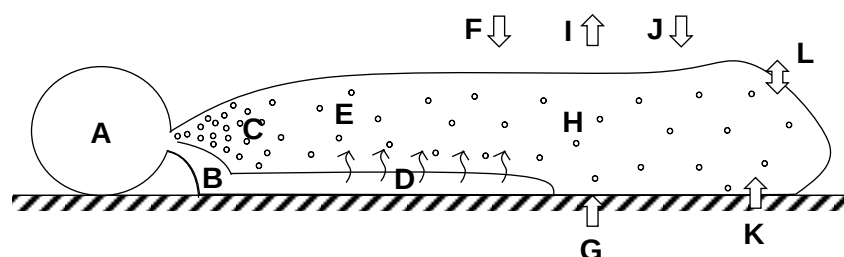
Atmospheric humidity is an important factor in dense gas dispersion when the released substance reacts with water. In some cases, chemical reactions with water vapour are the cause of the density difference, as discussed in Section 3.2.1.

Atmospheric humidity may become a factor when there is a large temperature difference between the dense gas and the ambient air. This is relevant for cryogenic liquid releases such as LNG spills. The ambient water vapour condenses and in some cases, with very cold substances like liquid hydrogen, it has been proposed that the air itself may condense

(Royle and Willoughby, 2014). Condensation and evaporation respectively give out and take up heat, affecting the density difference of the cloud.

3.4.3 Heat transfer and phase change

Low temperature releases, chemical reactions or releases from pressurised containers are some of the causes of density differences in gas releases, as mentioned in Section 3.2.1. All of these types of release typically result in heat transfer and phase changes. This has been discussed in relation to source conditions in Section 3.4.1. These factors can continue to affect dense gas clouds throughout their evolution, as illustrated in Figure 16 (based on Hanna et al., 1996).



A	Ruptured vessel	G	Ground heat flux to the surface
B	Liquid spill	H	Heat gain/loss due to condensation/evaporation
C	Cold temperature gas/aerosol mixture	I	Heat loss due to radiation
D	Evaporation and possibly aerosols thrown into the cloud by violent boiling	J	Solar energy input
E	Endothermic or exothermic chemical reactions	K	Convective heat flux from surface to the air
F	Entrainment of warm ambient air, subsequent condensation of water vapour	L	Heat exchange by convection

Figure 16 Illustration of the thermodynamic aspects of a typical hazardous material release based on Hanna et al. (1996)

External influences such as heated or cooled surfaces, porous media and obstructions can contribute to heat transfer and phase changes within the dispersing material, further modifying the buoyancy. For example, Kunsch and Fanneløp (1995) point out that when a cold front travels over a warmer surface it undergoes a 'thermal shock'. One result of this is a less dense frontal region, which is replenished from behind where the heating effects are less acute. This change at the front affects the lifetime of the cloud and subsequently the hazardous range.

3.4.4 Deposition

Wet and dry deposition can be important factors affecting dense gas dispersion. In general, the more mass of contaminant that deposits, the less there is in the cloud and the lower the hazard from the cloud.

The surface and atmospheric conditions have significant effects on deposition. Dillon (2009) suggested that deposition to vertical surfaces such as the built environment is more efficient than deposition to the ground. The extent of the hazard therefore varies significantly with the release environment. The presence of greenbelts in the path of the cloud can reduce the impact of large scale releases, even for relatively wide object spacings of 2-10 m.

Atmospheric conditions such as sunlight and humidity can change the rate at which chemicals react with a surface. Jonsson et al. (2005) found that for a ground level release, such as from an evaporating pool, there could be a 50% reduction in airborne substance within 500 m at low wind velocity and in neutrally- or stably-stratified conditions. They suggest that stably-stratified conditions should not be assumed to be the worst case and the effects of dry deposition could mean that neutral and unstably-stratified conditions could lead to higher toxic gas concentrations and the largest hazard zones. However, Dillon (2009) suggests that the reduction in hazard zone sizes is higher from deposition onto surfaces than due to atmospheric conditions.

Model predictions by Hanna and Chang (2008) and McKenna et al. (2017a) indicated that dry deposition could have a significant impact on the size of hazardous clouds of chlorine. However, the deposition models used in those studies used a simple approach that did not take into account the fact that the ground can become saturated with chlorine at high concentrations, limiting the deposition rate. This effect has been studied recently in wind tunnel experiments at Arkansas University. Preliminary findings have been published by Spicer et al. (2019) and work on this topic is currently ongoing.

3.4.5 Surface conditions

Surface roughness

The terminology “surface roughness” typically refers to groups (or arrays) of obstructions to flow, which can range in height from a few centimetres (e.g. grassland) to tens or hundreds of metres (e.g. urban buildings). Much research has been undertaken on the effects of different scales of surface roughness, particularly in the urban environment (Hanna and Britter, 2002, Britter and Hanna, 2003). There are rules of thumb to estimate when obstacle effects need to be accounted for as opposed to surface roughness. One such rule is when the smaller value of height or (cross-wind) width of the obstacles is larger than 0.5-1 times the local gas cloud height (Van den Bosch and Weterings, 2005).

There are two potential effects of surface roughness on dense gas dispersion. Firstly it can slow down the horizontal spreading of the cloud and secondly it can increase the atmospheric and cloud turbulence (Hall et al., 1982). The combination of these effects on the concentration is likely to be a reduced downwind distance to a given value. For small surface roughness, such as grassland, the influence on the dense gas cloud is likely to be less than for a comparable passive release (Britter and McQuaid, 1988). This is mainly because the stratification within the body of the dense gas cloud has a suppressing effect on turbulence generated by small surface roughness effects.

One significant difficulty with surface roughness is parameterising its effects for inclusion in models. A common approach is to use the aerodynamic roughness length, z_0 , which is the height above the surface at which the wind velocity is zero. Generally, this means that for a very rough surface, the zero velocity height will be shifted further from the ground and the aerodynamic roughness length will be bigger. Use of the aerodynamic roughness length provides a means to generalise the impact of different surfaces, as shown in Table 2. The use of z_0 is discussed further under consideration of common modelling assumptions and parameterisations in Section 5.2. However, Table 2 is included here to illustrate the types of terrain associated with increasing surface roughness.

Table 2 'Davenport classification' of surface roughness, z_0 , after Davenport et al., (2000), with modifications for industrial applications as per Hanna and Britter (2002)

Keyword	z_0 (m)	Landscape description
Sea	0.0002	Open sea or lake (irrespective of wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometres.
Smooth	0.005	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g. beaches, pack ice without large ridges, marsh, arid snow-covered or fallow open country.
Open	0.03	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g. grazing land without windbreaks, heather, moor and tundra, runway area of airports. Ice with ridges across-wind.
Roughly open	0.1	Cultivated or natural area with low crops or plant covers, or moderately open country with occasional obstacles (e.g. low hedges, isolated low buildings or trees) at relative horizontal distances of at least 20 obstacle heights.
Rough	0.25	Cultivated or natural area with high crops or crops of varying height, and scattered obstacles at relative distances of 12 to 15 obstacle heights for porous objects (e.g. shelterbelts) or 8 to 12 obstacle heights for low solid objects (e.g. buildings and/or industrial obstacles). Typical average building heights might be 5 m. Analysis may need d , which can be approximated as 2 m.
Very Rough	0.5	Intensively cultivated landscape with many rather large obstacles groups (large farms, clumps of forest) separated by open spaces of about 8 obstacle heights. Low densely-planted major vegetation like bushland, orchards, young forest. Also, area moderately covered by low buildings and/or industrial tanks with interspaces of 3 to 7 building heights and no high trees. Typical average building heights might be 5 to 10 m. Analysis requires d , which can be approximated as 5 m.
Skimming	1.0	Landscape regularly covered with similar-size large obstacles, with open spaces of the same order of magnitude as obstacles heights; e.g. mature regular forests, densely built up area without much building height variation. Analysis requires d .
Chaotic	≥ 2.0	City centres with mixture of low-rise and high-rise buildings, or large forests of irregular height with many clearings. Typical average building heights might be 10 to 20 m. d can be approximated as 5 to 10 m. Analysis by wind tunnel is advised.

Urban environment

The urban environment primarily affects gas dispersion through its effect on the atmospheric flow field. The increased and changeable surface roughness associated with conurbations modifies the atmospheric flow field and therefore modifies its impact on any gas dispersion. Studies on neutrally buoyant gas dispersion in urban environments have shown that street canyons and large open spaces such as parks and large courtyards can affect the gas cloud due to their impact on the atmospheric flow (e.g. Belcher et al., 2012).

The urban environment can also provide a heat source for the dense gas cloud due to the 'urban heat island' effect (Britter and Hanna, 2003), which may have direct impact on the cloud density or influence local convection in the atmosphere.

If a small scale dense gas cloud is released within the urban environment, local factors will affect the dense gas dispersion. Buildings and other obstructions can result in features such as blocking, wake effects and channelling of the flow. The impact of fixed structures is discussed further in Section 3.4.6. However, if the dense gas cloud is very large (deep), an urban area can also result in surface roughness effects on the gas cloud.

Other features of the urban environment that have the potential to affect dense gas dispersion are subterranean openings such as drains, basements and underground train lines and tunnels. The presence of these 'sinks' can result in accumulation of dense gases in confined spaces, which limit dilution, increase persistence times and present additional hazards. Examples of gases entering subterranean openings can be found in several incidents, for example in Mönchengladbach, Germany, where carbon dioxide persisted in basements (see Section 4.5.46) and in Mill Woods, Canada, where propane entered storm sewers (see Section 4.5.15).

Forest canopies and vegetation

As for the urban environment, forest canopies and vegetation affect the atmospheric flow field and any modification to this may have a subsequent impact on dense gas dispersion. A forest will act as a surface roughness for a large-scale dense gas cloud and for smaller scale clouds it will represent an array of fixed structures with the associated potential to block and divert the cloud among other features, see Section 3.4.6. Vegetation may result in congestion and could be considered a porous feature, as discussed briefly at the end of this section. It can also provide significant surface area for deposition, as discussed in Section 3.4.4.

According to the Davenport classification of surface roughness (Table 2), areas of shelter belt, low dense vegetation and clumps of forest can be said to have similar impact to more open ground with large collections of farm buildings or other low buildings. As the amount of forested area increases, the similarity tends towards more densely built up areas of similar heights, such as suburbia. Large forests of irregular height can be compared with city centres that have a mixture of low-rise and high-rise buildings.

Water

Many hazardous substances are transported by ship, and industrial sites are often located on estuaries or coasts. Subsea pipelines and offshore oil and gas platforms also involve the potential for dense gas releases onto water.

Water has significant impact on spills of refrigerated liquids, where the heat flux from the water can increase the evaporation rate as compared to spills on land. Dense gas clouds originating from low temperature releases form and evolve differently over large, deep water bodies because convection currents continually replenish the heat at the surface.

Away from land, water surfaces tend to be relatively smooth, fairly uniform in temperature and not subject to significant atmospheric stability changes (Hall and Waters, 1983). Hall and Waters (1983) suggest that a worst case condition on the sea would be a large release in light wind and stable atmosphere with a tide in the same direction and of similar speed to the wind. Under such conditions the forces available to disperse the cloud would be negligible.

Wave effects are unlikely to be important unless they are of significant enough size relative to the depth of the dense gas cloud. Vapour cloud depths can be expected to vary between

2 and 20 m so except for small vapour clouds in strong winds, the wave size will be small compared with the cloud depths (Hall and Waters, 1983).

If the release is from a ship, the aerodynamic disturbance caused by the vessel may affect the evaporation rate of a pool on the water surface and the formation of the vapour cloud (Hall and Waters, 1983).

If the water is shallow the surface temperature cannot be maintained and the water may freeze, affecting both heat transfer and surface roughness. This could happen during spills into containment bunds, which may contain a volume of water.

Pipelines can also run underneath bodies of water. The Maplin Sands experiments showed that when LNG was released from below the surface, the concentrations of the dense gas spread at the surface were lower (see Section 6.5.45).

Porous features

When a dense gas cloud passes over a porous surface various factors may affect the dispersion behaviour. Bubbles of lighter gas can be ejected into the cloud from the pores in the ground due to the density difference with the dense gas cloud, water trapped in pores can freeze to form ice or react with the dense gas cloud. The specific characteristics will depend on the cause of the density difference and the properties of the ground. Several of these phenomena result in heat transfer and phase changes, which affect the density difference of the dispersing gas cloud.

Porosity can also be attributed to features such as hedges and dense undergrowth. There is some evidence from the Buncefield and Festus incidents that vapour can build up behind hedges (see Sections 4.4.5 and 4.5.41).

3.4.6 Fixed structures

Fixed structures, or obstacles, can range in scale from fences to a city blocks. If the scale of the dense gas cloud is significantly greater than that of the fixed structures then the structures can be considered surface roughness, see Section 3.4.4.

Hall et al. (1991a, 1999) provided useful visualisations of gas releases interacting with fences and isolated buildings for neutral, positive and negative buoyancy gas releases.

Single obstacles and obstacle arrays

When the wind is present, the fixed structures can cause increased levels of turbulence resulting in an overall increase in dilution of the dense gas cloud downstream and therefore reduced distances to flammability or toxicity limits. Field tests have shown that ‘impact’ of a dense gas cloud on obstructions can increase the size of the cloud, both upwind of the obstruction and in its wake, see Figure 17. In other cases, obstacles can deflect and channel the cloud, as shown in the Jack Rabbit II trials in Figure 18³⁷ and previously in Figure 15.

³⁷ Image from UVU Jack Rabbit Final Report 2017 available from <https://www.uvu.edu/es/jack-rabbit/> Accessed on 13/02/2020



Figure 17 Carbon dioxide cloud dispersion around containers (Cleaver et al., 2016). Cloud motion is from left to right. Cloud builds up in front of the obstruction then travels round it and mixes in the lee downwind significantly increasing the depth of the cloud (© IChemE copyright 2016)



Figure 18 Image of a pressure-liquefied chlorine release from a rail car from Jack Rabbit II experimental Trial 4 (Byrnes et al., 2017, © UVU copyright)

In other configurations, the interaction of a large obstruction (e.g. a storage tank) with the wind field can cause the dense gas cloud to bifurcate, with near zero concentrations at ground level on the centre-line downwind (Havens et al., 2007; Hall et al., 1999).

Wind tunnel tests have been performed of dense gas flow through industrial sites where the obstacles were comparable to or larger than the vertical plume dimension. The results showed significant increases in dilution of the gas and a slight increase in lateral plume spread compared with an unobstructed release (Britter and McQuaid, 1988).

Obstacle arrays also delay the dispersion of dense gas clouds due to material captured in the wake of the structures. Behind the obstacles a recirculation zone exists which may extend to about 10 times the obstacles height (Duijm and Webber, 1994). This also means that a dense gas cloud passing through an obstacle array will have more variation in the

horizontal concentration distribution throughout the cloud compared with an unobstructed cloud.

Scaperdas and Hebden (2003) summarise building effects on dense gas dispersion with the diagram shown in Figure 19.

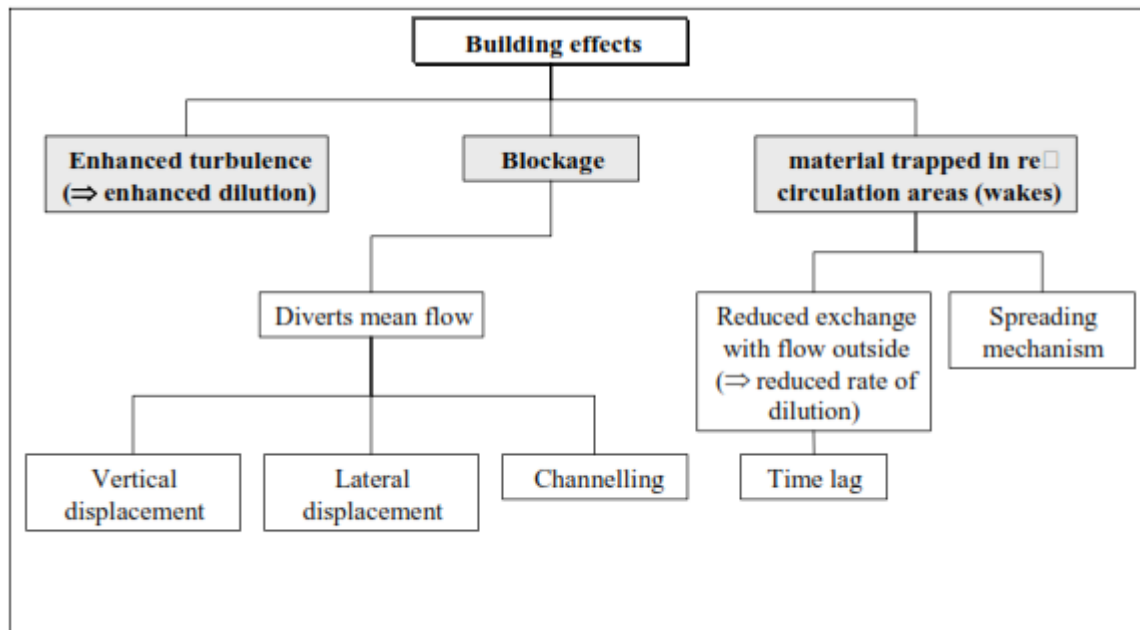


Figure 19 Building effects on dense gas dispersion, from Scaperdas and Hebden (2005)

Fences

A typical fence is defined as a long structure, which the cloud has to pass over, compared with obstructions where the cloud can pass around and/or over. Fences, or by analogy walls or a long row of terraced houses (depending on scale relative to the gas cloud), downwind of a dense gas source and perpendicular to the wind direction have a similar effect to obstacle arrays resulting in reduced concentrations downwind of the fence. There is evidence of a power-law relationship between the reduction in cloud concentration due to the presence of a solid fence and the fence height, at various dense gas cloud Richardson numbers (Davies and Hall, 1996).

Fences also cause the cloud to persist longer at higher concentrations nearer to the source (Hall et al., 1991a). Therefore, while it might reduce the downwind concentration of the cloud, the fence prolongs the persistence of the cloud upstream thereby prolonging the potential for ignition or exposure in the nearfield. Reflection of the gas cloud off of obstructions has also been observed, which can result in a double peak in concentration upwind of the obstruction (Hall et al., 1991a). Increased persistence of the cloud upstream consequently leads to increased persistence downstream.

Low wind and fixed structures

In very low wind speeds, dense gas dispersion is affected more significantly by the physical presence of the fixed structures than by their effect on the atmospheric flow field. In nearly still air, a dense gas cloud released at ground level with minimal momentum in the vicinity of an obstruction will simply spread all around it under gravity-spreading and remain close to the ground (Hall et al., 1999). Dilution occurs mainly from shear due to the cloud motion rather than due to the ambient conditions.

In low wind, a fence will more effectively block the cloud but this effectiveness decreases with increasing wind speed (Heidorn et al., 1992). Incidents where low wind speeds were recorded have shown evidence of channelling of the vapour flow on industrial sites by bund walls (for example at Amuay, Venezuela, see Section 4.5.53). In the Jaipur incident, the site was surrounded by walls which, combined with the low wind speeds, caused a deep layer of vapour to build up on the site (see Section 4.5.49).

Multi-phase flows and fixed structures

For multi-phase dense gas releases that contain fine droplets, such as ammonia, the impact on a vertical obstruction can cause a thin film to form which results in liquid running down the surface to form a puddle at the foot of the obstruction (Bouet, 1999). This was found to result in a reduction in the ammonia concentrations by a factor of two downstream of the obstruction as compared to an unobstructed release and shortened the distance to passive transition.

Infiltration

A significant factor associated with fixed structures is the potential for infiltration. Infiltration of gas into a structure temporarily removes it from the main body of the atmospheric gas cloud. It has been suggested that the presence of multiple buildings can make the ground level concentrations last longer due to infiltration and slow exfiltration increasing persistence (Watson, 2018).

Infiltration also provides a variety of potential surfaces for dry deposition and absorption. Some shelter-in-place studies (Green Book, 1992, also Section 7.5.6) note that fabrics provide surfaces for absorption of substances, which reduces the airborne concentration.

Factors affecting ingress of dense gases into structures are discussed in Section 3.5.

3.4.7 Topography

Topography can have a greater impact on dense gas dispersion than on neutrally or positively buoyant gas dispersion. The characteristic dispersion of dense gas clouds along the ground means that when topography is present they will tend to follow the features of the terrain. However, in a similar way to fixed structures, the effect of topography on the dense gas cloud also depends on topographical interaction with the atmospheric conditions.

Topography with wind present

When the wind is present the effects of relatively small topographical features may often not be important compared with other factors, such as fixed structures.

Pronounced topographical features such as hills, mountains, valleys and ridges can have variable impact on dense gas dispersion, particularly in relation to the atmospheric flow field. The study by McBride et al. (2001) considers the impact of some of these features on chlorine. Low-lying areas such as valleys may have local wind systems, which will affect cloud dilution if the cloud is released or channelled into them. For example, in Montana, Mexico about 300-350 te of chlorine was released downhill from the town. The prevailing wind was up the valley towards the town. The gas was recorded as spreading downhill, into the wind, at least 50 m, up the sides of the valley by a similar amount (vertical) and uphill 950 m into the town resulting in a cloud approximately 1000 m long and 340 m wide (see Section 4.5.22). Conversely, by flowing into a valley the cloud may also be protected from the diluting influence of atmospheric flows and persist for longer.

A dense gas cloud that encounters an upslope in its path may spread laterally at the base of it (McBride et al., 2001). The scale of the cloud in relation to the topographical feature controls whether the cloud flows over it or passes around it. When the release is very wide compared to the lateral extent of the feature, the following expressions can be used to

differentiate between when a cloud might flow over the topographical feature rather than around it (Britter and McQuaid, 1988):

If $\frac{U^2}{g'h} \gg 2 \left(\frac{h_c}{h} - 1 \right)$ the flow will pass over the crest of the feature

If $\frac{U^2}{g'h} \ll 2 \left(\frac{h_c}{h} - 1 \right)$ the flow will pass around the crest of the feature

where U is the ambient wind speed, h is the plume or cloud depth and h_c is the height of the crest of the feature.

Prominent ridges and isolated hills may also cause local acceleration of the wind at their tops (McBride et al., 2001). If there is an upslope wind, against the motion of the dense gas cloud, the cloud widens and dilution increases due to the increased shear at the interface between the ambient flow and the dense cloud compared with dispersion over flat terrain. The motion of the dense gas cloud can even be reversed back up the slope when the cloud is sufficiently dilute and the wind speed is high enough, as in the Montana incident (see Section 4.5.22). When the wind is downslope the cloud is typically narrower and the dilution is decreased compared with dispersion over flat terrain (Picknett, 1981). There is little information about the effects of crosswinds on dense gas dispersion down slopes. Hall et al., (1982) suggest that dilution may not be greatly affected.

Low wind and topography

In low wind speeds, topography becomes more important. It has been proposed that slope effects become significant when the aspect ratio of the dense gas release (height / radius) becomes equal to the gradient of the slope, assuming the initial release is axisymmetric (Ross et al., 2002). For both instantaneous and continuous sources released from the top of slopes up to about 1 in 9, ground level concentrations were higher downslope compared with a flat scenario in nil wind (Schatzmann et al., 1991). For instantaneous releases, the differences between the sloping and flat scenarios were greater than for the continuous releases and changes in the slope angle had greater effect.

Several of the incidents in Chapter 4 occurred in low wind speeds with stably-stratified atmospheric conditions where there were significant topographical effects. A notable case was the large instantaneous release of carbon dioxide from the volcanic Lake Nyos in Cameroon. The elevated position of the lake and the narrow valley leading downhill from it caused the dense carbon dioxide to be channelled downhill into an area 20 km long by 15 km wide killing 1700 people and 3500 livestock (see Section 4.5.26).

3.5 Factors affecting Ingress/infiltration

The previous sections have demonstrated that dense gas clouds are characteristically ground hugging and vertically stratified so that higher concentrations are low down, may persist for longer than neutrally buoyant clouds. The negative buoyancy means that when dense gases are released in, or enter a structure such as a building, they are likely to naturally accumulate at the lowest point, and so basements or cellars are particularly vulnerable. Riccardi et al. (2008, see Section 6.5.55) found that for dense gas releases within a ventilated room, stratification always occurred. Conversely, this also means that rooms may have lower concentrations at higher levels.

The following sections review factors that influence ingress of gas into buildings. For a more detailed review, see Hall and Spanton (2012).

3.5.1 Type and location of openings

In building ventilation, leakage paths are often classified as either “purpose provided” or “adventitious” (Etheridge and Sandberg, 1996). Purpose-provided openings are those

installed for ventilation and may include windows and air ducts. They are characterised by having known geometry and dimensions, and therefore more readily determined flow characteristics.

Adventitious openings are all other openings not purpose provided and can be divided into component openings and background openings (Etheridge and Sandberg, 1996). Component openings are defined as the gaps in purpose-provided openings, for example around doors. Background openings are all other openings including porous materials, cable and pipework glands, cracks in walls etc. The main feature of adventitious openings is that their geometry is unknown and they are not easily found by inspection.

The main air leakage paths in UK dwellings are summarised in Table 3 with their percentage contribution to the overall leakage (Johnston et al., 2014).

Table 3 Main leakage paths in UK dwellings and their contribution to the total leakage of the dwelling. From Johnston et al. (2014)

Leakage path	Contribution to leakage (%)
Windows and doors	16
Permanent vents	9
Loft hatches and windows and door surrounds	2
Cracks, gaps and joints in the structure, chimneys and flues and service entries, plasterboard dry-lining, areas of unplastered masonry wall, timber floors, joists penetrating external walls, internal stud walls, skirting boards, ducts and electrical components	71

The location of openings is important when considering ingress. For example, about 40% of the exchange of air for a one-family house takes place at the transition between the walls and the roof (Green Book, 1992). For dense gas clouds where the highest concentrations will be near the ground, this could mean that there is a reasonable chance of cleaner air at higher levels. However, the relationship is not straightforward. It will depend on the interaction of the dense gas cloud with the structure, which depends on factors such as the location of the dense gas cloud in relation to the structure, the density of the cloud, and the atmospheric conditions, see Section 3.4.6 and in particular the work of Hall et al. (1999).

3.5.2 Ventilation systems

Ventilation systems can be split into three types:

- Natural ventilation is when the air within the building changes due to seams and joints in the building and the external atmospheric conditions.
- Mechanical ventilation is when the air change in the building is supplemented by air con or HVAC or other mechanically driven/controlled ventilation systems.
- Intentional ventilation is due to opening windows or doors. (This is often grouped with natural ventilation since the ventilation still occurs naturally but through purpose-provided openings)

Natural and intentional ventilation, and therefore ingress under these systems, depends on the type and location of the vents, discussed in the previous section, and atmospheric conditions, which are discussed in the next section.

Mechanical ventilation is usually controlled by the user, affording some degree of control over potential ingress of contaminants. If a mechanical ventilation system is operational, it may actively draw contaminants into the structure.

3.5.3 Atmospheric conditions

Natural ventilation is dependent on external atmospheric conditions. When the wind impinges on a building, it creates a pressure difference on the outside of the building, compared with the inside, which drives ventilation. Wind speed and direction have a significant effect on infiltration. As the wind speed increases, the ventilation rate increases. The relationship is not linear and depends on various factors such as the shape of the building (BSI, 1991).

Ventilation can also be driven by buoyancy effects in combination with the wind. These might be induced by a temperature differential between the external and internal environments (see Section 3.5.4) but they could also be induced by an external dense gas cloud causing a density differential. Cleaver et al. (2016) found that under typical conditions (i.e. when the wind speed is not low) the ventilation rate, and therefore the gas ingress rate, is dominated by the ambient conditions and the buoyancy of the gas is less important. However, when the wind speed is low (and the atmosphere is relatively stable), the ventilation rate is driven by the buoyancy effects. For an external dense gas cloud, the additional contribution to the buoyancy of the cloud due to the density effects means a potentially higher gas ingress rate than for a passive gas.

3.5.4 Thermal effects

Temperature differences between the inside and outside of a building produce a pressure difference and can induce buoyancy-driven flows through openings and the ingress of contaminants.

Various studies have shown that within a residence the concentration distribution is fairly homogeneous and it has been suggested that this is also true for heavy gases due to convective mixing (Green Book, 1992; Purdy and Davies, 1985). In some of their experiments on carbon dioxide, Cleaver et al., (2016) found that concentrations upstairs were lower than concentrations downstairs. In Jack Rabbit II Sohn et al. (2016) found that indoor concentrations of chlorine within a room were approximately well-mixed but there were concentration differences between rooms. Both Cleaver et al. (2016) and Sohn et al. (2016) found that there was an 'accumulation period', i.e. while the gas was flowing at the structure, during which the internal air was fairly well mixed. After this period, Cleaver et al. (2016) found that in about third of their tests the cloud appeared to preferentially decay from upstairs first. Note that there was HVAC in place in some of the JR II trials, while the Cleaver et al. trials were naturally ventilated. The findings that individual rooms were well-mixed appears to be in contrast to Riccardi et al. (2008) but in that study the dense gas was released from within the room, not externally.

Note that there were no subterranean levels to the structures used in any of the above trials so they could not observe whether the dense gas accumulated preferentially at levels below ground level.

3.5.5 Proximity of structures to the source

In general, the closer the structure is to the source, the higher the internal (and external) concentration. Figure 20 shows the dose that a person might be subjected to based on proximity to the source for a finite duration release of a passive contaminant (Green Book, 1992). The zero point is the source. To the left is the outdoor dose, to the right is the indoor dose. The dose decreases with increased distance from the centre of the cloud. The dose at a certain indoor distance from the source, e.g. B, will be the same at a point outdoors but at a further distance, i.e. A. It follows that the area within which a certain dose is exceeded is higher outdoors than indoors.

There is no equivalent dose curve for dense gases but it can be anticipated that a similar general rule would hold.

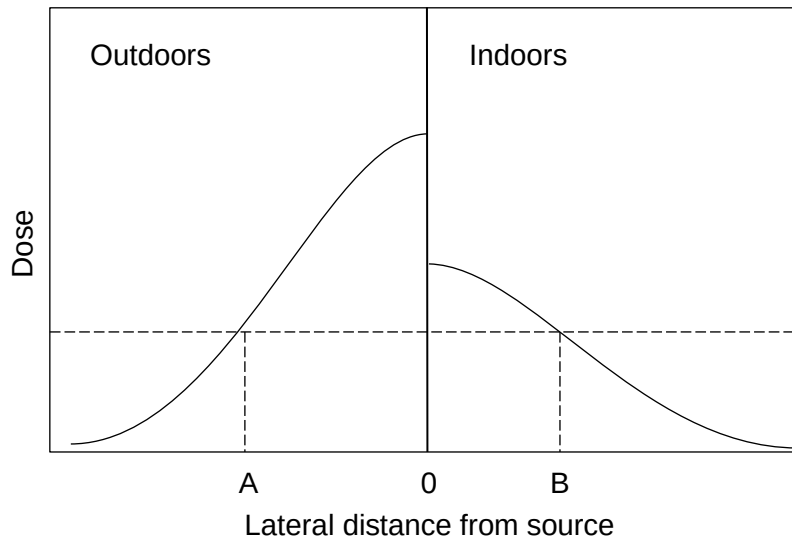


Figure 20 Dose outdoors and dose indoors as a function of distance from the contaminant source for a finite duration release of a passive contaminant. The zero point is the source.

The dose at a certain indoor distance from the source, eg B, will be the same at a point outdoors but at a further distance, i.e. A.

A dense gas cloud that penetrates a house at a substantial distance from the source is likely to be dilute through atmospheric turbulence so that it can be treated as effectively passive (Green Book, 1992).

A case study investigating the effect of distance from the source is presented in Lyons et al. (2015) for a hypothetical carbon dioxide pipeline rupture. The building is located at eight distances from the source from 100 m to 1000 m. Example toxic dose results are presented in Figure 21. It can be seen that occupant exposure is only predicted to remain below the toxic dose endpoints (SLOT and SLOD, see Section 3.6.2) if the building they are in is over 150 m from the source. Although, even if the building was within 150 m of the source then they may remain below these exposure levels for nearly an hour.

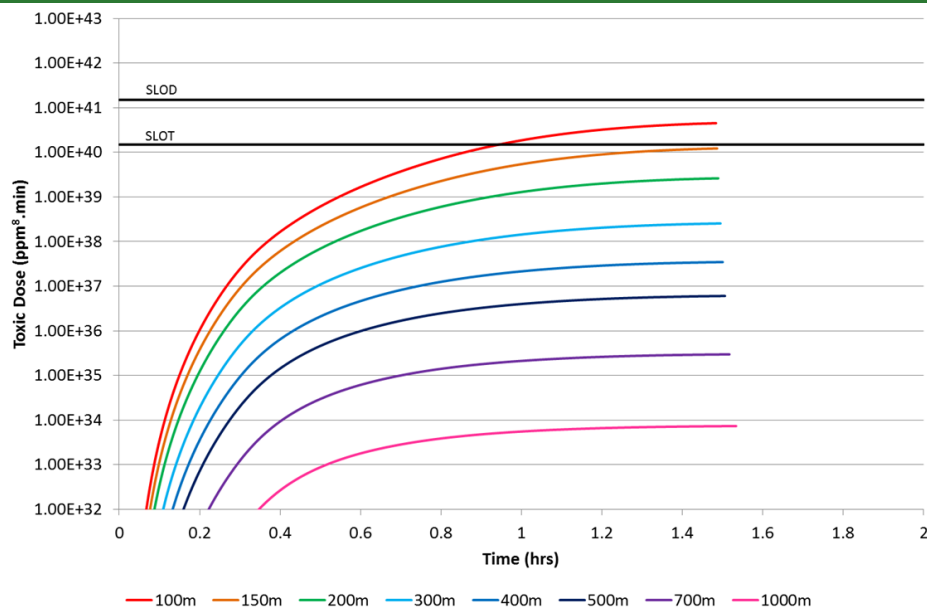


Figure 21 Toxic dose received by a building occupant with time after release, for a building located at distances from the source of 100 m to 1000 m. The SLOT and SLOD dangerous toxic load values are also shown. From Lyons et al. (2015, © IChemE copyright 2015)

3.5.6 Type of structure

The type of structure has significant impact on ingress. Examples are as follows:

- Isolated public dwellings
- Terraced rows
- Industrial units
- Purpose built shelters, eg bunker or temporary refuge
- Vehicles
- Public buildings

Each of these has different features that affect ventilation and ingress dependant on their standard operating procedures. They have different types of openings, different ventilation systems, windows, air conditioning etc, and thermal profiles / heat sources, as discussed above. Much of the information in this section derives from Johnston et al. (2014).

UK dwellings tend to be very leaky in comparison to international counterparts, mainly due to cracks, gaps and joints. The maximum recommended in ADL1A (2016) is $10 \text{ m}^3/\text{hm}^2$ at 50 Pa, which roughly converts to a normalised air change rate of 8.30 ACH @ 50 Pa (normalised using the approach described by Limb, 2001). Maximum normalised leakage rates for some other countries are shown in Table 4. It can be seen that Belgium and Sweden have very low maximum normalised ACH of about 3.00, compared with France which has a maximum of about 11.0 ACH.

Table 4 Maximum normalised leakage rates for several countries in Europe and the US
(Johnston et al. 2014)

Country	Maximum normalised leakage rates (normalised ACH at 50 Pa)
Belgium	3.00
France	11.0
Netherlands	6.50
Norway	4.00
Sweden	2.88
Switzerland	3.30
UK	8.30
USA	8.50

The following should also be considered to affect ingress:

Different shapes and densities

A row of buildings will affect ingress differently to an isolated building. This is primarily due to the interaction of the building and the flow field and the dispersion of the gas. This results in variation in concentration distribution along with variation in pressure distribution on building surfaces, which influences the ventilation rate (Hall and Spanton, 2012). For discussion of the impact of fixed structures on the gas dispersion see Section 3.4.6.

In terms of building height, multi-storey buildings have been found to be generally leakier than single storey buildings with the potential for greater ingress (Johnston et al., 2014).

Size and complexity

Larger and more complex floorplans and construction techniques have a greater number of junctions increasing the potential for air leakage and consequent ingress.

Operating hours / transience

Some buildings are closed at certain times of day and it follows that ingress may reduce.

Mobility

Vehicles are mobile and so exposure and chances of ingress may vary. The motion of vehicles may also affect ingress. Fletcher and Saunders (1994) predicted that a higher air change rate would be achieved for a moving vehicle than for a stationary vehicle. In the Jack Rabbit II trials (Byrnes and Matthew, 2016), it was found that for vehicles within the dispersing chlorine cloud there appeared to be a greater than 10 to 1 ratio from exterior concentrations to interior concentrations.

Purpose of the structure

Within the UK, there is a very large range of air leakage rates across residential buildings. Johnston et al. (2014) indicate that the least airtight dwellings are over 10 times as leaky as the most airtight dwellings with air change rates of 2-3 ACH compared with up to 29-30 ACH.

Public buildings have ventilation rates that are designed to maintain a fresh air supply and comfort level when occupied by a large amount of people. Approximate rates for these structures (in the Netherlands) can be found in Table 5 (Green Book, 1992).

In vehicles, there are several combinations of options available for ventilation, each with a different air change rate. Air change rates for cars can be seen in Table 6 (Park et al., 1998, Byrnes and Matthew, 2016).

Table 5 Ventilation rates for public buildings for comfort when occupied by a large amount of people

Space type	Air changes per hour (ACH)
Restaurants	8-12
Shops	4-8
Warehouses	6-8
Public offices	6
Hospitals	5-10
Covered swimming pools	1-2
Office spaces	5-7
Workshops	3-8
Schools	5-8
Trains	15-40

Table 6 Air change rates associated with different ventilation configurations for cars

Ventilation configuration	Air changes per hour (ACH)
Windows closed, no mechanical ventilation	1.0-3.0
Windows closed, fan set on recirculation	1.8-3.7
Window open, no mechanical ventilation	13.3-26.1
Window closed, the fan set on fresh air	36.2-47.5
Doors open	81-250

Temporary refuges, as found on off-shore installations, are specifically designed for sheltering in place. They are built to a high specification to maintain a low air change rate of 0.25 ACH to prevent ingress of toxic gases, while maintaining sufficient air supply to avoid impairment of the occupants.

With respect to dense gases, the purpose of a structure may be of particular relevance to ingress. Structures with more openings low down, or larger openings low down are perhaps at greater risk, for example subways, tunnels, underground car parks and buildings with features such as basements or cellars.

Site supervision and workmanship during construction work

Measurements have shown that nominally the same building design/construction on a site can result in essentially identical dwellings with different leakage rates and therefore, potentially different levels of ingress during a contaminant release (Johnston et al., 2014).

Age of structure

Generally speaking an older structure can be expected to have more holes or run less efficiently (HVAC/air conditioning) consequently having increased potential for ingress. Adventitious openings tend to appear as a result of degradation as the structure ages. Some of these, for example door seals and cable glands, are easily remedied through replacement. Openings due to structural movement may be more difficult to detect.

Despite these observations, there is data to suggest that the airtightness of new dwellings in the UK did not improve significantly over the century up to 2002 (Johnston et al., 2014).

Park et al. (1998) found that the air change rate for cars for the case with windows closed and no ventilation were higher for older models than for the newer models.

Construction materials

There are typical construction materials and techniques for buildings with different types of building favouring specific construction methods. The construction type can double the mean permeability of a building.

Typical construction methods for detached dwellings mean that they have the highest permeability values, compared with apartments, terraces and semi-detached dwellings (Johnston et al., 2014).

3.5.7 Persistence and exfiltration

Persistence of the gas inside the structure after ingress has occurred is also a factor that will impact on the dispersion. As with the ingress itself, it will depend on the ventilation. After the main toxic cloud has passed, relatively high concentrations may persist indoors and it will be necessary ventilate buildings appropriately. The impact of opening windows and doors on the ventilation rate can be seen in Table 7.

Table 7 Ventilation rates dependent on state of windows and doors in a dwelling (Green Book, 1992)

State of windows/doors	Ventilation rate (per hour)
Windows and doors closed	0-0.5
Windows ajar	0.8-4.0
Windows half open	5-10
Windows fully open	9-15
Windows and doors open against each other	40

In their experiments on carbon dioxide, Cleaver et al. (2016) found evidence that dense gases preferentially dispersed from upstairs levels of structures first and therefore persisted for longer downstairs. In the carbon dioxide incident in Mönchengladbach, Germany (see Section 4.5.26), the gas persisted for longer in lower levels and basements, in some cases requiring fans to ventilate it. This incident is also an example of where the contaminant gas was released inside of the building and escaped, resulting in a source due to exfiltration from a structure.

Another context in which persistence and egress could be an issue is releases in semi-confined spaces such as tunnels. A study on dense gas releases in road tunnels, which includes consideration of ventilation, tunnel slope and the presence of vehicles, can be found in Hall (2001).

3.6 Flammable and toxic end points and limits of exposure

One of the key requirements for any dispersion calculation is the provision of end points and limits from which the hazard can be quantified, for example, as zones shown on a map. For flammable materials, these end points are usually based on the flammability limits of the substance. For toxic substances, the end points are usually related to human physiology and the duration of exposure. Some substances, such as ammonia, may be both toxic and flammable, and therefore both criteria may be important.

End points and limits on gas dispersion are typically derived from predictions of concentration at points, the distances to specified concentrations, the volume, or mass, of clouds above a stated concentration and duration of exposure (for toxic clouds). They are specified for all gases, not just dense gases. Concentration limits for flammability are usually higher than those for toxic exposure (usually expressed in terms of percent by volume instead of parts per million). This usually means that distances to specific endpoints are shorter for flammable releases than for toxic releases.

Different flammable and toxic end points are summarised in sections 3.6.1 and 3.6.2, respectively.

3.6.1 Flammable end points

Flammability limits are determined by the physical properties of a pure gas or a mixture of gases. They can be measured experimentally under controlled conditions.

Lower Flammability Limit (LFL)

The LFL of a flammable gas is the lowest concentration of gas in air at which ignition can occur. Some examples of LFL for some substances in air at atmospheric pressure are given in Table 8, further values can be found in DiNenno et al. (2002).

Table 8 LFL (vol %) for substances in air at atmospheric pressure

Substance	LFL (vol %)
Ammonia	15
Butane	1.8
Ethylene	2.7
Hydrogen	4.0
Hydrogen Sulphide	4.0
Propane	2.1
Vinyl Chloride	3.6

When a flammable gas is released and disperses, the concentration within the gas cloud will vary both in space and time. The instantaneous concentration can be above the LFL, while the average concentration may be below it. In a review of experimental data and modelling, Webber (2002) concluded that a value of 50% LFL should be used to indicate the possibility of ignition in safety analyses. Models typically predict a mean concentration and validation studies have shown that even good models might only predict mean concentrations to within a factor of two of the measured values.

In some applications, a lower concentration threshold is used. For example, 10% LFL is the maximum concentration of hydrocarbon gas allowed within a helicopter operating area (CAA, 2016).

For gas detector networks, the concentration levels at which a network is expected to alarm or action will be a fraction of the LFL. The exact values will depend on the installation (Walsh and Kelsey, 2017).

3.6.2 Toxic end points and exposure durations

The toxic end points for a substance depend on the human response or uptake into the body, which is a function of the concentration of the chemical and the duration of exposure. Acute exposure results from a single accidental exposure to a high dose during a short time, which may produce biological effects within a short time after the event. Chronic exposure results from long term overexposure where the effects may not be apparent for years. Exposure can also be described as occupational, workplace or accidental exposure and ambient exposure, i.e. air quality and pollution. The concentrations associated with air quality and pollution in the atmosphere are low compared to accidental exposure but the duration of exposure can be long.

Occupational Exposure Limits (OELs)

Occupational exposure limits have been developed for planned workplace activities to avoid ill health in workers by controlling their exposure to hazardous substances while under

normal conditions in the workplace. Maximum average concentrations are specified for different durations of exposure. Common values are short-term exposure limits (STELs), which are usually 15 minutes duration, time-weighted average (TWA) exposures over an eight hour day (also called long term exposure limits or LTELs) or a 40 hour week, and threshold limit values (TLVs) for a lifetime occupational exposure. Ceiling values are also defined which are limits that should not be exceeded at any time.

The limits apply to airborne exposure to gases, vapours and particulates by inhalation and skin contact (and injection and swallowing but these are not relevant here). The exact values differ depending on the country and each country publishes its values³⁸, although the US limits are often adopted. In the UK, the above values are referred to as Workplace Exposure Limits (WELs³⁹) and are published by HSE (2020). In the US, there are different values for each limit for Recommended Exposure Limits (RELs) and Permissible Exposure Limits (PELs) set by National Institute of Occupational Safety and Health (NIOSH) and Occupational Health and Standards Agency (OSHA), respectively.

Immediately Dangerous to Life or Health (IDLH)

In the US, NIOSH also publishes another type of workplace exposure limit in the form of substance concentration values that are Immediately Dangerous to Life or Health (IDLH⁴⁰). IDLH exposure conditions are those that result in an immediate threat to life or health. They also cover conditions that result in immediate threat of severe exposure to contaminants, including radioactive materials, which are likely to have adverse cumulative or delayed effects on health.

The values associated with IDLH constitute the airborne concentration from which a worker could escape without injury or irreversible health effects should their respiratory protection equipment fail under the above exposure conditions. The IDLH value is designed as a maximum concentration above which only breathing apparatus providing maximum protection to the user should be used.

Public exposure guidelines and emergency exposure Limits

Public exposure guidelines are usually intended for use by emergency planners and responders to predict how members of the public would be affected if they are exposed to a particular hazardous chemical in an emergency response situation. In other words, they provide an estimate of the severity of the hazard.

The concentrations that occur during unplanned releases of substances can be much higher than those during normal operation. In these situations acute consequences, including death, must be considered. Under the UK Land Use Planning and COMAH regulations (see Chapter 2), the Dangerous Toxic Loads (DTLs⁴¹) associated with hazardous substances stored on sites are calculated for industrial facilities.

A DTL is a measure of a particular level of toxicity in the general population based on airborne concentration and duration of exposure. HSE uses two DTL values:

- The Specified Level of Toxicity (SLOT) is the level of toxicity, or DTL, that causes severe distress to almost all of the population in the vicinity, causes a substantial fraction of the exposed population to require medical attention, causes serious injury requiring prolonged treatment, and/or causes death to highly susceptible people.
- The Significant Likelihood of Death SLOD is the level of toxicity relating to the mortality of 50% of an exposed population.

³⁸ https://www.ilo.org/safework/info/publications/WCMS_151534/lang-en/index.htm Accessed on 12th February 2020

³⁹ <https://www.hse.gov.uk/coshh/basics/exposurelimits.htm> Accessed on 12th February 2020

⁴⁰ <https://www.cdc.gov/niosh/idlh/default.html> Accessed on 12th February 2020

⁴¹ <http://www.hse.gov.uk/chemicals/haztox.htm> Accessed on 13th February 2020

Further information on the SLOT and SLOD concepts is provided by Fairhurst and Turner (1993) and Franks et al. (1996). Reference values for SLOT and SLOD DTLs for some substances are shown in Table 9. Further explanation and a complete list are available from HSE⁴².

Table 9 Examples of SLOT and SLOD DTL values

Substance	SLOT DTL (ppm ⁿ .min)	SLOD DTL (ppm ⁿ .min)	n
Ammonia	3.78×10 ⁸	1.03×10 ⁹	2
Bromine	2.5×10 ⁵	8.67×10 ⁵	2
Carbon dioxide	1.5×10 ⁴⁰	1.5×10 ⁴¹	8
Chlorine	1.08×10 ⁵	4.84×10 ⁵	2
Hydrogen Sulphide	2×10 ¹²	1.5×10 ¹³	4
Vinyl Chloride	3.39×10 ⁶	1.36×10 ⁷	1

Models are used to predict concentrations from which toxic loads are calculated and DTLs can be presented as contours on maps. When used in combination, a pragmatic approach considers the number of people estimated to be between the SLOD and SLOT DTL contours as the approximate number of people injured by the release⁴³.

HSE's guidance notes that when estimating the numbers of people affected by a release, some of them will be indoors. There are models that can determine the outdoor concentration required to give an indoor SLOT or SLOD DTL (Davies and Purdy, 1986). Consequently, this (usually higher) outdoor concentration can be used to define the hazard range for people indoors.

There are limitations to the SLOT/SLOD DTL modelling approach. There are difficulties extrapolating animal data to humans, lack of relevant toxicity data, the use of animal data of poor or unknown quality, and there are uncertainties about the universal applicability of the concept used to calculate DTLs. The current approach is considered the best that can be achieved with the available data and current state of scientific knowledge.

In the US, the most commonly used public exposure guidelines are Acute Exposure Guideline Levels (AEGLs), Emergency Response Planning Guidelines (ERPGs) and Temporary Emergency Exposure Limits (TEELs), which are collectively known as Protective Action Criteria (PACs⁴⁴). The UK uses AEGLs to assess the severity of the impact of an exposure to a chemical release on public health.

Acute Exposure Guideline Levels (AEGLs⁴⁵)

Acute exposure guideline levels (AEGLs) are used by emergency responders when dealing with chemical spills or other catastrophic exposures and describe the human health effects from once-in-a-lifetime, or rare, exposure to airborne chemicals. They are specifically aimed at protecting individuals in society who may be more susceptible to an acute exposure.

There are three AEGL levels according to the severity of effects from exposure, as follows:

- Level 1: Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure

⁴² <http://www.hse.gov.uk/chemicals/haztox.htm> Accessed on 13th February 2020

⁴³ <http://www.hse.gov.uk/chemicals/haztox.htm> Accessed on 13th February 2020

⁴⁴ <https://edms.energy.gov/pac/> Accessed on 9th June 2021

⁴⁵ <https://www.epa.gov/aeql/about-acute-exposure-guideline-levels-aeqls> Accessed on 13th February 2020

- Level 2: Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape
- Level 3: Life-threatening health effects or death

For a released substance, each level has equivalent minimum concentrations provided in parts per million (ppm), or milligrams per cubic metre (mg/m³), above which it is predicted that the general population could experience the symptoms associated with that level. There are five values calculated for each level deriving from five exposure periods: 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours. An example is shown for chlorine in Table 10.

Table 10 AEGL levels for chlorine (in ppm)

	10 min	30 min	60 min	4 hour	8 hour
AEGL 1	0.5	0.5	0.5	0.5	0.5
AEGL 2	2.8	2.8	2.0	1.0	0.71
AEGL 3	50	28	20	10	7.1

AEGLs are set through a collaborative effort of the public and private sectors across the international community and have formal development standards. As a result of this consensus, they are considered a consistent set of values used worldwide.

Emergency Response Planning Guidelines (ERPGs⁴⁶)

In the US, the Emergency Response Planning Committee of the American Industrial Hygiene Association (AIHA) develops ERPGs for responding to potential single short-term exposures to airborne substances when AEGLs are not available.

ERPGs are estimates of the concentrations at which most people will begin to experience health effects if they are exposed to a hazardous airborne chemical for 1 hour. They are designed for use in community emergency planning and during emergency response to assist in evaluating potential health effects on the general public and emergency response personnel. Note that sensitive members of the public, such as the elderly, sick, or very young, are not covered by these guidelines and may experience adverse effects at concentrations below the ERPG values.

There are three ERPG levels according to the severity of effects from exposure of up to 1 hour, as follows:

- ERPG-1: The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing more than mild, transient adverse health effects or without perceiving a clearly defined objectionable odour.
- ERPG-2: The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action.
- ERPG-3: The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects.

There are about 150 chemicals with ERPGs, an example for chlorine is given in Table 11.

⁴⁶ <https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/emergency-response-planning-guidelines-erpgs.html> Accessed 13/2/20

Table 11 ERPG concentration levels for chlorine

	Concentration (ppm)
ERPG 1	1
ERPG 2	3
ERPG 3	20

For each chemical, the ERPG identifies the substance's chemical and structural properties, animal toxicology data, human experience, existing exposure guidelines, the rationale behind the selected ERPG value, and a list of references. The AIHA strongly advises against extrapolating ERPG values to longer periods of time.

Temporary Emergency Exposure Limits (TEELs⁴⁷)

The US Department of Energy (DOE) defines Temporary Emergency Exposure Limits (TEELs) as guidelines to predict the concentrations at which most people will begin to experience health effects if they are exposed to a hazardous airborne chemical for a given duration. TEELs should only be used when AEGLs or ERPGs are not available. Like AEGLs and ERPGs there are three levels, as follows:

- TEEL-3 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, when exposed for more than 1 hour, could experience life-threatening adverse health effects or death.
- TEEL-2 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, when exposed for more than 1 hour, could experience irreversible or other serious, long-lasting, adverse health effects or an impaired ability to escape.
- TEEL-1 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, when exposed for more than 1 hour, could experience notable discomfort, irritation, or certain asymptomatic, non-sensory effects. However, these effects are not disabling and are transient and reversible upon cessation of exposure.

There are about 3000 chemicals with TEELs.

3.7 Substance information sources

All substances have a unique Chemical Abstracts Service (CAS) number that can be used to look up substance information in a variety of resources, some of which are given below. Many of these resources prove useful for identifying whether a released substance is a dense gas and conditions or reactions under which the substance could result in a dense gas release. Several of the resources below also cover aspects such as potential mitigation measures and emergency response information.

A wide range of substance information, for most commonly available substances, is collated on the US National Institutes of Health (NIH)'s National Library of Medicine PubChem website⁴⁸. For each substance, information is compiled including physical characteristics, AEGLs, packaging guidance and emergency response approaches. All of the information from various referenced sources is given and is not consolidated to provide one set of information. The US NIH also supply the Wireless Information System for Emergency Responders (WISER⁴⁹) which is designed to assist emergency responders during hazardous

⁴⁷ <https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/temporary-emergency-exposure-limits-teels.html> Accessed on 13/2/20

⁴⁸ <https://pubchem.ncbi.nlm.nih.gov/> Accessed 5th March 2020

⁴⁹ <https://wiser.nlm.nih.gov/> Accessed 5th March 2020

material incidents. WISER provides a wide range of information on hazardous substances, including substance identification support, physical characteristics, human health information, containment and suppression advice.

The ILO and World Health Organisation produce International Chemical Safety Cards (ICSCs⁵⁰) for a wide range of substances in a standardised format aimed at use in the workplace.

In the UK, Public Health England provides a 'Chemical Hazards Compendium' resource, available on the government website⁵¹, to assist in response to chemical incidents. They are aimed at the public, emergency services and public health professionals and include general information about the chemical, a toxicological overview and information for incident management.

The International Programme on Chemical Safety (IPCS) and the Canadian Centre for Occupational Health and Safety (CCOHS) provide Internationally Peer Reviewed Chemical Safety Information (INCHEM⁵²), generated by consolidating current, internationally peer-reviewed chemical safety-related publications and database records from international bodies. It is designed to provide quick and easy electronic public access to thousands of searchable full-text documents on chemical risks and the sound management of chemicals.

CAMEO is a database⁵³ of hazardous materials provided by the US National Oceanic and Atmospheric Administration (NOAA). It includes emergency response information for chemicals and has a facility to build a bespoke collection of chemicals, for example substances involved in an incident. It has a 'reactivity' function to determine the hazards that might result if these chemicals mixed together.

Chemdata is a chemical hazard database provided by the UK's National Chemical Emergency Centre (NCEC)⁵⁴. It has been constructed for use on a variety of platforms and in several languages. It is designed to provide information that is written in non-technical language for use by emergency responders in the event of chemical spillages, fires and contamination incidents. For example, it can provide advice regarding personal protective equipment, precautions and decontamination for even very small spills of less than 1 litre.

The NIOSH Centre for Disease Control and Prevention (CDC) website⁵⁵ contains information for the emergency response community on chemical, biological and radiological agents that could be encountered by personnel responding to a terrorist threat.

⁵⁰ <https://www.ilo.org/dyn/icsc/showcard.home> Accessed 5th March 2020

⁵¹ <https://www.gov.uk/government/collections/chemical-hazards-compendium> Accessed 5th March 2020

⁵² <http://www.inchem.org/#/search> Accessed 5th March 2020

⁵³ <https://cameochemicals.noaa.gov/> Accessed 5th March 2020

⁵⁴ <https://the-ncec.com/en/emergency-response/chemdata-database> Accessed 10th February 2021

⁵⁵ <https://www.cdc.gov/niosh/ersbdb/> Accessed 5th March 2020

4 DENSE GAS DISPERSION INCIDENTS

4.1 Introduction

Analysis of previous incidents is crucial for learning both in terms of physical processes associated with modes of release and in terms of lessons learned for industrial regulation and emergency response. Incidents can also motivate experimental studies. If detailed information exists for an incident, it can be used for assessing the accuracy of models in a more realistic context than experimental studies. However, incident information is not often of high enough quality to be of use in model validation exercises.

This chapter summarises relevant incident information from various sources:

- Incident reporting systems and databases. There are several of these available and they vary in their availability and the amount of detail provided (see review below). They are often a good source of quick reference summary information.
- Review documents. There are various review documents collating incidents on a common theme, a specific physical phenomena or context. Some examples are given below.
- Incident-specific information. Incident reports, papers and media articles all provide sources of information on an incident. A collection of incident-specific summaries is given below for a range of contexts, release modes, substances and implications.

There are many incidents involving dense gases and the list included here is not exhaustive. Also, the high-level nature of this review means that the individual incidents have not been investigated in great detail here. In a few of the incidents, the dense gas cloud probably did not remain dense for very long before becoming effectively passive. These cases are included because it is useful to consider examples where transition has occurred.

4.2 Incident databases / reporting systems

A selection of databases and reporting systems for obtaining incident information are listed below. The usefulness of these resources will depend on the context. For example, whether it is important to know the site of the incident, or whether anonymous information is acceptable; whether transport incidents are of interest, or major chemical plant incidents, or smaller toxic/health-related incidents. Systems which are based on mandatory reporting of major accidents, such as eMARS, are potentially more likely to be up to date, compared with research-based resource such as MInA and PUPAD. On the other hand, the latter may draw on multiple sources and may provide more in depth information and analysis on particular topics.

4.2.1 eMARS

The European Major Accident Reporting System (eMARS) contains reports provided to the Major Accident and Hazards Bureau (MAHB) of the European Commission's Joint Research Centre from EU, OECD and UNECE countries (under the TEIA Convention). It was set up to facilitate the exchange of information relating to accidents and near misses involving dangerous substances in order to improve prevention and mitigation of chemical accidents. Reporting an event into eMARS is compulsory for EU Member States when a Seveso establishment is involved and the event meets the criteria of a "major accident" as defined by Annex VI of the Seveso III Directive (2012/18/EU). For non-EU OECD and UNECE countries reporting accidents to the eMARS database is voluntary.

The anonymised database is available on the European Commission website⁵⁶ along with high level statistical analyses of the database contents.

4.2.2 MHIDAS

The Major Hazards Incident Data Service (MHIDAS) is a database of incidents involving hazardous materials compiled by HSE. It was superseded by eMARS and is no longer updated.

4.2.3 MAIB

The UK government Marine Accident Investigation Branch (MAIB) includes investigation reports and safety bulletins, including incidents. Reports are publically available online⁵⁷.

4.2.4 IChemE

The British Institution of Chemical Engineers (IChemE) publishes a Loss Prevention Bulletin, which provides a means for the process industries to share information on accidents and lesson learned. It was first published in 1974 so there is over 40 years of experience documented. It is only available by subscription from the IChemE website⁵⁸.

4.2.5 ARIA

The ARIA database is a collection of technological accidents operated by BARPI (the French Office of Risk and Industrial Pollution Analysis). It includes accidents that could impact public safety or health and agriculture, nature and the environment. A description of the database and a search engine can be found on the website⁵⁹.

4.2.6 INRS EPICEA

The French national research institute for safety (INRS) hosts the EPICEA database of workplace accidents dating back to 1990. There are over 17,000 accidents included in the database. It is available online⁶⁰ in an extracted, anonymised form of the full, non-public version. The aim of the database is to share knowledge obtained from analysing work-related accidents. The accounts provided describe the causes and course of a specific type of accident without seeking to establish liability.

4.2.7 ZEMA

ZEMA is the German federal database for recording reportable major accidents under the Major Accident Ordinance. The most serious incidents, i.e. those involving loss of life, injuries, large-scale contamination of the environment or substantial damage to property are reported to the EU MARS database.

The database is owned by BAM and Umweltbundesamt, Germany, but does not appear to be readily accessible. ZEMA entries are in German.

4.2.8 PROCESSNET

PROCESSNET is an initiative of Dechema and VDI-GVC. The database is a compilation of events occurring in the German chemical industries, which are not reportable under the regulations. The events are voluntarily submitted and then anonymised for inclusion in the

⁵⁶ <https://emars.jrc.ec.europa.eu/en/emars/content> Accessed on 23rd February 2021

⁵⁷ <https://www.gov.uk/maib-reports> Accessed on 24th April 2020

⁵⁸ <https://www.icheme.org/lpb> Accessed on 24th April 2020

⁵⁹ <https://www.aria.developpement-durable.gouv.fr/the-barpi/the-aria-database/?lang=en> Accessed on 24th April 2020

⁶⁰ <http://www.inrs.fr/accueil/produits/bdd/epicea.html> Accessed on 24th April 2020

database and any subsequent analysis. The database is available to the public on the PROCESSNET website⁶¹.

4.2.9 FACTS

The Failure and Accidents Technical information System (FACTS) database was developed by TNO as an accident database. It contains information from more than 25,700 industrial incidents involving hazardous materials or dangerous goods that have occurred worldwide in the last 90 years. It is available online⁶². The search facility is publically available but full database entries are only available to subscribers.

4.2.10 MInA

The Major Industrial Accident (MInA) database is a compilation of 319 major accidents specifically chosen based on a set of criteria that allow them to be analysed and compared consistently. As of 2012, the database contained accidents from 1917 to 2011, which met the required criteria. Details can be found in Mihailidou et al. (2012).

4.2.11 CSB

The US Chemical Safety Board (CSB) is an independent, non-regulatory US federal government agency that investigates the causes of major chemical incidents. They publish selected chemical plant and refinery incidents dating back to 1998 online⁶³. The CSB also releases useful reconstructions/animations of some incidents⁶⁴.

4.2.12 NTSB

The US National Transportation Safety Board (NTSB) is an independent US federal government agency. It provides hazardous materials accident reports for rail, road, pipeline, marine and aviation accidents, which are available on its website⁶⁵.

4.2.13 PHMSA

The US Pipelines and Hazardous Materials Safety Administration (PHMSA) require written reports as part of the hazardous materials regulations. The information in the reports is used by PHMSA and other agencies for the purposes of mitigating risk, analysing knowledge gaps and improving safety. Statistical summaries and a search engine for reports are available from the PHMSA website⁶⁶.

4.2.14 OSHA

The US Occupational Safety and Health Administration (OSHA) provides fatality and catastrophe investigation summaries, which are available in a search facility on their website⁶⁷. There are a wide range of incidents reported, resulting from a variety of causes and at all scales, i.e. not only major accidents resulting from hazardous material releases.

4.2.15 CCPS

The Centre for Chemical Process Safety (CCPS) of the American Institute of chemical Engineers (AIChE) hosts the Process Safety Incident Database (PSID). PSID is available

⁶¹ https://processnet.org/en/incident_db.html Accessed on 24th April 2020

⁶² <http://www.factsonline.nl/> Accessed on 24th April 2020

⁶³ <https://www.csb.gov/investigations/> Accessed on 24th April 2020

⁶⁴ https://www.youtube.com/channel/UCXIkr0SRTnZO4_QpZozvCCA Accessed on 24th April 2020

⁶⁵ <https://www.nts.gov/investigations/AccidentReports/Pages/AccidentReports.aspx> Accessed on 24th April 2020

⁶⁶ <https://www.phmsa.dot.gov/hazmat-program-management-data-and-statistics/data-operations/incident-statistics> Accessed on 24th April 2020

⁶⁷ <https://www.osha.gov/pls/imis/accidentsearch.html> Accessed on 24th April 2020

online⁶⁸. It is designed so that participating companies can log any incidents and share incident information. PSID is available to non-governmental and non-regulatory CCPS member companies for free. The anonymity of organisations submitting incident data is protected.

The CCPS also publishes the CCPS Process Safety Beacon. The Beacon is a monthly one page newsletter covering various process safety topics, available online⁶⁹. It is aimed at delivering process safety messages to plant operators and other manufacturing personnel. Each issue presents a real-life accident, and describes the lessons learned and practical means to prevent a similar accidents occurring.

4.2.16 NTSIP / HSEES

The National Toxic Substances Incidents Program (NTSIP) was run by the US Agency for Toxic Substances and Disease Registry (ATSDR). From 2010 to 2014, NTSIP collated and analysed information from nine US states and other resources with the purpose of providing information to protect people from harm caused by unplanned releases of toxic substances. In particular, releases that resulted in a public health action, such as an evacuation.

The NTSIP superseded the Hazardous Substances Emergency Events Surveillance (HSEES) system. NTSIP itself has now been retired and an overall summary of the program can be found online⁷⁰.

Reported data is still available on the ATSDR website⁷¹ in various forms, including spreadsheets of data and reports. The data has been assimilated to provide statistics on characteristics such as chemicals involved in the largest number of incidents; specific details of incidents such as time of year; injuries categorised by various attributes such as public or employee, age, gender, PPE; cases where emergency response was required and where methods such as evacuation or shelter in place were implemented; and types and proportion of industries involved in incidents.

4.2.17 DGAIS

The Canadian Transportation of Dangerous Goods Directorate administers an accident reporting requirement made law under the Transportation of Dangerous Goods Regulations. The reports are collated in a system called the Dangerous Goods Accident Information System (DGAIS).

Statistics Canada undertake analyses of the database to provide summary information for annual comparisons. For example, analyses of the number of dangerous goods commodities involving reportable accidents are grouped by variables such as class, release location, damage type, containment type, emergency response personnel, phase of transport, accident type, action type and contributing factors⁷². The analyses show useful statistics, such as the annual number of 'human factors' contributing to incidents.

Details of individual incidents do not appear to be readily available through DGAIS, although independent analysis of DGAIS was undertaken by Bonvicini and Spandoni (2005) implying that the information may be available on request.

4.2.18 PUPAD

The Pondicherry University Process-Industry Accident Database (PUPAD) is an open source database developed with the objective of assisting with past accident analysis.

⁶⁸ <http://www.psidnet.com/> Accessed on 24th April 2020

⁶⁹ <https://www.aiche.org/ccps/resources/process-safety-beacon> Accessed on 24th April 2020

⁷⁰ https://www.cdc.gov/mmwr/volumes/69/ss/ss6902a1.htm?s_cid=ss6902a1_w Accessed on 24th April 2020

⁷¹ <https://www.atsdr.cdc.gov/ntsip/reports.html> Accessed on 24th April 2020

⁷² <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810025601> Accessed on 24th April 2020

The database contains over 8,000 accidents and includes a search engine with a user interface. The accident information is compiled from research of literature and other media and the use of existing databases, such as FACTS and eMARS. A description of the database, its format and sources can be found in Tauseef et al. (2011a).

4.2.19 JST

The Japan Science and Technology (JST) Agency Failure Knowledge Database is a collection of worldwide incidents covering a wide range of contexts from chemistry to food and IT. It is available online⁷³ in English.

4.2.20 RISCAD

The Relational Information System Chemical Accidents Database (RISCAD) is maintained by the Japanese National Institute of Advanced Industrial Science and Technology (AIST). It is a chemical disaster database including explosions, fires, gas releases and other chemical plant related incidents.

RISCAD is available from the AIST website⁷⁴ but was not accessible at the time of writing due to updating.

4.2.21 Other

There are several sources of accident data for offshore installations, which are not listed here. Details of HSE's Offshore Hydrocarbon Release Database, which records all significant releases from oil and gas facilities on the UK continental shelf, are available on HSE's website⁷⁵. Spouge (1999) gives a comprehensive guide to quantitative risk assessment for offshore installations, which also includes sources of accident data. Appendix II of Spouge (1999) identifies relevant collections of accident reports and databases and Appendix III contains descriptions of some specific accidents.

4.3 Existing incident reviews

No incident review documents have been found that focus solely on incidents involving dense gas dispersion. There are several studies looking at major hazards in general, examining features such as costs, fatalities, causes, types of facility and locations. They often split incidents into toxic releases, fires and explosions. Alternatively, there are reviews of specific substances which are known to exhibit dense-gas dispersion behaviour. The implications of density effects in an incident are often only found by reviewing details of the incident report, if this is available. The following sections summarise several incident review documents to provide an overview of the information they present.

4.3.1 Marsh

Marsh's "100 Largest Losses in the Hydrocarbon Industry" is a summary of the 100 largest property damage losses from the hydrocarbon extraction, transport, and processing industries, published every two years. The latest report by Marsh (2020) covered 1974 to 2019. It reviewed the industry's history to identify key issues and trends from large losses, and to understand whether the industry is making progress. Lessons learned from the root causes of events and emergency response are discussed. A short summary of each of the 100 incidents is included.

⁷³ <http://www.sozogaku.com/fkd/en/index.html> Accessed on 24th April 2020

⁷⁴ <https://www.aist-riss.jp/software/42553/> Accessed on 24th April 2020

⁷⁵ <https://www.hse.gov.uk/offshore/statistics/index.htm> Accessed on 7th December 2020.

The information in the report comes from analysis of Marsh JLT Specialty's proprietary energy-loss database, which includes information gathered from the hydrocarbon industry, and from public records. The information includes almost 10,000 individual loss records.

4.3.2 Atkinson et al. (2017)

Atkinson et al. (2017) provided an in-depth review of historical vapour cloud explosion incidents at Jaipur, Buncefield, Amuay refinery, Flixborough, San Juan (Puerto Rico), Brenham (Texas), Ufa, Port Hudson, Newark (New Jersey), St Herblain, Naples, Baton Rouge (Louisiana), La Mede, Norco (Louisiana), Pasadena (Texas), Skikda (Algeria) and LPG pipeline and storage incidents. The study includes discussion and evidence for the formation and dispersion of the vapour clouds and, in particular, the effects of nil wind.

A media package for the incidents was put together as part of the work and is available from HSE's Science and Research Centre, Buxton.

4.3.3 Lees' Loss Prevention in the Process Industries

The three-volume book by Mannan (2012) is a significant resource for many aspects of hazardous substance releases in the process industries. It includes discussion on typical release physics, models, experiments and incidents.

Appendix 1 "Case Histories" (Volume 3) is useful as a source of information for summaries of major accidents in the process industries between 1911 and 2009. There are nearly 600 accidents listed typically providing dates, locations, context, chemical event, number of deaths/injuries, cost and references. In addition, there are over 150 more detailed short summaries of major events. There are several other appendices covering incidents that have provoked significant changes in regulations, such as Seveso.

4.3.4 Mihailidou et al. (2012)

Mihailidou et al. (2012) analysed 319 accidents that are included in the MInA database. Results of their analyses include worldwide incident rates by country, causes of major accidents, size of accidents and cost.

They observed that the number of industrial accidents was generally decreasing and there were more industrial accidents in developed countries than developing countries, but the number of deaths and injuries was considerably less.

4.3.5 Danielsson et al. (2009)

Danielsson et al. (2009) undertook a review on behalf of the OECD aimed at occupational health and safety related to hydrogen sulphide. The main focus was on incidents in the geothermal industries, but those in the chemical industries were also discussed.

There were observations about common factors associated with hydrogen sulphide incidents and general conclusions for chemical accident prevention, preparedness and response relevant to hydrogen sulphide.

The annexes of the review include summaries from selected hydrogen sulphide incidents from the ARIA and ZEMA databases and from other sources.

4.3.6 Hanna et al. (2008)

Hanna et al. (2008) reviewed three railcar incidents involving chlorine at Festus (Missouri), Macdona (Texas) and Graniteville (South Carolina). The paper presents a particularly useful table summarising each of the incidents in terms of inputs for a modelling exercise.

4.3.7 Khan and Abbasi (1999)

Khan and Abbasi (1999) reviewed major accidents in the chemical process industries that occurred between 1926 and 1997. The aim of the review was to understand the damage potential of different types of accidents in fixed installations and transport. There are useful tables related to the causes of incidents, locations (on site) and contributing factors along with tables listing incidents themselves, the chemical and the type of incident (fire, explosion, toxic release). Several incidents are discussed in more detail to illustrate particular points.

4.3.8 Ferner (1993)

Ferner (1993) reviewed toxic chemical disasters and discussed medical involvement in mitigation. The study included a brief description of 15 incidents resulting from dispersing gases and their main references. Also included are references for toxic chemical incidents due to contamination of food or water.

4.4 UK incidents involving dispersion of dense gases

4.4.1 Flixborough

In June 1974, an incident occurred at an industrial facility in Flixborough, UK. An inadequate bypass pipe had been fitted while a reactor was removed from a series of six reactors. The bypass pipe failed and 30 tonnes of super-heated cyclohexane was released at high pressure from the two resulting 20 inch (0.51 m) orifices. The combination of vapour and fine droplets from the jets and the entrainment of air would have resulted in the formation of a dense gas cloud around the release.

The site was approximately flat and it was estimated that the eventual cloud area was approximately 60,000 m² with average cloud depth of 3-4 m and deeper than 15 m near the source. It was suspected that a deflagration to detonation transition (DDT) occurred. 28 people were killed and there were 36 injuries on the site, there were no fatalities off-site but 53 people were recorded as casualties and there were many others with minor injuries. There was property damage up to 4.5 km away including houses, shops and factories.

Further information can be found in HSE (1975) and Mannan (2012). The incident has been modelled using FDS and a summary of this can also be found in Mannan (2012).

4.4.2 Wealdstone

On 20th November 1980, propane was released through a leak in a drainage valve of a storage vessel in the factory yard of Whitefriars Glass Ltd at Wealdstone, Middlesex, UK. The storage vessel was a vertical cylindrical 10 tonne capacity storage tank of 2.1 m diameter and 7.4 m high, which was half filled with propane. The tank was supported on four legs approximately 0.3 m high and it was situated within a compound approximately 7 m by 8.5 m surrounded by a breeze-block wall 0.25 m high. There was a break in the wall for a gateway. The tank was positioned on a concrete base, the area between the edge of the concrete base and the compound wall was filled with gravel. The area surrounding the tank was considered to be adequately ventilated.

The release occurred due to removal of three out of four bolts on an adapter part on the drainage valve of the tank. The personnel that undertook the work did not realise that the adapter was an essential part of the valve. The valve was of 50 mm nominal bore and length 168 mm. There was a gap of 87 mm between the bottom of the adapter and the concrete pad.

The night watchman was alerted by the smell of the gas and eventually found a white cloud about 1.2 m deep accumulating round the base of the storage vessel within the compound. A passer-by called the fire brigade, who applied water to the tank. They also rang the police

who closed the adjacent roads and advised residents living nearby to close all doors and windows and extinguish any naked flames. Eventually, approximately 2100 people were evacuated from the area, some on buses to a local leisure centre. The evacuees returned to their homes the following morning.

The escape lasted for several hours. There are comments that the smell of propane was strongest to the rear to the houses in an adjacent road (Whitefriars Avenue), 200 m from the storage tank. Explosimeter readings were taken in the area surrounding the site but were not reported. A gusting south-westerly wind contributed to dispersing the cloud. Several people, including fire personnel suffered from nausea and one person was hospitalised.

Additional information can be found in the HSE Report (HSE, 1981a).

4.4.3 Ellesmere Port

From the HSE website⁷⁶:

At about 8.23 pm on 1 February 1994 there was a release of reactor solution from a recirculating pump near the base of a 25 tonne ethyl chloride (EC) reactor vessel at the factory of The Associated Ocel Company Ltd, Ellesmere Port, Cheshire. The reactor solution was highly flammable, corrosive and toxic, mainly consisting of ethyl chloride, a liquefied flammable gas, mixed with hydrogen chloride a toxic and corrosive gas, and small quantities of solid catalyst, aluminium chloride. A dense, white cloud soon enveloped the plant and began to move off-site.

The on-site and external emergency services were called in accordance with pre-arranged procedures for major incidents involving chemical release. Over the next one and a half hours action was taken to isolate the leak, to suppress the further release of vapour and to prevent the cloud spreading.

In spite of these attempts a pool of liquid continued to collect and at 10.08 pm the flammable vapours of ethyl chloride ignited, causing a major pool fire which was most intense at the base of the reactor. As the incident developed there were also fires at flanges damaged in the fire, including jet flames at the top of two large process vessels on the plant. Although these vessels and the reactor were protected by a fire resistant coating, there was concern at one stage that the vessels might explode and the damage extend to chlorine storage vessels on the adjacent plant.

The leak occurred at a point between fixed pipework and the discharge port of a pump recirculating liquids to the reactor, as a direct consequence of either (a) the failure of a corroded securing flange on the pump working loose; or (b) the failure of a PTFE flexible connection ("bellows") connecting the pump discharge to the pipe. The HSE believes the first of these possible causes was the more likely. The most likely source of ignition was an electrical control box to a compressor nearby.

Eventually, the fire was put out by applying a significant amount of foam to the tank. There were no fatalities but firefighters were treated in hospital.

4.4.4 Runcorn

From the MAIB Safety Bulletin (MAIB, 2005, Appendix A):

At about 11.10 on 10 August 2004, 594 kilos of Vinyl Chloride Monomer (VCM) was accidentally released into the atmosphere from *Coral Acropora* a 3096 grt Gas Carrier during a cargo sampling operation, prior to discharging cargo at the Runcorn Lay-By berth on the Manchester Ship Canal.

⁷⁶ <http://www.hse.gov.uk/comah/sraqtech/caseoctel94.htm> Accessed on 24th April 2020

The vessel was loaded with 2829 tonnes of Vinyl Chloride Monomer and securely moored starboard side alongside the Runcorn Lay-by berth on the Manchester Ship Canal. Shore personnel had boarded the vessel on arrival to connect the cargo manifold to the shore chocks [a flexible coupling used in high-pressure lines], and a Cargo Surveyor was trying to take samples from the vessels' cargo tanks. The vessels' Chief Officer was attempting single handedly to circulate cargo in the aft cargo tank by running the tank deepwell cargo pump at the request of the Cargo Surveyor. However, one valve on the full forward cargo tank had been opened and a second was inadvertently opened, with the effect that cargo was internally transferred into this tank. The pressure in the forward cargo tank rose as the tank filled, to such an extent that the tank pressure/vacuum valve lifted and cargo erupted from the forward tank mast riser.

The gas cloud directly affected all of those on the ship and several persons in the terminal. A number of members of the public were also affected by the incident.

VCM is a gas at typical ambient temperatures and it was being transported in a pressure-liquefied, refrigerated state. When it was released, it was initially forced upwards as a plume (see Figure 22a) but the density effects caused it to slump back down and spread towards the land. At least 600 kg of liquid and vapour VCM was released in 1-2 minutes from the vessel's forward cargo tank mast riser after the forward tank became over-pressurised.

At the time of the accident, the sky was overcast and it was raining but the rain stopped shortly after the accident. The wind was recorded as about 5 m/s from the north, although a witness said it was light (Brownless, 2005). Coral Acropora was lying alongside on a heading of 40° and the wind was northerly (relative wind was about 40° on the vessel's port bow). CCTV (Figure 22b) showed the edge of the cloud and indicated that the dense gas travelled at least 150 m upwind. The vessel was enveloped in cloud for about 6 minutes and the area was declared safe at about 14.00.



Figure 22 CCTV footage of a released cloud of Vinyl chloride monomer from the Coral Acropora cargo ship (Brownless, 2005)

During the incident, the chief officer exited the accommodation block equipped with breathing apparatus and observed that the ship's flag on the front mast, where the front tank gas risers were located, had frozen. Also, he observed that the deck was coated in white crystals of polymerised VCM.

There were various alarms in operation on the ship but these were ignored and reset on at least one occasion during the build up to the incident and even during the incident itself.

At least 33 people were exposed to the vapours. Several personnel including the chief officer and the cargo surveyor were able to take refuge in the vessel's accommodation block and other offices before the vapour cloud reached them. Later on during the incident, the second officer found levels of between 10 and 50 ppm in the internal accommodation (the TLV-TWA for VCM is 2 ppm).

Information is available on this case both from the MAIB report (2005) and the supporting HSE report (Brownless, 2005). This body of information includes both on board and on land CCTV of the gas cloud (see Figure 22) and modelling using Phast 6.4. The modelling showed no significant toxicity hazard but a flash fire hazard within 50 m of the release.

4.4.5 Buncefield

On the morning of 11 December 2005, there was a large explosion and fire at the Buncefield Oil Storage Depot near Hemel Hempstead, UK. The explosion registered 2.4 on the Richter Scale and broke windows up to 1 km away. It was the largest explosion in peacetime Europe. The resulting fire burned for several days and destroyed most of the site.

The incident was caused by overfilling of a gasoline storage tank. Approximately 260 m³ of petrol cascaded down the side of the tank from the roof, forming a dense cloud of petrol vapour/mist which spilled over the containment bund wall and dispersed across the site. The very low wind conditions meant that the dense cloud maintained high concentrations and was able to spread large distances across the relatively flat site before finding an ignition source.

There is CCTV footage showing the build up of the dense gas cloud during the event and many photographs of the damage from which further information has been deduced, see Figure 23.



Figure 23 CCTV of the Buncefield incident showing the dispersing gas cloud (Buncefield Major Incident Investigation Board, 2008)

Over 40 people were injured and there was significant damage to commercial and residential property. There were no fatalities, primarily due to the incident occurring at night. The cost of the incident in terms of the damage to property and loss of business is estimated to have been in the region of £1bn. There are about 10,000 similar facilities worldwide.

The incident resulted in a large investigation and publication of several reports and recommendations⁷⁷ alongside the main incident reports. HSE commissioned both experiments and modelling to study the physics that lead to the release and cloud formation and dispersion (Gant and Atkinson, 2011; Atkinson and Coldrick, 2012; Atkinson and Gant, 2012; Atkinson et al., 2015). It was analysed in the context of similar releases in the review of Atkinson et al. (2017).

4.5 Worldwide incidents involving dispersion of dense gases

The incidents summarised below represent a range of scenarios and were chosen to illustrate different substances, sources, factors affecting the gas dispersion, health and safety impacts, effectiveness of mitigation and emergency response. Comments on the quality and quantity of information available are also included.

The incidents are arranged in date order from 1915 to 2020. A table summarising these incidents, and others, can be found in Section 4.7.

4.5.1 Ypres, Belgium

In 1915 chlorine gas was used as a chemical warfare agent for the first time. Fitzgerald (2008) describes the incident as follows:

In the late afternoon of April 22, 1915, members of a special unit of the German Army opened the valves on more than 6000 steel cylinders arrayed in trenches along their defensive perimeter at Ypres, Belgium. Within 10 minutes, 160 tons [145 tonnes] of chlorine gas drifted over the opposing French trenches, engulfing all those downwind. Filled with pressurized liquid chlorine, the cylinders had been clandestinely installed by the Germans more than 3 weeks earlier. The order to release the gas was entrusted to German military meteorologists, who had carefully studied the area's prevailing wind patterns. Disregarding intelligence reports about the strange cylinders prior to the attack, the French troops were totally unprepared for this new and horrifying weapon.

The surprise use of chlorine gas allowed the Germans to rupture the French line along a 6-kilometer (3.7-mile) front, causing terror and forcing a panicked and chaotic retreat. Within a matter of minutes, this slow moving wall of gas killed more than 1000 French and Algerian soldiers, while wounding approximately 4000 more.

A photograph from the time showing the dispersion of the gas can be seen in Figure 24.

⁷⁷ <https://www.hse.gov.uk/comah/buncefield/index.htm> Accessed on 26th August 2020



Figure 24 Chlorine gas released from cylinders during World War I. Image from Reynolds and Taylor (1918)

4.5.2 Brooklyn, New York

On 1st June 1944, a leakage occurred in Brooklyn, New York from a truck carrying 27 cylinders of chlorine. Each cylinder contained 100 lb (45.4 kg) liquid chlorine and one of them was leaking. The cylinder was stored vertically near the rear of the truck on the curb side. The leak occurred from a hole approximately 1/8 inch (0.32 cm) diameter in the bottom of the cylinder.

At about 14:43, the driver had stopped the truck next to the curb about 30 ft (9.1 m) north of a subway station entrance and about 18 inches (45.7 cm) from a series of gratings covering ventilation shafts leading down onto the subway station platform. The escaping chlorine spilled from the back of the tank into the gutter and the curb next to these gratings.

The driver was unable to approach the cylinder and at 14:46 pm the police emergency equipment was requested. At about 15:00 pm firemen moved the truck away from the curb into the street and the cylinder, which was still leaking, was removed. Ashes were thrown on the liquid in the gutter and the area was then flushed with water. In total, the chlorine was released for about 17 minutes.

At 14:46 a train pulled into the subway station and sufficient chlorine was present in the station that several passengers left the train to go into the street. When the train left the station, the concentration of chlorine in the forward cars was sufficient that passengers left the train at subsequent stations to seek medical aid.

At 14:47 a second train arrived at the subway station, where it found heavy concentrations of chlorine gas. All of the passengers and train crew left the train and went into the street. Witnesses said that it was possible to see a visible cloud of chlorine.

By 14:53 subway employees arrived at the subway station and were able to traverse the platform and the rest of the station without serious irritation due to chlorine concentration.

No visible cloud of chlorine gas formed on the street, except in the immediate vicinity of the truck. The concentration was sufficient to force people indoors for a few minutes and odour of chlorine was detected 800-1000 ft (244-305 m) downwind. The evidence showed that most of the chlorine released entered the subway.

The wind direction potentially carried the chlorine cloud over about ten of the subway ventilation shafts and towards the subway entrance. There were no blowers or fans in the ventilation shafts, they relied on the passing of the trains to instigate flow resulting in multiple possible ventilation combinations, including sucking air down the shafts. As a result, the concentration of chlorine in the subway was sufficient to cause multiple casualties.

The incident caused 418 people to be examined in hospitals and 208 admissions. Of those affected, 104 noted the location of their exposure. 102 were in the subway, one was in a shop which opened onto the street and one was in a vehicle which was following immediately behind the leaking truck.

The ambient temperature at the time was 75°F (24°C), the relative humidity was 65% and the cloud coverage was about 8/10, there was no sunshine. There had been light rain earlier in the day between 12:35 and 14:10. The wind was northerly and the wind speed at 45 ft (137 m) above street level was 12 mph (5.4 m/s).

Further information, in particular on the medical implications of the exposure, can be found in Chasis et al. (1947).

4.5.3 Manhattan, New York

From NRC (2004)

On September 2, 1944, an accidental UF₆ release occurred at a Manhattan Engineering District pilot plant located at the Philadelphia naval shipyard (Kathren and Moore, 1986). A weld ruptured in a 2.4 m × 0.2 m cylinder containing gaseous UF₆, causing the cylinder to act as a rocket. It traveled 164 m, tore out pipes and fittings in its path, and released an estimated 182 kg of UF₆. The released UF₆ and steam produced a dense cloud of UF₆ and hydrolysis products that enveloped the area within 91.4 m of the rupture site. The cloud rapidly dispersed and exposure duration was estimated to be 17 seconds. Twenty workers were exposed at varying degrees, depending on their location during the rupture. Two people, both in a direct line with the cylinder, died - one died 10-16 min after exposure, and the other died 70 min after exposure. Three people were seriously injured, 12 were hospitalized for observation, and three were without symptoms.

4.5.4 Cleveland, Ohio

On 20th October 1944 a tank containing LNG, equivalent to about 90 million cubic feet (2.5 million m³) of gas, exploded. The Case Western Reserve University website⁷⁸ has the following brief description of the event:

At approx. 2:30 P.M., white vapor began leaking out of Storage Tank No. 4, which had been built by the East Ohio Gas Co. in 1942 to provide additional reserve gas for local war industries. The gas in the tank, located at the northern end of E. 61st St., became combustible when mixed with air and exploded at 2:40 P.M., followed by the explosion of a second tank about 20 minutes later. The fire spread through 20 blocks, engulfing rows of houses while missing others. The vaporizing gas also flowed along the curbs and gutters and into catch basins, through which it entered the underground sewers, exploding from time to time, ripping up pavement, damaging underground utility installations, and blowing out manhole covers. The immediate area surrounding the burning district was evacuated and refugees were sheltered in Willson Jr. High School on E. 55th St. where the Red Cross tried to care for approx. 680 homeless victims.

By late afternoon Saturday much of the fire had burned itself out, electricity was restored in some areas, and the next day a few residents began returning to their homes. The fire destroyed 79 homes, 2 factories, 217 cars, 7 trailers, and 1 tractor; the death toll reached 130. The fire and subsequent analysis of its cause led to new and safer methods for the low-temperature storage of natural gas.

⁷⁸ <https://case.edu/ech/articles/e/east-ohio-gas-co-explosion-and-fire> Accessed on 5th April 2020

Another part of the report mentions a tidal wave of fire engulfing homes and businesses over an area of more than a square mile.

An unconfirmed account on Wikipedia⁷⁹ adds additional information:

...the cylindrical above-ground storage tank number 4, holding liquefied natural gas in the East Ohio Gas Company's tank farm, began to emit a vapor that poured from a seam on the side of the tank. The tank was located near Lake Erie on East 61st Street, and winds from the lake pushed the vapor into a mixed-use section of Cleveland, where it dropped into the sewer lines via the catch basins located in the street gutters.

As the gas mixture flowed and mixed with air and sewer gas, the mixture ignited. In the ensuing explosion, manhole covers launched skyward as jets of fire erupted from depths of the sewer lines. One manhole cover was found several miles east in the Cleveland neighborhood of Glenville.

At first it was thought that the disaster was contained, and spectators returned home thinking that the matter was being taken care of by the fire department. At 3:00 p.m., a second above-ground tank exploded, leveling the tank farm.

However, the explosions and fires continued to occur, trapping many who had returned to what they thought was the safety of their own homes. Housewives who were at home suddenly found their homes engulfed in flame as the explosion traveled through the sewers and up through drains. The following day, Associated Press wire stories contained quotes from survivors, many of whom were at home cleaning in preparation for the coming Sabbath. Survivors said that within a split second after the explosion, their homes and clothes were on fire.

Cuyahoga County Coroner Dr. Samuel Gerber estimated that the initial death toll stood at 200; however, Gerber was quoted in newspaper wire stories stating the magnitude of the fire and the intense temperatures had the power to vaporize human flesh and bone, making an exact count impossible until weeks after the disaster. The final death toll was lower than the coroner's initial estimates.

The toll could have been significantly higher had the event occurred after local schools had let out and working parents returned to their homes for the evening.

About 300 people were injured in the event (Khan and Abbasi, 1999).

4.5.5 Poza Rica, Mexico

On 24th November 1950, an incident occurred in an area next to a recycling and sulphur recovery plant at Poza Rica, Mexico. The plant had only begun operation on 21st November and was still in the commissioning stages, receiving hydrogen sulphide rich natural gas at 40,000,000 cubic feet (1,132,673 m³) per day. From 2:00 on 24th November gas would be delivered to the plant at the desired rate of 60,000,000 cubic feet (1,699,010 m³) per day for the first time. As the plant was unfinished, the hydrogen sulphide rich gas was sent to a 90 ft (27 m) flare.

The atmospheric conditions at the time were a low altitude temperature inversion, very light wind and fog. It is suspected that on the morning of the incident, there was a surge of gas through the system resulting in unburned hydrogen sulphide escaping into the atmosphere. At 4:40 on the day of the incident, supervisors at the refinery received reports of gas in the area next to the plant. At 4:50, the manager arrived and shut down the operation, which was complete by 5:10. These 20 minutes represent the acute phase of the release where

⁷⁹ https://en.wikipedia.org/wiki/Cleveland_East_Ohio_Gas_explosion Accessed on 5th April 2020

pollutant gas had escaped from the flare and, under the inversion conditions, spread towards the village downwind of the plant.

In the village, eye witnesses reported people screaming and becoming unconscious. 320 people were hospitalised and 22 died. Many animals in the area were killed by the gas. Analysis after the event (McCabe and Clayton, 1952) found that the symptoms were consistent with hydrogen sulphide poisoning. The acute reactions were symptomatic of exposures to concentrations over 1000 ppm.

The area affected by the incident is a valley at 173 ft (53 m) elevation. The immediate area is at an elevation of 163 ft (50 m) to the north, 179 ft (55 m) to the south, 176 ft (54 m) in the west and 246 ft (75 m) in the east. There are hills of approximately 328 ft (100 m) elevation surrounding the entire valley. The local population inhabited simple houses constructed of split bamboo, shiplap and galvanised iron or thatched roofs. They were built to maximise air movement through the home and therefore it could be assumed that the concentration of any contaminants outside the property would be similar inside. This is consistent with analysis which found that in some cases those that sheltered in place, rather than fleeing, suffered worse.

4.5.6 Menzengraben, Germany

From Hedlund (2011):

An extreme outburst of carbon dioxide took place 7 July 1953 in a potash mine in the former East Germany. During 25 minutes, a large amount of CO₂ was blown out of the mine shaft with great force. [There were still wind conditions] and concentrated CO₂ accumulated in a valley leading to multiple asphyxiation casualties. Based on a review of concentration-response relationships, the location of victims, and other information, it is concluded that concentrations of 10-30% carbon dioxide may have occurred 450 m from the point of release for at least 45 minutes. It is concluded that 1,100-3,900 tonnes of CO₂ were blown out of the mine shaft, possibly with intensities around 4 tonnes per second. It is also concluded that the large majority of the gas escaped as a near vertical high-velocity jet with only little loss of momentum due to impingement.

There was a warning siren on site but it only let off one cycle before it was cut off by a power failure caused by impact damage to electrical installations below ground. The local inhabitants heard the siren go on and off and experienced the blackout. Many people at the facility ran to higher ground. Eventually, the site operations manager managed to sound the disaster alarm, mobilise rescue teams from neighbouring mines and alert nearby hospitals and doctors. The police blocked the main road to stop traffic entering the valley, and a passenger train was stopped. Once PPE was available, search teams went to look for casualties. The rescue efforts were praised at the time but it took three hours to set up the command centre to coordinate it.

There were three fatalities in total and about nine people were hospitalised.

The paper by Hedlund (2011) included site details, timeframes and estimates of concentration, and the incident was modelled using PHAST. The modelling results were not consistent with the observations and could not explain the casualties. The model predicted that the released gas would not reach the ground and would instead disperse safely.

4.5.7 La Barre, Louisiana

From Mannan (2012):

At about 8.15 a.m. on January 31, 1961, some 6000 US gal [22.7 m³] of liquid chlorine were spilled from a derailed tank car in the community of La Barre, Louisiana. A cloud of chlorine gas spread of over an area of approximately 6 square

miles. For the most part it hung close to the ground, but in places ‘boiled upward’ to a height of 8090 ft [2466 m]. Some 1000 people were evacuated. A series of determinations of the chlorine concentration were made by a team using mobile equipment. The first samples were taken at about 11.15 a.m., when a concentration of 10 ppm was measured at the end of a contaminated area some 200 yd [183 m] long on a highway parallel to the railway. At about 3.00 p.m., a concentration of 400 ppm was measured 75 yd [69 m] from the wreck. One person died and about 100 were treated for exposure to chlorine. The fatality was an 11-month-old infant in a family, which lived in a house approximately 50 yd [46 m] from the tank car. The chlorine in the house made the infant choke and gasp and the frantic father carried it outside, where the gas concentration was higher still. Although most of the exposure occurred inside the house, this exposure outside was probably critical. The child died in hospital. A 2-month old infant who remained in the house survived.

4.5.8 Feyzin, France

From the HSE website⁸⁰:

On 4th January 1966, an operation to drain off an aqueous layer from a propane storage sphere was attempted. Two valves were opened in series on the bottom of the sphere. When the operation was nearly complete, the upper valve was closed and then cracked open again. No flow came out of the cracked valve, so it was opened further. The blockage, assumed to be ice or hydrate, cleared and propane gushed out. The operator was unable to close the upper valve and by the time he attempted to close the lower valve this was also frozen open. The alarm was raised and traffic on the nearby motorway was stopped. The resulting vapour cloud is thought to have found its source of ignition from a car about 160 m away. The storage sphere was enveloped in a fierce fire and upon lifting of the relief valve a stream of escaping vapour was ignited.

The LPG tank farm where the sphere was located consisted of four 1200 m³ propane and four 2000 m³ butane spheres. The fire brigade arrived on site, but were not experienced in dealing in refinery fires, and it appears they did not attempt to cool the burning sphere. They concentrated their hoses on cooling the remaining spheres. About 90 minutes after the initial leakage, the sphere ruptured, killing the men nearby. A wave of liquid propane flowed over the compound wall and fragments of the ruptured sphere cut through the legs of the next sphere which toppled over. The relief valve on this tank began to emit liquid.

The fire killed 18 people and injured 81 others. Five of the storage spheres were destroyed.

The vapour cloud was about 1 m deep as it spread towards the motorway.

There were a few design features and mitigation measures that led to, or exacerbated, the incident. The tank drainage system should not have required manual operation and should have included measures to prevent ice blocking the valves, such as insulation. The containment bund successfully contained the escaping liquid but it did not allow it to drain away from the sphere where it could burn relatively harmlessly. There were no permanent water sprays in place to cool the spheres.

The emergency response procedures for the site were also inadequate. There was no strategy for raising an alarm should a flammable release occur. In the event, it took ten minutes to raise the alarm because the operator had to travel 800 m on foot because he was afraid of using the local telephone or starting his truck to drive. The local fire brigade had not

⁸⁰ <http://www.hse.gov.uk/comah/sraqtech/casefeyzin66.htm> Accessed on 5th April 2020

been briefed on how to deal with this sort of incident. Therefore, the fire fighting strategy was not appropriate and attempts to keep motor vehicles away from the incident were only partially successful.

Following this event features such as insulating of valves, reinforced legs on the spheres and permanent water sprays were incorporated in standard codes of practice.

Further information can be found in Mannan (2012) and ARIA Report No. 1 (ARIA, 2008a).

4.5.9 Glendora, Mississippi

From Mannan (2012):

At about 2.45 p.m. on September 11, 1969, a train entered Black Bayou junction near Glendora, Mississippi, pulling 157 rail cars, including eight containing vinyl chloride monomer (VCM). A pedestrian was struck and injured, and application of the emergency brake caused a derailment of 15 cars.

At 3.30 p.m., the VCM manufacturer was informed that his chemical was involved and at 5.00 p.m. that the eight cars were derailed and that one was leaking. A technical expert was requested and the manufacturer sent the VCM plant superintendent, who had 25 years' experience with the chemical.

At about 8.00 p.m., one of the VCM tanks was ruptured and leaking, and by 10.00 p.m. the leak had ignited. A heavy fog was noticed over the area and it was considered that it might be VCM. The railway management consulted the Handbook of Hazardous Materials, which stated that phosgene could be formed in VCM fires. They rang the company office, who advised that a hazard from phosgene was highly improbable and that the main problem was likely to be from HCl and smoke. Nevertheless, the railway management, the police, the National Guard, and the Civil Defence Authorities continued to be worried by the phosgene hazard. The Civil Defence director consulted university chemists, who advised that burning VCM would release phosgene, which could be a hazard to life at a radius of 35 miles [56 km]. Accordingly, the police and National Guard evacuated all the towns nearby. The evacuation was reported as involving some 30,000 people.

At 6.45 a.m. the next day, an explosion occurred which demolished one of the eight VCM tank cars. The explosion caused a second tank car to rupture and ignite. After the fires were extinguished, only five full tank cars were recovered. A report in The Commercial Appeal of Memphis, Tennessee (September 13, 1969), read Dawn opened on this tiny Mississippi town Friday with an eerie display of a dirty yellow mushroom cloud rising with a clinging ground fog. The silence was as thick as the fog, and just as unnatural. It was like something from an Alfred Hitchcock movie, one plantation manager was to remark later. Throughout Thursday night, thousands of people in 11 Delta towns and outlying rural areas in a 25 mile [40 km] radius were evacuated... For many it was a night of fear resulting from lethal gas being blown away from derailed railroad tank cars.

It is difficult to tell in this incident whether the gases released retained their density effects in the presence of the fire. A "clinging ground fog" might indicate that there were density effects present or this could result from the atmospheric conditions at the time.

Further information for this incident can be found in NTSB (1970).

4.5.10 Blair, Nebraska

From Mannan (2012):

On November 16, 1970, an overflow occurred on a 40,000 ton [36,287 tonne] refrigerated anhydrous ammonia storage tank at the Gulf Oil Company's installation

at Blair, Nebraska. 160 tons [145 tonnes] of ammonia was released, but there were no deaths or serious injuries.

The overfilling was the result of an operator error. A factor which may have contributed to the error was the fact that the table of tank levels, or 'strapping table,' did not indicate clearly the position of the overflow pipe. In addition, the high-level alarm and shut-down system failed to operate and apparently the overflow discharge valve also failed to operate at the set pressure, so that the liquid level in the tank rose until it reached the roof, at which point the overflow valve did open. There was an isolation valve on the overflow line directly below the relief valve. It was not possible to reach this valve and close it on account of the ammonia cloud. If isolation of the overflow line had been possible, much of the overflow could have been prevented. Once the overflow valve had opened, there was a discharge of ammonia to atmosphere. The discharge continued for 2.5 h.

There was almost no wind and an atmospheric inversion existed, so that initially the weather conditions were at their most unfavorable for dispersion. A low visible cloud of ammonia formed some 830 ft [253 m] thick, covering approximately 900 acres [364 hectares] and extending over 9000 ft [2743 m] from the tank... Later, a light breeze arose and helped to keep the cloud from populated areas.

Mannan (2012) also included photos of the ammonia cloud spreading over a large area at relatively shallow depths, as shown in Figure 25.

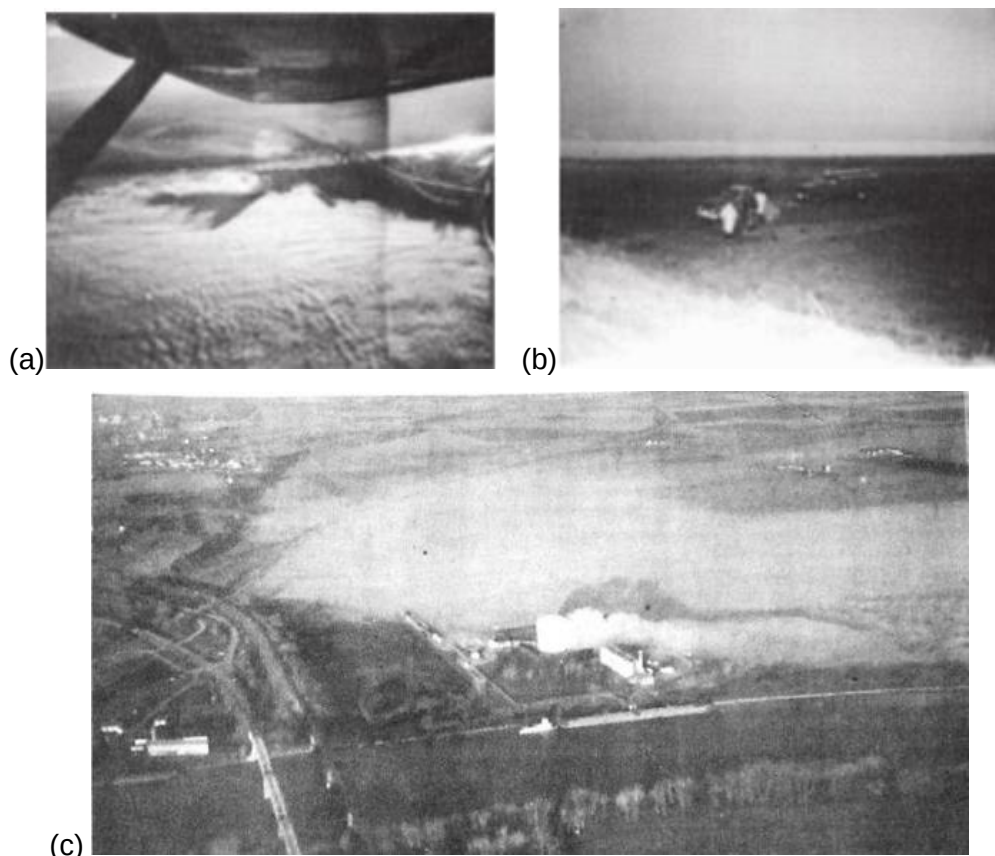


Figure 25 Photos of the ammonia cloud resulting from the release at Blair, Nebraska. (a) Aerial view showing ammonia cloud covering whole of foreground; and (b) ground level view showing relatively shallow cloud depth, (c) Aerial view (© Washington County Enterprise copyright 1970)

4.5.11 Port Hudson, Missouri

At about 22:00 on 9th December 1970 an abnormality was recorded at an LPG pipeline pumping station following a rupture of the pipeline. Approximately 102 m³ of LPG was released in about 24 minutes. The pipeline failed at about 65 bar and resulted in a two-phase release, reported by witnesses as a 15 m - 25 m plume of white spray. A vapour cloud formed and spread to cover an area of about 40,000 m². The cloud subsequently ignited and produced a vapour cloud explosion.

The atmospheric conditions were recorded as stable, cool and with a low wind speed of 2.5 m/s. The terrain surrounding the pipeline was fairly rural farmland and woods. The vapour cloud was observed to settle in a valley around a collection of agricultural buildings.

There were no fatalities. Four families evacuated their homes and moved to higher ground.

This incident was summarised in Mannan (2012) and reviewed by Atkinson et al. (2017). The original reference is Burgess and Zabetakis (1973). There does not appear to be a large body of information available.

4.5.12 Potchefstroom, South Africa

From Mannan (2012):

At 4.15 p.m. on July 13, 1973, a sudden failure occurred in an anhydrous ammonia storage vessel at the Potchefstroom works of TRIOMF, a company part-owned by African Explosives and Chemical Industries Ltd. The tank was one of four 50 ton [45 tonne] horizontal pressure storage vessels. An estimated 30 tons [27 tonnes] of ammonia escaped from the tank itself and another 8 tons [7 tonnes] from a tank car. The failure gave rise immediately to a gas cloud some 150 m diameter and 20 m deep. At the time of the accident the air was apparently still, but within a few minutes a slight breeze arose which caused the cloud to move toward a township some 200 m to the north-east. The visible cloud then extended some 450 m downwind and 300 m across. Deaths occurred both inside and outside the factory fence. At the time there were some 350 persons working in the plant, of whom some 30 were within 70 m of the failed tank. One employee was killed by the blast and eight died while trying to escape from points within a 100 m radius of the tank. Three others died of gassing within a few days. Outside the factory fence, four people were killed immediately and two died a few days later. Thus altogether 18 people were killed. The occupants of the granulation plant control room 80 m south-east of the failure survived. They put wet cloths over their faces and were taken to safety after some 30 min.

The failures occurred in tank No. 3 while it and tank No. 4 were being filled simultaneously from a tank car. Actuation of an excess flow valve on the line between the two tanks prevented the release of the contents of tank No. 4 also. The tank car did not have an excess flow valve and did suffer escape of material.

The cause of the failure was brittle fracture of the dished end of the tank. Evidence suggested that there had been no overpressure or overtemperature of the tank contents and no other triggering event was determined.

The Potchefstroom incident was modelled in Britter and McQuaid (1988) and is also discussed and modelled in Kaiser and Walker (1978).

The original details were reported by Lonsdale (1975).

4.5.13 McPherson, Kansas

From Mannan (2012):

At 4.30 a.m. on December 6, 1973, a major leak occurred on the Mid-America Pipeline System at the Conway pump station near McPherson, Kansas. Prior to the leak, an ice storm had been raging for 2 days and the pump station had lost power for 18 h, although it was partially restored by 3.00 a.m. The pipeline had been shut-down and upon start-up at 4.12 a.m. a block valve failed to open, the line was overpressured and burst at a point where it had already sustained construction damage.

An estimated 230 tons [209 tonnes] of anhydrous ammonia escaped over a period of half an hour. A low, visible plume of ammonia formed and drifted over Highway 56, which is some 1000 ft [305 m] to the south. The weather conditions were very stable with a wind speed of some 5-10 mph [2.2-4.5 m/s] and the plume remained narrow. Irritation symptoms were experienced and odor was detectable for about 3.5 and 8 miles [5.6 and 12.9 km] from the escape, respectively.

The incident caused no serious casualties. Many residents had moved into a nearby town on account of power failures caused by the severe weather. Two truck drivers drove into the gas cloud on the highway. They escaped and were kept in hospital several days. People in dwellings 3/4 mile [1.2 km] south of the leak and directly in the cloud path were safely evacuated by the Sheriff's office and company personnel.

By 4.30 p.m., the line had been stopped.

The same pipeline failed again on August 13, 1979, at a point about 22 miles [35 km] from the first failure. There was a release of some 360 tons [327 tonnes] of anhydrous ammonia. Again there were no casualties, but there was a large fish kill.

Further details of the incident can be found in NTSB (1974).

4.5.14 Chicago, Illinois, 1974

From the HSE website⁸¹:

Bulk Terminals was a storage tank farm with 78 tanks ranging in size up to 4900 m³. At about 12:30 hours on Friday 26 April 1974 a dull thud was heard and fumes were seen rising from the bund surrounding a 3300 m³ tank of silicon tetrachloride. It was discovered that a pressure relief valve on a 6-inch line leading to the tank had been inadvertently closed. The pressure in the system was sufficient to burst a flexible coupling in the line, shifting the piping system and cracking a 3-inch line on the tank wall. Liquid silicon tetrachloride escaped forming an irritant cloud containing hydrogen chloride gas.

The terminal management waited for the owners of the chemical to take emergency action and the fire service did not respond, as there was no fire. The EPA sent lime trucks to neutralise the chemical, but these were refused entry to the site. By 15:00 hours the cloud was 400 m wide, 300-450 m high and 1600 m long.

At 04:10 hours on Saturday 27 April, foam was added to blanket the liquid in the bund but this failed. At 09:00 hours fuel oil was added along with eight truck loads of lime. The vaporisation reduced dramatically and operations began to transfer the liquid from the damaged tank. At 08:00 hours on Sunday 28th April, it began to rain. Power lines were corroded by the hydrochloric acid in the rain, and four pumps became inoperable due to corrosion before a general power failure stopped all pumping.

⁸¹ <http://www.hse.gov.uk/comah/sraqtech/casechicago74.htm> Accessed on 5th April 2020

The materials added into it had reduced the capacity of the bund, and a further pit had to be dug to take the overflow in the event of a full tank failure. It was attempted to seal the leak on the tank using quick drying cement. The first attempt failed and it wasn't until 23:30 hours on Monday 29 April that the leak was sealed. It took until 3 May to empty the tank and until 15 May before emissions had reduced to tolerable levels. One person was killed, 160 hospitalised and 16,000 people were evacuated during this incident.

The site on which the incident took place was in a built up area and Mannan (2012) says that the cloud extended 8– 16 km at times. On the Monday morning, about three days into the incident, when seeking to determine if the leak had been sealed, the visibility within the cloud was only about 45 cm.

4.5.15 Mill Woods, Canada

A pipeline incident that took place in March, 1976. From the HSE website⁸²:

The Rimbey pipeline system in Alberta, Canada transports liquid propane, butane and condensate products in an 8-inch [20 cm] pipeline. On the day of the incident the operating pumps were pumping against a closed valve. The line failed at a pressure of approximately 8000 kPa, which is below the 8372 kPa maximum operating pressure for the pipeline.

Liquid propane erupted violently and formed a pond of boiling propane. The propane quickly formed a ground level flammable gas cloud, which rolled across topsoil until it reached a road where it was ignited by a passing truck. Liquid propane entered a nearby storm sewer catchment basin. The propane spread into adjacent sewer lines. Explosive mixtures were detected over a wide area within the sewer system.

No injuries were recorded, however the incident instigated a large-scale evacuation of 19,000 people while efforts were made to eliminate the explosive danger.

A combination of water flushing, ventilation and nitrogen gas blanketing successfully eliminated the danger about 23 hours after the original fracture. Maintenance crews plugged the pipeline either side of the fracture to stop the flow of leaking gas.

There was no coordinated emergency plan in this incident. A hierarchy for emergency response was not put in place and no central information centre was established. As a result, essential information, such as details about the pipeline and identification of the product in the sewers, were not available.

4.5.16 Baton Rouge, Louisiana 1976

From Mannan (2012):

On December 10, 1976, a massive chlorine release occurred from a storage vessel at Baton Rouge, Louisiana. The vessel was a horizontal bullet tank 125 ft long x 311 ft diameter resting on a load cell weighing system. An internal explosion caused the vessel to fall off its supports so that it was pierced by a metal upstand on the ground. Over a period of 5.6 h, 90.7 tonnes of chlorine was released. A gas cloud formed described as a 42 mile [68 km] long wedge, lying over the Mississippi river and sparsely populated areas. Ten thousand people were evacuated. Three persons were treated for minor irritation.

The cause of the tank displacement was an internal explosion of a natural gas-chlorine mixture at one end of the vapor space in the half full tank which produced a liquid surge along the length of the tank so that the momentum of the liquid caused

⁸² <http://www.hse.gov.uk/comah/sraqtech/casemillwoods76.htm> Accessed 24th April 2020

the tank to jump off its supports. The tank was normally padded with nitrogen. The same nitrogen system was connected to the gland seals of hydrogen compressors in order to exclude air from the hydrogen. There was in addition a natural gas system which could be used on the gland seal as a more economic alternative. Due to the cold weather, trouble had been experienced with natural gas condensate and the nitrogen system was in use. At some stage, the lines to the nitrogen and natural gas systems were open at the same time and natural gas at higher pressure got into the nitrogen system. When the plant was restarted, an explosion occurred in the chlorine liquefaction system. It then spread via a balance line to the vapor space of the chlorine tank.

4.5.17 Houston, Texas

From Mannan (2012):

At about 10.45 a.m. on May 11, 1976, in Houston, Texas, a tractor tank semi-trailer carrying ammonia went through a bridge rail on the interstate highway 1610 and fell some 15 ft [4.6 m] onto the South-west Freeway, US 59. The interchange was the busiest in the state and at the time traffic was quite heavy. The tank, which held 19 tonnes of liquid anhydrous ammonia, burst. The crash was caused by the excessive speed of the vehicle and by sloshing of the liquid in the partially loaded tank. However, the speed did not exceed 54 mile/h [87 kmph]. The ammonia was released and formed a visible fog. It was a bright sunny morning with a wind speed of 7 mile/h [3.1 m/s]. The initial height of the cloud determined from photographs was about 30 m. The cloud was observed to reach a width of about 300 m and a length of 600 m. One photograph showed a tail to the left-hand side, indicating the typical slumping behavior of heavy gas. It is estimated that the ammonia evaporated and the cloud dispersed within about 5 min. The driver of the truck and five other people were killed, 78 taken to hospital, and about another 100 injured. Apart from the driver, all the casualties were due to gassing.

A photograph of the release can be seen in Figure 26 and shows that the released gas demonstrated characteristic dense gas behaviour.

The incident was an approximately instantaneous release and was discussed and modelled by Jagger and Kaiser (1981) and Kaiser and Walker (1978).



Figure 26 Photography of the Southwest freeway in Houston, Texas taken about one minute after the Houston tanker crash. Photograph taken by Texas Air Control Board (© Texas Commission Environmental Quality copyright 1976).

4.5.18 Seveso, Italy

From the HSE website⁸³:

At approximately 12:37 on Saturday 10th July 1976 a bursting disc on a chemical reactor ruptured. Maintenance staff heard a whistling sound and a cloud of vapour was seen to issue from a vent on the roof. A dense white cloud, of considerable altitude drifted offsite.

Among the substances in the white cloud was a small deposit of 2,3,7,8-Tetrachlorodibenzo-p-dioxin ('TCDD' or 'dioxin'), a highly toxic material.

The release lasted for some twenty minutes. Over the next few days following the release there was much confusion due to the lack of communication between the company and the authorities in dealing with this type of situation.

The nearby town of Seveso, located 15 miles [24 km] from Milan, had some 17,000 inhabitants. No human deaths were attributed to TCDD but many individuals fell ill. 26 pregnant women who had been exposed to the release had abortions. Thousands of animals in the contaminated area died and many thousands more were slaughtered to prevent TCDD entering the food chain.

The Seveso incident motivated many questions about industrial safety and the relationship between industry and the surrounding populations, and gave rise to standardised industrial safety regulations, such as the Seveso Directives.

Further information can be found in the papers by Homberger et al. (1979) and Pocchari et al. (1983).

4.5.19 Chicago, Illinois, 1978

On 14th February 1978 a sodium sulphide solution was mistakenly discharged from a road tanker into an intake valve connected to a tannery tank containing an acidic solution of chromium salts, instead of the correct storage tank. When the sodium sulphide mixed with

⁸³ <http://www.hse.gov.uk/comah/sraqtech/caseseseveso76.htm> Accessed 24th April 2020

the acid, solution fumes of hydrogen sulphide were released into the plant. Many workers in the plant were admitted to hospital and seven men died.

Limited information can be found in Smith and Gosselin (1979).

4.5.20 Youngstown, Florida

From Mannan (2012)

At about 1.55 a.m. on the night of February 26, 1978, a freight train of the Atlanta and Saint Andrews Bay Railway derailed near Youngstown, Florida. In the derailment, a rail tank car containing liquid chlorine was punctured when it struck another tank car...

A chlorine gas cloud formed and moved toward State Highway 231, which ran parallel to the railroad at a distance of 300 ft [91 m]. The weather conditions were a temperature of 50-55 F [10-13°C] and a light westerly wind of 2-3 knots [1-1.5 m/s]. There were already some patches of fog around and drivers, used to foggy conditions and unable to see the color of the cloud as it was night, drove into it. Three vehicles drove right off the road and into the ditch. One motorist said the gas was so thick 'You could not see your hand in front of your face.' Seven motorists abandoned their cars and died while trying to escape, while an eighth drove through the cloud but died a short distance down the road.

The train's engineer at the head of the train alerted the conductor at the rear by radio and then tried to escape through the cloud; he became lost and mired in a swamp, being rescued 6 h afterward. The head brakeman, who had been with the engineer, circled around to the highway and started to alert traffic. The conductor and rear brakeman tried to inform the railroad facility at Panama City, but it was not manned after midnight. They began to rouse local residents and notified the police; almost 30 min had elapsed before the first emergency call was completed. They then went to the highway to assist in alerting traffic.

...The head and rear brakeman both imperiled their lives by their repeated exposure to the chlorine gas cloud to stop and warn motorists of the dangerous situation. Their heroic actions saved many people from death or serious injury.

The emergency service evacuated people, first in a 5 mile [8 km] and then in a 10 mile [16 km] radius. At 9.00 a.m., aerial observation revealed a gas cloud 3 miles [5 km] wide and 4 miles [6 km] long with a maximum height of 1000 ft [305 m]. If the wind had been in a less favorable direction, the town of Youngstown would have been engulfed in the cloud. The chlorine gas killed eight people, as mentioned, and injured another 50. Some 2500 people were evacuated.

The original details of this incident can be found in NTSB (1978).

4.5.21 Mississauga, Ontario

From Mannan (2012):

At 11.52 p.m. on Saturday, November 10, 1979, at Mississauga, Toronto, a freight train derailment led to fires, explosions, and a chlorine gas release, in an emergency lasting 11 days. The train had 25 rail cars of which 19 held hazardous materials, in a mixed load of flammables and toxics, including propane, toluene, styrene, caustic soda, and chlorine.

The derailment occurred due to lack of lubrication of a plain journal axle bearing on the 33rd car, a propane tanker. The red-hot axle, complete with wheels, parted from the tank car. Some 2 km further on at a location where there was a road crossing and

points, this vehicle became detached from the front portion of the train. Many of cars in the rear section derailed. Several tanks were ruptured and a fire broke out. The brakes in the front section of the train were applied automatically and looking back the locomotive crew saw a fire and a tank car rocketing off.

There followed a series of explosions, one within a minute and another just after midnight at 12.10. At 12.15 a propane tank suffered a boiling liquid expanding vapour explosion (BLEVE) in which one half travelled 2300 ft [701 m] and buried itself 20 ft [6 m] into the ground. At 12.24 another BLEVE of a propane tank car occurred.

There was a single chlorine tank car containing 90 tonnes of liquid chlorine. This tank lost part of its insulation and a flame impinged on the bare metal. There was an iron-chlorine reaction which burned a 3 ft [0.9 m] diameter hole in the tank. Chlorine began to escape through the hole. The effect was less serious than it might have been, since the effect of the fire was to cause the gas to rise in the thermal currents.

The emergency developed over an extended period. Initially the emergency services did not know what was in the train: the manifest was found, but it was in code. There was, however, a strong smell of chlorine. At 1.30 a.m. a readable version of the manifest was obtained, identifying the chlorine tank car. At 3.00 a.m. the decision was made to evacuate the surrounding population, an exercise which eventually resulted in the evacuation of 215,000 people. The holed chlorine tank car was identified by a helicopter survey.

At 9.00 a.m. on Tuesday, November 13, an initial attempt was made to plug the hole in the chlorine tank car, but without success; a second attempt succeeded. When subsequently the tank was emptied, only 18 tonnes of chlorine was recovered.

During Tuesday afternoon, 143,000 people were allowed back home. The rest did not return until after an absence of 6 days.

The only injuries were those caused to eight firemen by inhalation of the noxious gases.

4.5.22 Montana, Mexico

From Mannan (2012)

At 5.52 p.m. on August 1, 1981, a train derailment resulted in a massive release of chlorine near Montana, Mexico. The train consisted of 38 wagons, including 32 rail tank cars containing liquid chlorine. It was moving down a steep and winding valley at a 3% gradient when its brakes failed. The driver radioed to other trains on the single track to warn them, and two trains drew into loops. The train derailed at over 80 km/h on a bend 350 m beyond Montana station.

All the chlorine tank cars were 55 short tons, say 50 tonnes, capacity. The pile-up included 28 of the 32 chlorine cars. Most were badly damaged. One tank car lost its dished end and the shell was propelled 2000 m. A second was split along its side. A third had a 0.5 m diameter hole, probably the result of an iron-chlorine fire, which could well have resulted from ignition of the cork insulation by red hot brakes. Four other tank cars suffered damage to their valves, which were ripped off or dislodged so that they leaked. It is estimated that 100 tonnes of chlorine escaped in the first few minutes and 300-350 tonnes in all.

The population of Montana was some 400 people. There was also a passenger train with some 300 people at the station. The weather conditions to be expected at the time of day would be a warm wind blowing up the valley, toward the village. The vegetation up the valley was bleached by the gas cloud passing up it; there was also discoloration some 50 m down the slope and up the sides for a vertical distance of

about 50 m. The highest concentrations appear to have occurred in a strip 1000 m long 340 m wide. Seventeen persons died, four in the caboose of the train and 13 from gassing. About 1000 people were received in hospital and 256 were detained.

4.5.23 Geneva, Switzerland

From Morabia et al. (1988):

On 8 November 1984, at 9.30 am, 550 kg of liquid bromine accidentally leaked out of a container at a chemical plant employing 250 workers, located in a densely populated area and specializing in the production of perfume and food additives. The bromine was being used to halogenate an unsaturated aliphatic hydrocarbon and was propelled by nitrogen under pressure; the leak occurred because of a defective joint on the container.

Part of the bromine in gaseous form was pumped out by a combination of the normal ventilation system assisted by an emergency unit and was thus nebulized outside the building with sufficient force to form a dense brown cloud that drifted into the neighbourhood. From there it travelled through the centre of the city and then gradually dissolved over the lake around 2.30 pm. Since bromine is heavier than air the cloud stayed low over the ground and did not rise above the third storey of buildings.

The Ecotoxicological Centre of the Canton of Geneva attempted to define the outside limits of the potentially contaminated zone. Bromine concentrations measured...were between 0.2 and 0.5 ppm They were probably much higher initially in the immediate surroundings of the plant. In the bromine cloud concentrations reached values higher than the short term exposure limit of 0.3 ppm. The exposed population was estimated to be about 25000. It was a busy time of day in the centre of town, but the schools were closed that day.

Bromine interaction with an air measurement sensor indicated that the exposure time in the affected areas was between 9 am and 11.30 am.

The fire brigade attempted to redissolve the bromine by nebulising thiosulfate but this was ineffective. The factory was evacuated and the immediate surroundings were cordoned off. The public were asked to remain indoors and close all windows. The radio and television were unable to provide useful information in the first few hours of the release and while there was no large-scale panic reaction from the public the telephone network was jammed with calls. There was no emergency number for public enquiries available and there was no communication possible between the hospital, the first aid teams and the Swiss Toxicological Centre in Zurich during the most crucial hours of the incident.

Concentrations were nearly twice the short-term exposure limit. 91 people were seen in the hospital. Morabia et al. (1988) commented that the use of questionnaires in the hospital was an effective method of obtaining information and recording it for use in doctors notes and any future epidemiological studies of the incident. Using the geographical location of the patients at the time of the onset of symptoms, they were able to estimate the limits of the exposed area and a map is provided by Morabia et al. (1988).

There was a light south-westerly wind blowing on the day.

4.5.24 Mexico City, Mexico

From the HSE website⁸⁴:

⁸⁴ <http://www.hse.gov.uk/comah/sraqtech/casepemex84.htm> Accessed on 29th May 2020

At approximately 05:35 hours on 19 November 1984 a major fire and a series of catastrophic explosions occurred at the government owned and operated PEMEX LPG Terminal at San Juan Ixhuatepec, Mexico City. As a consequence of these events some 500 individuals were killed and the terminal destroyed.

Three refineries supplied the facility with LPG on a daily basis. The plant was being filled from a refinery 400 km away, as on the previous day it had become almost empty. Two large spheres and 48 cylindrical vessels were filled to 90% and 4 smaller spheres to 50% full.

A drop in pressure was noticed in the control room and also at a pipeline pumping station. An 8-inch pipe between a sphere and a series of cylinders had ruptured. Unfortunately the operators could not identify the cause of the pressure drop. The release of LPG continued for about 5-10 minutes when the gas cloud, estimated at 200 m x 150 m x 2 m high, drifted to a flare stack. It ignited, causing violent ground shock. A number of ground fires occurred. Workers on the plant now tried to deal with the escape taking various actions. At a late stage somebody pressed the emergency shut down button.

About fifteen minutes after the initial release the first BLEVE occurred. For the next hour and a half there followed a series of BLEVEs as the LPG vessels violently exploded. LPG was said to rain down and surfaces covered in the liquid were set alight. The explosions were recorded on a seismograph at the University of Mexico.

Four of the six spherical storage tanks had a volume of 1600 m³ and two had volumes of 2400 m³. The 48 horizontal cylindrical bullet tanks were different sizes. At the time of the disaster the storage tanks contained 11,000 m³ of a mixture of propane and butane.

According to Arturson (1987) "Unburned and burning gas entered the houses south of the plant area and set fire to everything".

The US authorities concluded that the total destruction of the terminal occurred because there was a failure of the overall basis of safety which included the layout of the plant and emergency isolation features. There were various mitigation measures that were inadequate or absent. The terminal's fire water system was disabled in the initial blast and the water spray systems in place were inadequate. There was no gas detection system and so the emergency isolation was delayed and ineffective. The arrival of the emergency services was hindered by chaotic traffic due to local residents fleeing the area.

This incident was one of the largest industrial disasters in history. There were about 40,000 inhabitants in San Juan Ixhuatepec and about 60,000 more living in smaller settlements in the hills surrounding the village. In addition to the fatalities there were about 2500 injuries.

Details and other references can also be found in Mannan (2012).

4.5.25 Bhopal, India

Bhopal is probably the world's worst industrial disaster in history. In the early hours of the morning on 3rd December 1984 a relief valve on storage tank which contained methyl isocyanate lifted. About 23 tonnes of methyl isocyanate gas was released through a vertical pipe with diameter of about 20 cm from a height of about 33 m over approximately 2 hours. Reports state that a cloud of gas enveloped the area and the cloud drifted off the site into nearby housing. The atmospheric conditions (inversion and low wind speed) contributed significantly by slowing the dispersion of the gas.

More than half a million people within a radius of approximately 7 km were exposed to the gas. The acute irritant effects of MIC created panic, anxiety, and disorientation. As a result, people left their homes which increased their dose of the chemical.

Over 2000 people and hundreds of cattle died within a short period of time and hundreds of thousands were injured. The exact numbers of dead and injured are uncertain, as people have continued to die of the effects of exposure over a period of years but numbers in the order of 20,000 deaths have been approximated. The incident overwhelmed the emergency services and the hospitals which were unaware of the gas involved or the effects of exposure.

The scale of the incident means that it has been the subject of much investigation. A summary can be found in Mannan (2012). It has also been modelled and information that has been collected for modelling purposes can be found, for example, in papers by Singh et al. (1987), Havens et al. (2012) and Mishra et al. (2015).

4.5.26 Naples, Italy

On 21st December 1985 gasoline was spilled from an overfilled floating roof tank during filling from a ship at a fuel tanker terminal. The overflow continued for about 90 minutes during which time about 700 tons (635 tonnes) of fuel was spilled. The vapour spread and covered an area of about 49,000 m² before finding an ignition source, which resulted in a VCE. Three people were killed on site and two local residents were killed when their houses collapsed. The site was destroyed.

The site was in an urban environment near the port with residential buildings nearby. It was surrounded by high walls, buildings and an embankment to an average height of 8 m. There were 37 storage tanks on the site, two buildings, loading gantries and some rail tankers. The atmospheric conditions were stable with low wind speed and air temperature of 8°C.

This information is summarised from Atkinson et al. (2017).

4.5.27 Lake Monoun and Lake Nyos, Cameroon

In late evening of 21st August 1986 Lake Nyos exploded in a 'limnic eruption', which resulted in the release of approximately 1.6 million tonnes of carbon dioxide. There were about 1700 fatalities and 3500 livestock losses in local towns and villages and thousands more were injured. Trees and vegetation in the vicinity of the lake were destroyed.

Lake Nyos, is approximately 1.9 km long, 1.2 km wide and 200 m deep. The lake is situated in an elevated position with the lake surface at about 250 m higher than the valley floor less than 3 km to the north of the lake, as shown in Figure 27. The release occurred on a calm night and the dense gas flowed north down the valley, through villages and along other valleys into an area approximately 20 km long and 15 km wide.

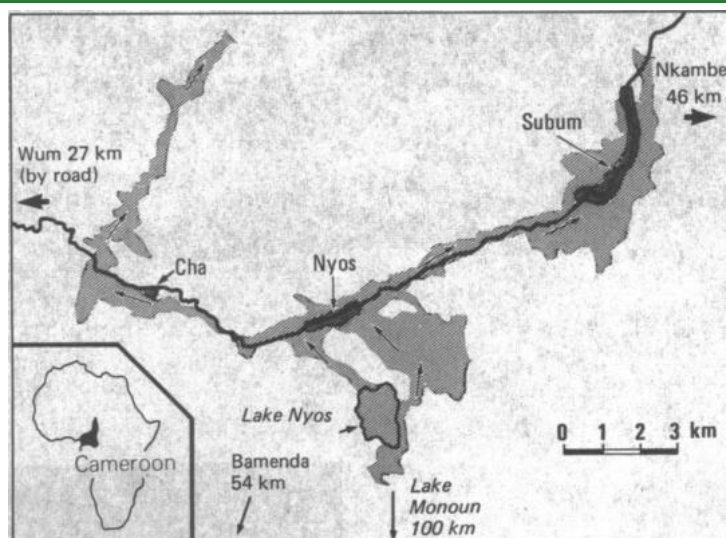


Figure 27 Location of Lake Nyos, Cameroon and the villages in the valley about 250 m below. Direction of flow of gas is shown with arrows (Baxter et al., 1989, © BMJ Publishing Group Ltd.)

Previously, on 15th August 1984 a similar event occurred at Lake Monoun. Another 'limnic eruption' released a large cloud of carbon dioxide in which 37 people were killed.

These lakes are naturally saturated with carbon dioxide from a magma chamber beneath them which continually leaks the gas. There are only three lakes in the world that are known to be saturated with carbon dioxide such that this phenomenon could occur.

Additional information can be found in the work of Baxter et al. (1989).

4.5.28 Gore, Oklahoma

On January 4, 1986 at the Sequoyah Fuels uranium conversion facility in Gore, Oklahoma a uranium hexafluoride release occurred. The event is described as follows (NRC, 2004):

A 12,700 kg overloaded cylinder containing approximately 13,500 kg of UF_6 ruptured when it was being heated in a steam chest to remove excess UF_6 . The release lasted for approximately 40 min. A dense white cloud formed and was pushed by the wind. It quickly engulfed the process building (the facility's main structure) and formed a plume expanding to the south-southeast. When the UF_6 left the ruptured cylinder, not all of it reacted immediately to form UO_2F_2 and HF; pieces of solid UF_6 were scattered widely around the steam chest area. Any UF_6 remaining when the area was sprayed down reacted with the water and was likely captured in the water spray. It was estimated that approximately half of the released UF_6 was washed into an emergency pond. Therefore, approximately 6,700 kg contributed to the noxious white cloud. When completely reacted with water, 6,700 kg of UF_6 forms 5,900 kg of UO_2F_2 and 1,500 kg of HF. Peak 10-min UO_2F_2 concentrations ranged from 0.011 mg/m^3 to 8.8 mg/m^3 , and peak 10-min HF concentrations ranged from 0.008 mg/m^3 to 2.4 mg/m^3 . One-hour average uranium concentrations ranged from <0.052 $\mu\text{g/m}^3$ to 20,000 $\mu\text{g/m}^3$. It was assumed that 4.55×10^6 g of uranium was released into the atmosphere in a 45 min period. The isotopic composition was 1.49 Ci of ^{234}U , 0.07 Ci of ^{235}U , and 1.49 Ci of ^{238}U .

There were 42 workers at the plant site when the accident occurred. Seven of the workers (contract workers) were in a trailer well away from and upwind of the release point. One worker (an operator in a scrubber building 50 ft from the steam chest) died from pulmonary edema produced by HF inhalation within a few hours of the

exposure. Another was treated for skin irritation and burns from HF exposure, and 21 others were examined at a hospital and kept overnight for observation. Four of the 21 workers were released the following morning, 14 were kept more than 1 day (d) and were given oral sodium bicarbonate to enhance uranium excretion, and three were transferred to another hospital for observation and treatment of potential lung damage from HF exposure. Of the eight employees who returned to spray water on the fumes, one was in the group transferred to another hospital with serious respiratory symptoms, and five were hospitalized for more than 1 day (including the individual with HF burns). Only two of those workers were released on the day of the accident.

Local off-site residents were also asked to report to a hospital for examination. One resident was kept overnight for observation, but no medical treatment was deemed necessary. Urine samples were collected from all on-site workers and from 100 off-site members of the public for uranium bioassay and urinalysis.

Brugge et al. (2007) provides some further details:

The facility ventilation system carried the plume of uranylfluoride and hydrofluoric acid toward the scrubber building 15 m away where Harrison inhaled the hydrofluoric acid, which caused acute respiratory injuries that led to his death. The plume left the plant and travelled 29 km (the wind was registered at 40 km per hour) south of the plant, past I-40, and over several sparsely populated residential areas.

On the day of the rupture, Sequoyah Fuels Corporation lacked a systematic procedure to deal with the emergency. The Gore Police Department was called, and they notified the Sequoyah County Sheriff's Department and Oklahoma Highway Patrol to close down I-40 and Highway 10, the side road that passed directly in front of the plant. The general public was notified through the local radio, by workers calling home, and by Sequoyah Fuels Corporation's Manager of Personnel and a representative of Gore Civil Defense going home-to-home prior to the media being informed. A hotline at Sequoyah County Department of Health also was established.

Sequoyah Fuels Corporation had not arranged in advance with Sequoyah Memorial Hospital to treat workers in such an emergency.

4.5.29 Texas City, Texas

From the HSE website⁸⁵:

On 30th October 1987, a crane carrying a 50 foot [15 m] section of a convection heater dropped its load onto an anhydrous hydrogen fluoride tank within the HF alkylation unit, shearing two lines leading to the top of the tank. This resulted in an air release of hydrofluoric acid at the Marathon Petroleum Company refinery in Texas City.

One line was a 4-inch [10 cm] acid truck loading line, and the other was a 2-inch [5 cm] tank pressure relief line. The tank was at the normal operating pressure of approximately 125 psi, so that when the incident occurred a cloud of HF was produced which moved with the prevailing wind. The tank originally contained 35,700 gallons [162 m³] of AHF, of which about 6,548 gallons [30 m³] was released over a 44 hour period, although the majority of the release took place during the first two hours as the tank depressurised. The release also included some light hydrocarbons (primarily isobutane) and water vapour.

⁸⁵ <http://www.hse.gov.uk/comah/sraqtech/casemarathon87.htm> Accessed on 29th May 2020

The first mitigation action was to place stationary fire monitor nozzles and to erect a water spray curtain about 10 feet [3 m] downwind of the release to control the HF acid vapour plume.

Approximately 4,000 people were evacuated from the residential areas threatened by the plume and the three area hospitals treated 1,037 patients, of which nearly 100 were hospitalised. There was extensive damage to trees and vegetation in the residential area.

4.5.30 Jonova, Lithuania

From Mannan (2012):

On March 20, 1989, a refrigerated atmospheric ammonia tank failed at Jonova, Lithuania, leading to both a toxic release and a fire of ammonia as well as fire in a fertilizer store. Seven people were killed and 57 injured. The tank was 29 m diameter x 20 m high of single wall construction with perlite insulation held in place by an outer steel shell and with a surrounding 14 m high reinforced concrete wall. It had a capacity of 10,000 m³ and at the time held 7000 tonnes of liquid ammonia at -33 °C. The capacity of each of the two pressure relief valves was 4200 m³/h. The site also had two fertilizer stores, one for 15,000 tonnes and one for 20,000 tonnes as well as one for 20,000 tonnes of ammonium nitrate. The rupture was sudden and the force of the release caused the tank to move sideways from its base, smash through the concrete wall, and fetch up 40 m away, leaving its bottom still on the foundations. The devastation around the tank was severe. The escaping liquid ammonia formed a pool which in places was 0.7 m deep. The vapor above the pool suddenly caught fire and the whole area was engulfed in flames. The fire set alight material on a conveyor belt to the 15,000 tonnes store of NPK fertilizer, a 'cigar burning' material. The burning conveyor fell into the store and initiated a self-sustaining decomposition. After 12 h, the pool of ammonia had evaporated. The fertilizer continued to burn for 3 days. The plant was 12 km from Jonova, a town of about 40,000 inhabitants. A large cloud of ammonia and nitrous fumes spread 35 km, covering an area of 400 km². The cloud height is described as being 100, 400, and 800 m at distances of 5, 10, and 20 km, respectively. Some 32,000 people were evacuated. The events leading up to the rupture were as follows. Due to an error, 14 tonnes of warm ammonia at 10 °C were transferred to the tank, where they formed a layer on the bottom. In due course, this layer rose suddenly to the surface. The event was akin to a 'rollover,' although this term is normally associated not with a pure liquid but with one of varying composition, such as LNG. The higher vapor pressure of the warmer liquid caused a sudden rise in pressure in the tank, which the pressure relief valves were unable to handle, and the tank burst. At the time the refrigeration compressors were not working, but this probably played little part in the incident.

The ARIA Report No. 717 (ARIA, 2007) of the incident says that the 'rollover' type event may not have occurred and there could be other causes of a sudden rise in pressure. The report also mentions that there was only a light wind (< 2 m/s). There is the following additional information:

According to the report from the Soviet authorities, the concentration of ammonia along the track of the cloud and within a radius of 3 km did not exceed 200 mg/m³. The levels found at a distance of 10 to 15 km were between 20 and 40 mg/m³. These relatively low levels of ammonia could be explained, at least in part, by the ignition of the ammonia vapour in the plant. The maximum distance over which the presence of ammonia could be detected in the air was 23 km.

To reduce the impact of the cloud on the surrounding areas, water curtains were set up using fire hoses all along the track of the gas cloud. Furthermore, special

measures for the protection of water courses were taken to avoid the risk of pollution of the nearby NERIS river. Pumping of the extinction water, positioning of containment basins...

The incident has been modelled as a passive gas release by Kukkonen et al. (1993) using a Gaussian plume model. The objective of the study was to analyse the data and to determine whether this sort of release could cause long range effects such that any impact might be observed in Finland. They argue that an evaporating liquid pool of ammonia does not produce a heavier than air gas cloud because ammonia vapour at its boiling point is lighter than air at ambient temperatures. As a result, a heavy gas cloud could be formed only if there was significant aerosol formation, which they considered to be unlikely in the conditions at the time of the incident.

4.5.31 Ufa, Russia

At about 01:00 on 4th June 1989 the trans-Siberian LPG pipeline ruptured and discharged LPG from both ends. A very large vapour cloud formed with approximate area 1.5 km². The cloud ignited when two trains on the Trans-Siberian railway passed each other within the cloud and a very large VCE occurred. 1224 people on the trains were killed or badly injured, many with 70-80% burns.

The pipeline was 1852 km long and the pipeline diameter was 700 mm with a design flow rate of 116 – 120 kg/s. The working pressure was 38 bar. It was buried at a depth of 1.2 – 1.5 m. The cause of the rupture is unknown but suspected to be a material failure. When the drop in pressure was detected by the pipeline operators, they increased the flow rate in an attempt to sustain the level of flow. It has been suggested that this continued for 3 hours.

The release occurred in a very rural, densely forested location about 1.5 km from the pumping station. The pipeline was approximately 0.8 km from the railway line and at a slightly higher elevation. The vapour cloud was strongly affected by the topography. The cloud size increased due to spreading down valleys leading away from the source. It was suggested to have accumulated in two large terrain depressions. Villages up to 7 km away could smell the release before the explosion occurred.

This incident was summarised in Mannan (2012) and in the review of Atkinson et al. (2017). There does not appear to be a large body of information available.

4.5.32 Baton Rouge, Louisiana 1989

On 24th December 1989, a design error caused a refinery facility at Baton Rouge to enter 'fail safe mode' after a power outage, which caused various components of the system to default to wide open or fully closed. Ethane and propane were released at high pressure due to a valve automatically opening on an 8 inch (20 cm) line. The release rate of the ethane/propane vapour/mist was approximately 1500 lbs/s (680 kg/s) for approximately 2.5 minutes. The cloud footprint had a circumference of approximately 1000-1500 ft (305-457 m) and was approximately 80 ft (24 m) deep. Eventually the cloud found an ignition source, which resulted in a VCE.

The site was situated on a flat flood plain in an urban, residential setting next to the Mississippi river. The atmospheric conditions were stable with wind speeds of approximately 1.5-2.1 m/s and a temperature of about -1.7-0°C.

There was one employee fatality and seven injuries as a result of the incident.

This information is summarised from Atkinson et al. (2017).

4.5.33 St Herblain, France

On 7th October 1991 a large leak from an inadequate seal on a fitting at the foot of a gasoline tank at a fuel depot resulted in an upward pointing spray. The fitting was attached to a 12 inch (30 cm) line and the tank was filled to a depth of about 9 m. A vapour cloud developed over about 20 minutes to a volume of about 25,000 m³, with an observed depth of about 1.5 m. Eventually the cloud found an ignition source, which resulted in a severe VCE. There were no fatalities.

The site was in a fairly flat urban industrial area at a port. The vapour flow was affected by the presence of bunds.

The incident occurred during stable conditions, with nearly nil wind < 1m/s, 100% humidity and ambient temperature of 5°C.

This information is from Atkinson et al. (2017). Additional information can be found in the paper by Lechaudel and Mouilleau (1995).

4.5.34 Dakar, Senegal

On 24th March 1992 at an oilseed processing facility in Dakar, Senegal, an ammonia transport tank failed catastrophically to release liquefied ammonia.

From ARIA website⁸⁶:

An unconnected tanker truck carrying liquid ammonia (NH₃) burst open at an industrial facility. Propelled by chemical reaction, with the front part “of the tanker clipped some of the installations then smashed into the wall of an electrical service building, while the back part angled at 45° upward violently smashed against the reinforced concrete lintel of a neighbouring building, then ricocheted in the direction of the unit, seriously damaging its upper level. An axle was found 200 m away on a nearby site. A portion of the 22 tons [20 tonnes] of NH₃ contained in the tank spread through the installation, while another portion was projected with the back of the tank beyond the site boundary. According to eyewitness accounts, the whitish toxic cloud moved about 250 m and dissipated within 10 to 15 min. Liquid NH₃ projection lengths reached some 30 meters. The noxious atmosphere hindered the emergency intervention team, which was not equipped with adequate protection, including masks and oxygen cylinders. Both the time (1:30 pm, as a new shift was taking over) and the place of the accident, near the port’s industrial rehabilitation zone, would explain in part the tremendous number of casualties: 129 dead and 1,150 injured, with some victims being burned directly by NH₃ or intoxicated by NH₃ vapours. Other victims with outbreaks of lesions were diagnosed as not serious at first, but went on to develop a fatal pulmonary oedema just a few days later. According to the press, onlookers heard the sound of the explosion and flocked towards the contaminated zone, only to fall victim to the accident as well.

This accident was due to overfilling of the tank (22.2 tons [20 tonnes] for a 17.7 ton [16 tonne] capacity), which seems to reflect frequent practice. The tank broke at the level of a repair weld performed 2 years prior upon detection of a leak during a hydraulic test.

Additional details can be found in the full ARIA Report 3485 (ARIA, 2006).

⁸⁶ https://www.aria.developpement-durable.gouv.fr/fiche_detaillee/3485_en/?lang=en Accessed 8th March 2020

4.5.35 Brenham, Texas

Early in the morning on 7th April 1992, LPG escaped from an underground storage cavern due to overfilling. It is not known how much was released but it has been estimated to have been between 400 m³ and 1360 m³. A vertical two-phase jet of gas/liquid LPG exited via a brine pond and, according to witnesses, the fountain of liquid reached a height of 50 ft. A large vapour cloud formed with an eventual area of about 625,000 m². Once it found an ignition source, the gas ignited and produced a large VCE.

The atmospheric conditions were stable with almost nil wind at the time of the incident. The cloud spread was influenced by rolling hilly terrain and the vapour accumulated in shallow valleys near the source. There was woodland and some small residential areas also in the vicinity.

There were three fatalities of members of the public and several injuries. Some livestock were also killed and houses within 2 km of the edge of the cloud were damaged.

The overfilling occurred for several reasons. The storage capacity of the underground tank was unknown and the 'well-head' safety system was not working. The operators lost track of the fill level because the accounting system for deliveries was defective. There was a vapour detection system installed on site but the response involved an operative travelling to the site to investigate.

This incident was summarised in the review of Atkinson et al. (2017). There does not appear to be a large body of information available.

4.5.36 La Mede, France

On 9th November 1992 at La Mede, 15 tons of LPG and light naptha were released in about ten minutes through a 25 cm² (80 x 20 cm) opening in an 8 inch bypass pipe. The resulting vapour cloud covered an area of approximately 14,000 m², including various other site units and varied in height between 4 and 6 m. Eventually, the cloud ignited on the main furnace. The subsequent knock-on effects led to further loss of containment and escalation. Six operators died and two were seriously injured.

The site was situated in an open rocky dale in a rural setting. The ambient temperature at the time of the incident was approximately 5°C. The bypass pipe failed due to thinning by internal corrosion. It had been in service for 36 years but it was not regularly inspected because it was a bypass pipe.

This information is summarised from Atkinson et al. (2017). Further information can be found in the Aria Report 3969 (ARIA, 2008b).

4.5.37 Richmond, California, 1993

An unconfirmed report from a media article⁸⁷ recorded the event as follows:

JULY 27, 1993 A huge white cloud of sulfuric acid spewed from a ruptured railroad car Monday, engulfing thousands of homes in Contra Costa County and sending more than 3,200 people to hospitals with such symptoms as burning eyes and breathing problems, authorities said.

The stinging, smelly chemical poured out of the rail car for more than three hours, creating a cloud 1,000 feet [305 m] high and up to eight miles wide, before rail yard workers were able to cap the leak.

⁸⁷ <https://www.latimes.com/archives/la-xpm-1993-07-27-mn-17514-story.html> Accessed 24th April 2020

The thick chemical fog rolled east and north, growing larger as it moved through densely populated neighborhoods and industrial sections of Richmond, San Pablo, El Sobrante and Pinole before dissipating over San Pablo Bay.

"The cloud was so thick you could hardly see," said Orlean Pitri, who lives near the General Chemical Corp. rail yard where the leak occurred. "By the time I closed the windows, the whole house smelled like rotten eggs. It smelled terrible."

The spill temporarily shut down Interstate 80, commuter trains, bus service and mail delivery in the Richmond area, across the bay from San Francisco.

Paramedics set up a first aid station at a firehouse, hosed down victims in the parking lot and gave them hospital gowns to wear before busing them to hospitals for further treatment.

Local hospitals were inundated with people who came by ambulance or on their own with complaints of breathing difficulties, nausea, irritated skin and burning eyes, mouths and throats.

At least six people were hospitalized with complications of pre-existing lung conditions. Most victims were treated for exposure to the chemical and released.

As much as 70 tons [64] of oleum--a highly concentrated form of sulfuric acid used in manufacturing soap, among other products--escaped from the General Chemical Corp. tank car when the disc in a safety valve ruptured.

The safety valve was designed to pop open if pressure reached the dangerous level of 100 pounds per square inch [689 kPa]. Instead it ruptured when the pressure was only 55 pounds per square inch [379 kPa], General Chemical spokesman Eric Miller said.

"We're still at this time uncertain about the cause," he said.

The chemical, which was manufactured at the General Chemical facility, was being transferred from one part of the plant to another when the accident occurred.

About 30 tons [27 tonnes] of oleum had been unloaded from the car when the valve broke at 7:15 a.m. Workers were forced to wait until most of the remaining gas had escaped and the pressure was sharply reduced before they were able to stop the leak about 11 a.m.

Authorities evacuated a small area around the scene and directed residents in the path of the cloud to stay indoors, shut their windows and turn off their air conditioners.

But children playing outside, morning joggers, residents working in their yards and motorists on their way to work were caught by the toxic cloud as it passed through the area. Shortly after noon, the directive to stay inside was lifted.

4.5.38 Savannah, Georgia

On 10th April 1995 there were a series of explosions and a fire at a commercial bulk liquid chemical storage and transfer facility located about 2 miles (3 km) outside of the centre of the city of Savannah, Georgia. The fire broke out within an enclosure (bund) with 5 ft (1.5 m) high concrete walls containing six large storage tanks. The enclosure was approximately 100 ft by 200 ft (30.5 m by 61 m). During the fire, part of the bund wall was breached.

The EPA report (US EPA, 1998) says the following:

After the fire, chemicals leaking from the storage tanks in the enclosure area reacted and produced toxic hydrogen sulfide gas. The hydrogen sulfide gas release forced residents

within one-half mile of the facility to evacuate. As many as 2000 people were involved in the evacuation. An elementary school nearby was also forced to close. Approximately 300 people went to hospital emergency rooms complaining of symptoms attributed to hydrogen sulfide exposure. For many nearby residents, the evacuation lasted more than 30 days because of the continued evolution of hydrogen sulfide gas from the PDTI site. After the incident, extensive cleanup of the site and neighboring area was required.

The hydrogen sulphide gas cloud not only impacted on the surrounding population but also hampered the emergency response and clean-up of the initial fire.

The EPA identified several procedures and mitigation measures that were either not in place or failed that would have prevented or restricted the gas formation and spread. In particular, the storage of incompatible chemicals in the same walled enclosure. A quantity of 340,000 gallons (1287 m³) of 45% sodium hydrosulfide solution was stored in the same enclosed area as 250,000 gallons (946 m³) of acidic cleaning solution and when the tanks leaked the chemicals reacted generating hydrogen sulphide. Also, the enclosure wall was breached during the fire-fighting, which allowed the gas to escape more readily.

4.5.39 Baden-Wurttemberg, Germany

On 25th January 1999 an indoor release of hydrogen sulphide escaped and could be smelled in a nearby residential area. The ZEMA report was translated and summarised by Danielsson et al. (2009) as follows:

Wash water from a reactor was transferred to a multi-purpose collection tank by nitrogen pressure. The automatic pumping of the waste water to the waste water treatment could not take place as the tank was full and the valve closed. This led to an overfilling of the multi-purpose collection tank and the escape of waste water into the exhaust gas system leading to the exhaust gas treatment.

Another container into which ca. 4,000 kg Phosphorous Pentasulphide had been charged was also connected to the same exhaust gas system. Water was thus able to enter this container so that the Phosphorous Pentasulphide and water were able to react, generating Hydrogen Sulphide. Due to the sudden increase in pressure a seal partially failed releasing Hydrogen Sulphide into the room in which the plant was housed. The H₂S alarm was triggered automatically. Through the mechanical ventilation system and through doors and windows, the Hydrogen Sulphide was able to escape into the neighbourhood where it was rapidly dispersed. However the smell was clearly noticeable in the nearby residential area.

There were no injuries or fatalities recorded.

4.5.40 Richmond, California, 2001

The same site as described in Section 4.5.36 had another incident in 2001 as reported in an unconfirmed media article⁸⁸:

2001-05-02 04:00:00 PDT Richmond - A freak power failure at the General Chemical Corp. plant in Richmond sent a potentially dangerous cloud of sulfur dioxide and sulfur trioxide billowing into the air yesterday, forcing thousands to stay in their homes and sending more than 100 people to local hospitals for treatment.

The leak began at 2:11 p.m. about 20 minutes after a tank truck hit a power pole outside General Chemical on Castro Street near Interstate 580, knocking out the plant's electricity.

⁸⁸ <https://www.sfgate.com/bayarea/article/Industrial-accident-releases-toxic-gas-Sulfur-2923960.php> Accessed on 24th April 2020

Once power was restored by Pacific Gas and Electric Co., workers spotted a problem with a compressor in a system that transforms sulfuric acid into sulfur dioxide and trioxide. A safety valve that had shut down the compressor would not reopen, causing the chemicals already in the system to escape.

Within minutes the chemicals were spewing into the air, though at first the cloud went straight up and appeared to pose no threat -- so no alert went out to the thousands of residents who live near the plant, said Terry Lee, spokeswoman for the Bay Area Quality Management District.

Then at 3:55 p.m. -- more than 90 minutes after the leak began -- winds started pushing the cloud east and toward the ground. At that point, Contra Costa County health officials ordered sirens sounded and shelter-in-place phone calls to begin to residents within a half-mile of General Chemical. The calls recommend that residents stay inside and close all windows and doors.

Police closed the Richmond Parkway and a 10-block area around the plant.

Company spokesman Tom Brafford said General Chemical alerted county officials immediately after the power went out and followed proper safety procedures.

Lee said it was not clear whether the toxicity of the fumes was enough to cause serious harm to residents, but about 80 people sought treatment at Kaiser Permanente Medical Center in Richmond. Forty more went to Doctors Medical Center in San Pablo.

Most complained of irritated eyes and throats, said Dr. Alan Whippy of Kaiser's emergency room. No one was admitted to either hospital.

General Chemical workers were not able to reopen the valve until 6:20 p.m. -- and the chemicals were being released throughout that time, Brafford said.

No employees were evacuated or hurt, Brafford said. The cloud rose less than a hundred feet [30.5 m] into the air at its highest and was about 300 yards [274 m] wide, said Richmond fire officials.

The company estimated that as much as 506 pounds [230 kg] of sulfur dioxide and 244 pounds [111 kg] of sulfur trioxide were released into the environment during the nearly five-hour episode.

Sulfur dioxide and sulfur trioxide are lung irritants that are especially harmful to people with asthma, according to Paul Blanc, chief of the division of occupational and environmental medicine at the University of California at San Francisco.

"Lower-level exposures are very common," Blanc said. "Very high-level exposures can be fatal, but they are not that common because it's not that commonly used."

The leak revived nightmarish memories of an oleum spill at General Chemical in 1993 that sent 24,000 people to hospitals seeking medical attention, and it caused new anger over the perils of living next to chemical plants.

The article goes on to describe eye-witness accounts of the incident and, in particular, a lack of information provided to the surrounding neighbourhood. Warning sirens were sounded but locals were unsure how to react. There was a ten block police cordon around the plant and the police drove through streets advising people to stay inside.

4.5.41 Festus, Missouri

From Hanna et al. (2009):

The Festus accident began at 9:20 a.m. CDT on August 14, 2002... The chlorine was being offloaded from a railcar parked at a chemical facility. The tank pressure was estimated to be 175 psig and the tank temperature was assumed to be the same as the ambient temperature, 20°C. A 2.5 cm diameter hose ruptured at a height of 3.5 m near the railcar. However, because of the sequence in which the automatic closing of various safety valves in the system occurred, the actual release jet was seen to initiate from a pipe at a height of 3 m adjacent to the industrial tank structure and to impinge on the side of the railcar 2 or 3 m away. Most of the jet was deflected underneath the railcar and could be seen coming out from the other side; 21,792 kg of liquid chlorine were released at a nearly steady rate over 3 h, for an average release rate of 2.02 kg/s. The written government reports, on-site observations by witnesses, and Fox News videos confirm the steady nature of the release and the visible cloud. After 3 h, the release was stopped by the emergency responders. Videos and photos show a large visible chlorine gas cloud, of depth about 1 m and width about 20 or 30 m around the railcar. In the Fox News videos, the earliest indicated time is 9:56 a.m., i.e. 30 min after the release started. Therefore, no information exists about the observed arrival times of the visible gas cloud from photographs and videos.

Weather conditions were overcast with some drizzle, implying that atmospheric stability was neutral (class D). Wind speeds were observed to be 3 m/s at the St. Louis airport, which is about 60 km north of Festus. Surface roughness length of the general area was estimated to be 20 cm.

Tree leaves and vegetation turned brown due to the effects of the chlorine cloud passing.

The Festus incident has been analysed in some depth along with Macdona, Texas and Graniteville, South Carolina, in order to extract information for input in a model evaluation exercise by Hanna et al. (2008) and Hanna et al. (2009). The input data is summarised in those references.

4.5.42 Pennington, Alabama

From the CSB incident investigation report (CSB, 2003):

Burkes Construction employees were working on a construction project at the Naheola mill in the vicinity of the tank truck unloading station, where various chemicals could be unloaded. Sodium hydrosulfide (NaSH) was being unloaded on January 15–16 [2002].

The unloading station consists of a large concrete pad sloped to a collection drain. A shallow concrete pit containing unloading pumps and associated process piping is located directly next to the pad and collection drain. This pit—commonly referred to as the oil pit—collects rainwater, condensate, and occasionally spilled chemicals from the unloading station. Due to environmental concerns about oil from the fuel oil pumps getting into the mill effluent, the drain valve from the oil pit to the acid sewer was locked closed.

The job required Burkes employees to work in or near the oil pit, which—at the time of the incident on January 16—contained liquid. Those interviewed estimated that it was typical for approximately 5 gallons [0.02 m³] of NaSH to collect in the oil pit from various sources (pump leaking, flushing unloading lines, etc.) during each offloading of a tank truck.

Fifteen tank trucks of NaSH had unloaded in the 24 hours prior to the incident. Consequently—though the material in the pit was mainly water—it also contained NaSH from the unloading of the 15 trucks. To avoid having the construction crew

stand in the fluid-filled pit, an operator opened a valve to drain the oil pit; after 5 minutes, the valve was closed and relocked.

In the same area, three Davison Transport tank trucks arrived carrying NaSH. With the assistance of two Georgia-Pacific operators, one of the truck drivers connected his vehicle to the unloading hose. Witnesses estimated that when the connection was made, up to 5 gallons [0.02 m³] of NaSH spilled to the collection drain. (The tank truck, however, was not actually unloaded.)

On the day of the incident, sulfuric acid was being added to the acid sewer to control pH downstream in the effluent area. NaSH from the oil pit and the collection drain drained to the sewer and reacted with the sulfuric acid to form H₂S. Within 5 minutes, an invisible cloud of H₂S gas leaked through a gap in the seal of a manway in the area of the Burkes Construction workers. Two contractors near the manway were killed by H₂S poisoning; seven other Burkes employees and one Davison Transport driver were injured due to H₂S exposure.

Seven of the injured contractors were driven in private vehicles to Thomasville Infirmary in Thomasville, Alabama. Choctaw County Emergency Medical Services (EMS) transported three other victims (including the two fatally injured) to hospitals in Meridian, Mississippi. The clothing of one victim was completely removed and placed in a bag; the clothing of the other two victims was not removed.

The six Choctaw County paramedics who transported the victims reported symptoms of H₂S exposure; however, the two paramedics who removed the clothes of their patient reported milder symptoms. All of the County paramedics were medically evaluated and then released.

4.5.43 Dalton, Georgia

On 12th April 2004 highly toxic and flammable allyl alcohol and toxic allyl chloride were released into the community near to MFG Chemical Inc. in Dalton, Georgia after a runaway chemical reaction during production of triallyl cyanurate.

A 4000 gallon (15 m³) reactor was over-pressurised by the runaway reaction which caused a manway gasket to blow and the dense white vapours to spray out of the manway. After about 30 s, a rupture disk also blew and more vapour escaped out of a 4 inch (10 cm) vent pipe near the reactor base. The released vapours formed a dense cloud and continued to escape from the reactor for more than eight hours because neither the local fire department, nor the MFG personnel, had appropriate PPE to safely enter the area and stop the release. The cloud rapidly expanded and spread off-site.

Firefighters responding to the incident unknowingly drove through the vapour cloud as it spread over a road to the east of the facility. Their eyes and nostrils were irritated by the toxic cloud. Water sprays were used on the vapour cloud and foam was sprayed on the liquid pool under the reactor to mitigate the release. The fire brigade ordered all residents and businesses within half a mile (0.8 km) radius of the facility to evacuate. There were no emergency sirens or community-wide emergency alert systems so the police were dispatched to alert residents of the evacuation. This meant that the police had to enter the vapour cloud.

Thick chemical odours were observed in the local neighbourhoods. One employee suffered chemical burns and 154 people required decontamination and treatment for chemical exposure, including 15 police and ambulance personnel.

In their analysis of the event, the CSB found that the fire brigade should have directed the emergency response personnel to remain at a safe distance from the vapour cloud in order to mitigate exposure.

Modelling of the gas dispersion from this release was undertaken by the CSB using SafeSite_{3G}⁸⁹ and is summarised in their report of the event (CSB, 2006). Specific details such as whether a dense gas model was used are not recorded in the report.

4.5.44 Macdona, Texas

From Hanna et al. (2008):

Macdona, Texas, June 28, 2004, 5:03 am CDT

A collision of two trains occurred along a rail line where the main line met a side track in a rural area. The total release (including the initial large two phase cloud and the subsequent smaller vapour release) lasted about 7 hours, ending when wooden plugs were forced into the puncture, which was about 2" by 11" [5 cm by 28 cm] on the lower part of the end of the car. However, most of the mass was released in the flashing plume during the first 3 min. A much smaller gas release rate occurred over the next few hours. Witnesses reported a visible cloud in the neighbourhood of the accident shortly after the release. Grass was turned brown over an area of radius of about 200 m... About 120,000 lb [54 tonnes] of liquid chlorine was released.

Additional details of the emergency response are summarised by Endregard et al. (2011) as follows:

On 28 June 2004, two trains collided near Macdona, Texas, in the United States. A tank car containing 90 tonnes of chlorine ruptured, resulting in a chlorine release of 60 tonnes. 78 000 gallons [295 m³] of urea fertilizer were also released, in addition to diesel fuel from the four derailed locomotives (Aristatek, 2007). The conductor of the Union Pacific train was killed, while two residents died from chlorine inhalation. In addition, 43 people were hospitalized due to chlorine inhalation. Responders from the Southwest Volunteer Fire Department were the first to arrive on the scene. They reported driving into a "yellow cloud" of an unknown substance (Aristatek, 2007).

Emergency personnel had problems rescuing nearby residents because of the train derailment which blocked the main road (Aristatek, 2007). A flooded river made the rescue even more complicated. In addition, the emergency personnel did not possess sufficient personal protective equipment, making the rescue less efficient. When a team finally entered the area and reached the residents, many of the residents were in considerable respiratory distress (Aristatek, 2007). The two people who died from chlorine inhalation were reached approximately seven hours after the accident.

In the aftermath of the accident, there has been some criticism regarding lack of coordination between the responding agencies (Aristatek, 2007). It has also been highlighted that the residents could have been rescued sooner. The cleanup costs of the chlorine spill near Macdona were estimated to approximately \$7 million (Aristatek, 2007).

The Macdona incident has been analysed in some depth along with Festus and Graniteville, in order to extract information for input in a model evaluation exercise by Hanna et al. (2008). Input data is summarised in that reference.

4.5.45 Graniteville, South Carolina

From Hanna et al. (2008):

Graniteville, SC, Jan 6, 2005, 2:45 am EST

⁸⁹ <https://www.bakerrisk.com/products/software-tools/safesite/> Accessed 4th June 2021

The train collided with a parked train in an area consisting of a mixture of woods, fields, industrial buildings, and residences. Early reports indicated a hole with diameter about 4" or 5" [10 cm or 13 cm] in the side of the car. Witnesses reported a visible cloud spread in all directions near the release point... At larger distances from the release point, the cloud followed the general airflow. The location was near the intersection of US Route One and State Route 191... The NTSB report stated that about 120,000 lb [54 tonnes] of chlorine was released. Most was released as a two-phase jet in the first minute, but smaller amounts of gas were released for several hours.

The incident occurred when a previous rail crew had used the rail switch and forgotten to switch it back, so that the train was sent down a different track rather than staying on the main line. Nine people died after inhaling chlorine, and it is estimated that 550 people needed medical assistance. About 5400 people had to evacuate as a result of the chlorine spill (Endregard et al., 2011).

The Graniteville incident has been analysed in some depth along with Festus, Missouri and Macdona, Texas in order to extract information for input in a model evaluation exercise by Hanna et al. (2008). Input data is summarised in that reference. Graniteville was also modelled more recently in a comparison exercise of ALOHA with HPAC (Jani, et al., 2016).

4.5.46 Mönchengladbach, Germany

On 16th August 2008 at about 06:10 am, there was a fire in a paint shop in the town of Mönchengladbach. The fire alarm in the building sounded and the fire brigade were called to the scene. The fire triggered the fire extinguishing system in the building, which emitted carbon dioxide as an extinguishing agent. A system fault meant that the extinguishing system continued well beyond the extinction of the fire. In the end about 40 m³ of the 50 m³ liquefied carbon dioxide tank was gone. Due to failure of the door seals, the gas spread out of the building. The density of carbon dioxide and the very still atmospheric conditions meant that it remained near the ground and displaced the oxygen in the local neighbourhood. The first fire-fighters on scene found that their vehicles stalled due to the lack of oxygen. Fire-fighters, residents and passers-by experienced respiratory problems and some were incapacitated.

As a result, the fire brigade raised the alert level to the highest level for mass casualties and help was sought from surrounding towns. A 2 km safety perimeter was established and rail and motorway traffic was stopped. A treatment centre was set up at a safe distance from the site. 107 people with signs of injury were rescued and 19 people were hospitalised including six rescue personnel. The inhabitants of the area were either evacuated or told to close all windows and doors and go to upper levels of buildings.

The fire department used fans to mix and displace carbon dioxide from lower rooms and cellars of buildings and measuring teams checked for carbon dioxide and oxygen levels. When the carbon dioxide cloud did not dissipate, police helicopters were used to mix the air and dilute the concentration of the gas. This took several hours. The residents were allowed to return to their homes at the end of the afternoon.

While measurements were made of carbon dioxide levels during the event, it is unknown whether this data was recorded and if it is available.

Information about the incident can be found in ARIA (2008c) and the online ARIA Report 35063⁹⁰ (French summary).

⁹⁰ https://www.aria.developpement-durable.gouv.fr/accident/35063_en/?lang=en Accessed on 29th May 2020

4.5.47 Antwerp, Belgium

On 2nd September 2008 at a refinery in Antwerp, a safety valve opened and released 70 kg of hydrogen sulphide. The plant is situated on the eastern riverbank of the river Schelde to the north of Antwerp and about 6 km south of the border between Belgium and The Netherlands.

The ARIA Report No. 35905 (ARIA, 2009) says the following about the incident:

The morning of September the second, maintenance work was planned by the company that supplies the electrical power to the refinery. The two power lines had proved to be fragile and it was planned to replace the connections in both power lines. To that order one of the power lines was shut off at 11.56 am.

A plan to do this had been communicated beforehand, and it was tested that the remaining power supply would have enough capacity to transmit the necessary electrical power.

At 11.57, whilst maintenance work was being carried out at one of the two the electrical power supply lines, the remaining second supply line failed, thus rendering the refinery without electrical power supply.

At 11.57, start of the execution of the emergency plan, implying emergency shut down of the refinery, evacuating all not necessary personnel and retaining only the emergency staff and starting of the emergency power supply to restart the central operating desk.

At 12.00, product stream is led to torch, leading to large flame and release of soot (carbon black) to the atmosphere. At the same time opening of several safety valves emitting several kinds of hydrocarbons to the atmosphere among which Benzene. Also H₂S (hydrogen sulphide) is emitted.

At 12.14, the Antwerp environmental services are by fax informed of the incident with an emergency shut down. No assistance was deemed necessary by the operator or the environmental services.

At 12.30, assistance of emergency services is requested by neighbouring companies because of large soot deposits on their sites and respiratory problem of some of their personnel.

At 12.41, arrival of the emergency services at the site. They are informed of the incident.

At 13.00, the crisis staff of the ministry of the interior of the state of Belgium is informed about the incident.

At 17.15, the supply of electrical power is restarted, and preparations are started to restart the refinery.

In the first minutes of the incident a safety valve opened and released 70 kilograms of hydrogen sulphide (approximately 40 m³ of pure H₂S gas).

The safety valve is situated at a height of about 40 metres. After the release a cloud of H₂S formed, which migrated, with a speed of 45 kilometres/hour in north-north-eastern direction.

Later analysis revealed that at ground level the concentration of H₂S reached about 0.6 ppm whilst in the centre of the cloud the concentration was in excess of 10 ppm. After ca. 5 minutes the cloud reached inhabited areas to the north of the refinery, causing acute illness, nausea, respiratory problems and a general feeling of unwell being.

In the course of the next 70 minutes the cloud travelled about 50 kilometres over Belgium and parts of The Netherlands, affecting several hundreds of people. Fifty-seven people needed medical care, but nobody was seriously injured.

4.5.48 Viareggio, Italy

Just before midnight on 29th June 2009, a train transporting LPG derailed while passing the railway station in the city of Viareggio at 90 kmph. It is thought that the derailment was caused by the rupture of a wheel axle on the front tanker.

The train had 14 tankers with capacity 110 m³, each loaded with 45 tonnes of LPG. Five of the 14 rail tankers overturned. The front tanker was breached with a hole about 40 cm long and 2 cm – 5 cm wide. All of the LPG was lost from this tanker, but there was no loss of containment from the other tankers.

The released liquid formed a boiling pool on the railway ballast, which emitted a dense gas cloud. Eyewitnesses saw a low white cloud of gas moving towards their houses. The meteorological data at the time of release indicated 22°C, 92% relative humidity, stability class F and 0.7 m/s wind speed resulting in near calm weather conditions which meant that the cloud spread radially and did not disperse quickly.

The cloud spread through a fence separating the station from a long narrow street parallel to the railway line on which people lived. The warm temperatures meant that windows were open and the gas entered houses and accumulated in basements in flammable concentrations. After between 100 s and 300 s (witness approximations) it found an ignition source and ignited causing a flash-fire in the cloud and a large scale fire near the damaged tanker.

32 people died and more than 30 people were seriously injured. About 1100 people were evacuated. Buildings up to distances of approximately 200 m were damaged by collapsing apartment blocks. About 300 firefighters were involved in the incident and by dawn all of the fires were under control.

Information has been gathered from eyewitness accounts and subsequent damage analyses. The Viareggio incident was modelled by Brambilla and Manca (2010) and Pontiggia et al. (2011), soon after the event. Manca (2014) reported subsequent information that may assist any future modelling and further information about the incident can be found in the paper by Landucci et al. (2011) and ARIA Report No 36464 (ARIA, 2011).

4.5.49 Jaipur, India

On 29th October 2009 on the Indian Oil Company site in Jaipur, the incorrect operation of a valve at the bottom of a large gasoline tank resulted in a fountain of gasoline being emitted vertically upwards from near ground level. The slot was approximately 5 cm x 25 cm and over a period of 75 to 90 minutes approximately 450 – 540 m³ of gasoline was released. A vapour cloud formed and spread along the ground as a density current. The very low wind and stable conditions limited dilution and assisted the spread of the cloud, which spread to cover the whole site, an area of about 700 m x 700 m. Unlike other VCE events, such as Buncefield, the humidity levels were low which meant that there was no condensation of atmospheric moisture and the vapour cloud was not visible.

The site was flat and sparsely occupied with large open areas between site buildings and structures. There was a 2.5 m wall around the site which was very effective as a mitigation measure against spread of the vapour cloud into the neighbourhood around the site, but it also meant that the cloud depth built up within the contained area. An emergency exit through the wall had been blocked up, so some travel distances through the cloud to evacuate the site were very large (~700 m). As a result, some personnel were unable to

escape and were trapped in buildings. Eventually the spreading cloud found an ignition source and a severe VCE occurred.

The tank was fitted with remote shut off valve that should have mitigated the release and prevented the loss of containment, but it had not been operational for several years.

During the event 11 people were killed, including 2 deaths from asphyxiation, and over 100 people were injured.

Detailed information is available on this event, see for example Johnson (2012). It was recently analysed in depth in the review of Atkinson et al. (2017) and has been modelled by the Indian Oil Company Accident Committee using Phast (MoPNG Committee, 2010).

4.5.50 San Juan, Puerto Rico

In the very early hours of 23rd October 2009 at a fuel storage depot at San Juan (Puerto Rico), a five million gallon (18,927 m³) above ground storage tank overflowed into a secondary containment bund during off-loading of gasoline from a tanker ship. Approximately 200,000 gallons (757 m³) of liquid were released. The gasoline cascaded down the side of the tank and formed a large vapour cloud, which overtopped the bund wall and spread across the site. The approximate radial distance from the tank was about 385 m when it reached an ignition source and ignited, causing a very large VCE. There were no fatalities and three people off-site had minor injuries.

The event took place in near calm conditions.

Failure of the tank side gauge or 'float and tape' apparatus were the likely cause of the overfilling, with potential failure of the tanks internal floating roof and variations of the flow rate from the tanker also contributing factors.

Analysis suggested that the leak may have entered the drainage system and triggered an explosion at a more distant vent.

Detailed information is available about the event. There is CCTV footage and physical evidence in photos. The incident was analysed in depth in the review of Atkinson et al. (2017). Also, the CSB created a video reconstruction which is available on their website⁹¹.

4.5.51 Theodore, Alabama

On August 23, 2010, at the Millard Refrigerated Services facility in Theodore, Alabama, hydraulic shock caused a roof-mounted 12-inch suction pipe to catastrophically fail leading to the release of more than 32,000 pounds (14.5 tonnes) of anhydrous ammonia. The hydraulic shock was enabled during the restart of the plant's ammonia refrigeration system following a 7-hour power outage. In addition to the catastrophic failure of roof-mounted piping, the pressure developed by the hydraulic shock event also caused an evaporator coil inside the facility to rupture.

The ammonia cloud released from the roof mounted pipe travelled 0.25 miles (0.4 km) across the river adjacent to the plant. Downwind of the release were crew members on ships docked at Millard and over 800 contractors working outdoors at a clean-up site for Deepwater Horizon oil spill.

The local Mobile Fire Department (MFD) conducted air monitoring after arriving on scene. According to the MFD report on the incident response, colorimetric gas detection tubes used to sample ammonia on the dock detected ammonia concentrations between 250 and 450 ppm. The U.S. Coast Guard conducted air monitoring later that afternoon and reported concentrations of 500 to 600 ppm inside the Millard facility.

⁹¹ <https://www.csb.gov/caribbean-petroleum-refining-tank-explosion-and-fire/> Accessed on 29th May 2020

Nine ship crew members and 143 of the offsite contractors downwind reported exposure. The DWH workers were advised to leave. They used their own vehicles to evacuate the facility and attend an impromptu triage site about 2 miles from the DWH clean-up site. Most of the offsite contractors went to the triage site for medical evaluation, and some were then transported to the hospital. Of the exposed victims, 32 required hospitalization, and 4 were placed in intensive care.

The CSB produced a video reconstruction of the event⁹².

4.5.52 Chelyabinsk, Russia

On 2nd September 2011, there was a bromine chemical leak in the Russian city of Chelyabinsk. 24-50 litres of bromine were released from 2267 two-litre glass containers that were being transported by train. The release occurred as the train carriages were being moved around in the train station. There was a breach of the regulations on handling, transporting and storing chemical substances by the railway staff. The released chemical formed a dense gas cloud which spread out of the railway yard and into a residential district and resulted in a large orange cloud hanging over the town.

High doses of bromine can cause damage to internal organs and the nervous system. News reports⁹³ suggest that at least 42 people but possibly as many as 207 received hospital treatment.

There does not appear to be a large amount of information available on this incident. There is an entry in the FACTS⁹⁴ database and there is video footage⁹⁵ from bystanders showing the gas leaking from the source rail carriage, the cloud dispersing over the city and the removal of the rail carriage from the city while it was still releasing the chemical. Figure 28 shows a selection of stills from the video footage.

⁹² <https://www.youtube.com/watch?v=icf-5uoZbc> Accessed on 24th April 2020

⁹³ <https://www.bbc.co.uk/news/world-europe-14755874> Accessed on 24th April 2020

⁹⁴ <http://www.factsonline.nl/ViewArticle/61/toxic-chemical-cloud-hits-russian-city> Accessed on 24th April 2020

⁹⁵ <https://www.youtube.com/watch?v=sle-LkV3vPs> and <https://www.youtube.com/watch?v=OszlK-1xxuA> Accessed on 24th April 2020



Figure 28 A selection of stills taken from video footage of the bromine release in Chelyabinsk. References in main text

4.5.53 Amuay, Venezuela

At about 01:00 on 25th August 2012, a serious seal failure in a pump caused a large leak from a tank containing light hydrocarbons (propane and butanes). 67 kg/s was released for 68 minutes (in total 273 tonnes). The source was a two-phase release of pressure-liquefied product which resulted in the formation and spread of a dense vapour cloud. The eventual cloud footprint was approximately 1100 m x 800 m before it was ignited causing a very large VCE.

In the evening of 24th August there had been very still conditions. The site was flat with a suburban neighbourhood at its boundary. The vapour cloud spread out of the site boundary in the direction of the neighbouring town. Some adverse channelling of the vapour cloud by bund walls appears to have occurred.

There were more than 50 fatalities, mostly off-site. Many site buildings were destroyed and there was severe damage to many off-site buildings. Houses within about 100 m of the cloud edge were also badly damaged.

It is not known whether there was a vapour detection system on the site but prior to the event levels of flammable gas above LEL were detected outside the site boundary and an off-site plant was evacuated. This was during a spell of low wind. Unfortunately, the conditions improved and some of the workers returned to work of whom some were subsequently killed in the blast.

The cloud spread away from the refinery off-site, not further into the refinery from the source. Atkinson et al. (2017) suggested that this could be due to flow induced by the convection of refinery process heat – i.e. convection currents causing inward airflow towards the heat source. The vapour cloud flow on the refinery side would be drawn towards the refinery and

the convective currents would be such that the cloud was diluted and prevented from accumulating. Conversely, vapour released on the side further from the refinery would not be as affected by the airflow and the gravity flow dominated, causing the cloud to continue spreading at dangerous concentrations in that direction.

The incident was analysed in depth in the review of Atkinson et al. (2017) and there is information available, although it is mostly from photo journalists and is often not suitable for assisting analysis. Atkinson et al. (2017) noted that there are two different accounts of this incident, although they both agree on the location of the leak and the extent of the vapour cloud.

4.5.54 Wisconsin, US

From Shutske et al. (2017):

On August 15, 2016, at approximately 6:30 a.m., a previously healthy male employee of a Wisconsin beef farm was found dead near the edge of an outdoor 60,400 square foot (1.4 acre) manure storage basin (Figure 29). The basin was approximately 15 feet (4.6 meters) deep and nearly full. The victim, aged 29 years, was discovered by another worker; the coroner was notified at 6:50 a.m., and he pronounced the victim dead at the scene. Thirteen dead cattle were discovered in an adjoining pen; three others were struggling to stand and were euthanized. The owner of the farm reported that at 3:00 a.m., the victim had used a tractor-powered agitator to agitate the manure, which a contractor was scheduled to pump and spread on cropland later that morning. The last contact from the victim was a social media post at 4:10 a.m. At the time he was discovered, he was approximately 3 feet [0.9 m] downslope from the rear of the tractor, which was running.

Weather conditions from a nearby airport reported temperatures at 4:15 a.m., 5:15 a.m., and 6:15 a.m. of 54.5°F (12.5°C), 53.6°F (12.0°C), and 52.9°F (11.6°C), respectively, with no wind. The high temperature the previous day was 0°F (26.7°C), and reached 87°F (30.6°C) the preceding week (August 7–13), which was 10°F (5.6°C) warmer than the historical weekly average. Relative humidity measured at the nearby airport during these same time intervals ranged from 97% to 100%. The National Weather Service's Green Bay office documented a temperature inversion in the area that morning, citing warmer air temperatures 1,000–1,300 feet (300–400 meters) above ground level.

... A University of Wisconsin farm safety expert advised the coroner to test the decedent's blood for evidence of hydrogen sulfide exposure; blood thiosulfate level was 9.2 µg/ml, consistent with lethal hydrogen sulfide exposure as the cause of death.

The incident was unusual because the deaths occurred in an outdoor environment and asphyxiation deaths associated with manure storage normally occur in confined spaces. Shutske et al. (2017) proposed that the incident could have occurred due to the temperature inversion and low wind.



Figure 29 Image of the farm with the location of the victim, from Shutske et al. (2017)

4.5.55 Philidelphia, Pennsylvania

In June 2019 at a refinery in Philidelphia, Pennsylvania, a corroded pipe elbow ruptured in the refinery alkylation unit and released process fluid composed mostly of propane with a small amount of hydrofluoric acid. The release formed a large ground-hugging vapour cloud as shown in Figure 30. Within about two minutes, the cloud found an ignition source and ignited resulting in a large fire and explosions. There were no injuries or fatalities.

The incident is of interest because there is good CCTV video footage⁹⁶ of the advancing gas cloud showing clear density effects. This footage has also been incorporated into a video reconstruction of the incident by CSB⁹⁷.

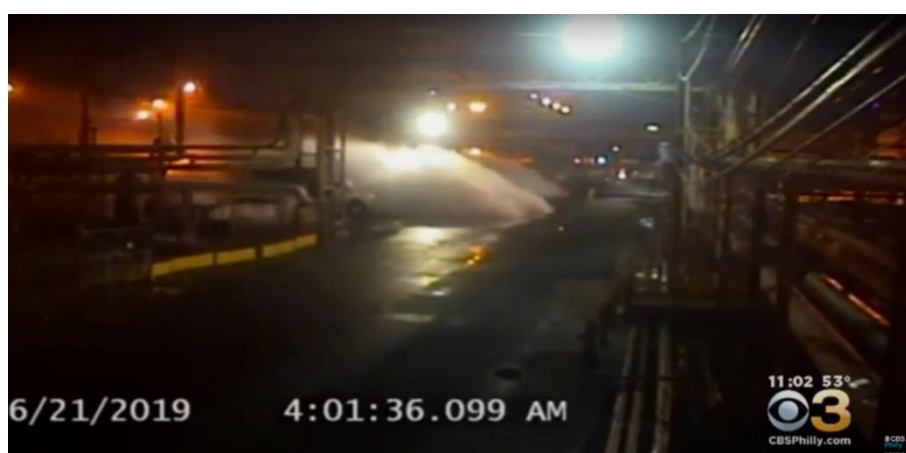


Figure 30 Still from CCTV footage of the cloud of propane and hydrofluoric acid

⁹⁶ <https://www.youtube.com/watch?v=rIssNWNwYHM> (cloud footage from about 1:13) Accessed on 24th April 2020

⁹⁷ https://www.youtube.com/watch?v=J4wKjGHvs_4&feature=youtu.be Accessed on 24th April 2020

4.5.56 Yazoo County, Mississippi

This is a very recent incident and therefore full information is not available. From the Mississippi Emergency Management Agency website⁹⁸:

The Mississippi Emergency Management Agency is assisting the Yazoo County Emergency Management Agency after a 24-inch [0.6 m] pressurized pipe ruptured, February 22, 2020, around 8:00 p.m. The rupture happened in a heavily wooded area near Highway 433 near Satartia. More than 300 residents were evacuated. At this time, 46 people are being treated at area hospitals.

The pipe contained Carbon Dioxide (CO₂) and Hydrogen Sulfide (H₂S). Residents in the area complained of green gas and a noxious odor. The pipeline belongs to Denbury Enterprises.

Currently, the Mississippi Department of Environmental Quality is working to determine if the area is safe so residents can return home. Meanwhile, a shelter is open at Yazoo County Junior High School, located at 116 Panther Drive, Yazoo City.

Through an initial investigation, the rupture could be a result of recent weather events. It appears the ground caved into a ravine damaging the 24-inch [0.6 m] pipe.

The above article also contains photographs of the incident shown in Figure 31 and the following update:

Residents forced to evacuate following a 24-inch [0.6 m] pipe rupture in Yazoo County will soon return to their homes, with an escort. Environmental Specialists will conduct air quality tests to ensure no gas is lingering in low-lying areas.

Officials informed MEMA that those residents and first responders treated for their injuries at area hospitals have been released.

The Time online report⁹⁹ adds a few more details:

The Yazoo County Emergency Management Agency told residents of Satartia on Saturday in a Facebook post that if they were located within a quarter-mile [0.4 km] of Satartia hill they could “shelter in place” if they were in a house or sturdy trailer and “cut off all heaters and air conditioners.” But the agency said if they smell a noxious odor in their homes, they needed to evacuate.

Denbury Enterprises acknowledged the leak in a statement, saying, “the affected area of the pipeline was isolated within minutes, and the leak site was evacuated as a precaution,” according to WJTV. The company said that it was “working closely with state and local officials” to “ensure the safety and welfare of the community” and that it would be “available to assist residents as they return.”

⁹⁸ <https://www.msema.org/news/pipe-ruptures-in-yazoo-county-dozens-hospitalized/> Accessed on 24th April 2020

⁹⁹ <https://time.com/5789425/pipe-rupture-mississippi/> Accessed on 24th April 2020

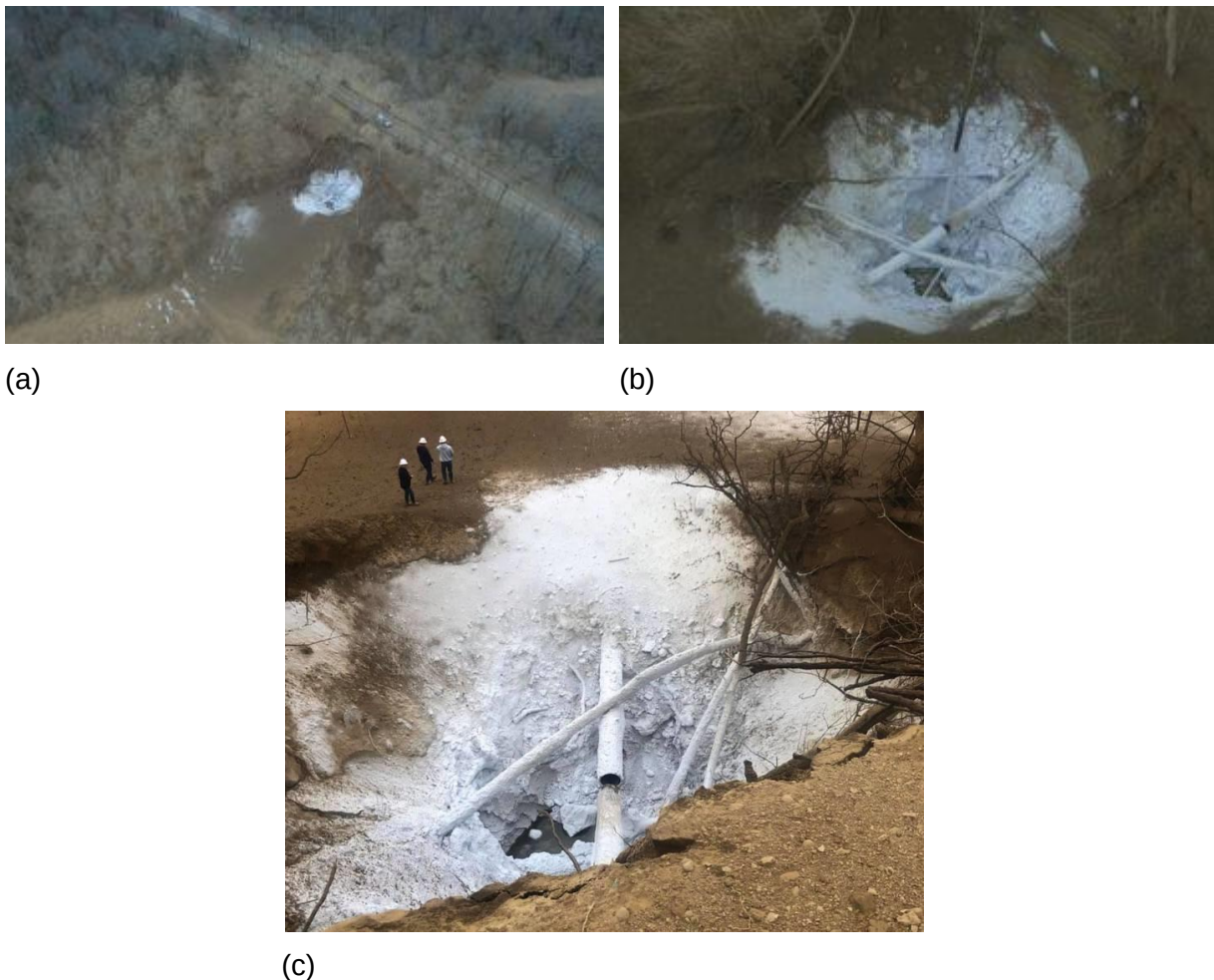


Figure 31 Images of the failed pipeline in Yazoo County from the MEMA website (© Yazoo County Emergency Management Agency copyright 2020)

4.6 Semi-confined cases

The following incidents are examples of the combined effects of dense gas releases in confined or semi-confined spaces. While they are not strictly relevant to the atmospheric dispersion of dense gases, they are included here because they are relatively common scenarios.

4.6.1 Trubshaw Cross, UK

On 11th February 1980, a fire occurred at a warehouse in a factory at Trubshaw Cross, Longport, Stoke on Trent. The fire was followed by a series of explosions. The warehouse contained about 49 tonnes of LPG in cartridges and aerosol containers, about 1 tonne of petroleum mixtures in small containers, as well as other materials such as packaging.

The source of the ignition was most likely a battery operated fork lift truck. The source of the flammable atmosphere was unknown. It was thought that it may have developed from a leak of one of the fuel cartridges. The released gas would have spread at low level due to the high density of LPG vapour and may have gone unnoticed, despite stenching agent, due to the low depth of the cloud. The semi-confined environment of the warehouse would result in inadequate low level ventilation to disperse the vapour.

The fire occurred sometime between 14:15 and 14:25. The local fire brigade were called to the scene at 14:28 and they called for reinforcements not long after, which included a foam

tender and a hydraulic platform. The adjacent roads were closed off and the residents and industrial and commercial premises were evacuated at about 14:30. There were twelve appliances in attendance for about an hour, after which they began to be released. At 20:59 only two appliances remained along with ten monitors (five hand held and five ground level around the building).

It was considered that the fire was under control at about 17:00 hours and residents were allowed to return, although the roads remained closed. Then at about 21:00 two large explosions occurred and the area was re-evacuated. At 24:00 another explosion occurred. The fire continued burning, with decreasing intensity, for about 60 hours. Local residents were allowed to return the following day. The adjacent roads were reopened in the afternoon on 13th February. The fire brigade maintained a presence on site until 20th February, while the remains of the building were demolished.

The warehouse was destroyed and other site buildings were damaged. The explosions damaged a neighbouring building. One employee was admitted to hospital with burns and two members of the public received treatment for minor lacerations and shock.

The prevailing wind was a moderate south-westerly.

There were several non-compliances with HSE codes of practice, which contributed to the situation. A full description of the incident can be found in the HSE Report (HSE, 1981b).

4.6.2 Japan

Two similar incidents involving hydrogen sulphide have been reported in Japan. In the first incident, a man suddenly lost consciousness when he entered a pit to collect seepage at an industrial waste site. Three colleagues who entered the pit to rescue him also lost consciousness. Two of the men died soon after the incident, one died 22 days later and one survived. Hydrogen sulphide gas was detected in the pit and toxicological analyses confirmed that all four men were victims of hydrogen sulphide poisoning.

The second incident was similar and occurred in a dye works in Japan. A man entered a pit to remove sludge, which had built up in a drainage pipe. He lost consciousness when he took a joint off the pipe and the sludge flowed into the pit. Three colleagues entered the pit to rescue the man and all three lost consciousness. All four men died soon after the incident and toxicological results showed that they died of hydrogen sulphide poisoning. Further information can be found in Kage et al. (2004).

4.6.3 Cleveland, Ohio

The OSHA accident database¹⁰⁰ report states:

At approximately 11:00 a.m. on September 5, 2006, Employee #1, a sewer worker, entered a sewer to manually clean and vacuum. Two other workers stayed at street level. No atmospheric readings were taken prior to the worker's entry into this combination sanitary and industrial 60-inch [1.5 m] sewer that was approximately 35 feet [11 m] below street level. Employee #1 entered the sewer without any respiratory protection and was not tied off for retrieval or emergency rescue. He worked in the sewer for approximately one hour and during this time the two other workers, both of whom were at street level, observed that the odor coming from the sewer was becoming stronger. Employee #1 came back to street level for approximately 10 minutes, complaining of difficulty breathing. Against the warnings of the other two workers, he went back into the sewer, again without any atmospheric readings being taken and no personal protective or rescue equipment. A few moments later, the attendant was not able to communicate with Employee #1 and called emergency

¹⁰⁰ https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=200102515 Accessed on 24th April 2020

services. Rescue crews arrived, retrieved him from the sewer, and transported him to the hospital where he died less than 24 hours later. Readings obtained by the rescue crew, prior to their entry, indicated high levels of hydrogen sulfide. Readings obtained from the Northeast Ohio Sewer department, taken shortly after the accident, showed high levels of ammonia.

4.6.4 Arkansas, US

From Christensen et al. (2016):

In June 2011 at approximately 0900 in the southern United States, an estimated 40 pounds [18 kg] of chlorine gas was released inside a poultry processing plant. The release resulted from an accidental mixing of sodium hypochlorite and FreshFX (SteriFX, Shreveport, LA), a US Department of Agriculture–approved antimicrobial treatment comprising a combination of acids. At the time of the incident, approximately 600 workers, who primarily spoke Spanish or Marshallese, were present in the plant. The release resulted in a complete evacuation of the plant.

... Fire department personnel were called to the scene for a pregnant woman in distress and were not immediately aware that there was a mass casualty hazardous materials (hazmat) incident. When they arrived and saw multiple people experiencing respiratory symptoms, they realized there was a toxic gas release. They did not initially recognize the gas as chlorine because the US Environmental Protection Agency Tier 2 Chemical Inventory Reports from the facility did not indicate that chlorine was used at the plant. They predicted the gas to be chlorine because of the description of the green cloud and the chemistry of the mixed chemicals and confirmed this prediction with a positive Draeger tube air sampling test. Because chlorine gas is heavier than air, the chlorine gas fell to the floor, and the negative pressure of the plant carried the chlorine gas through a major hallway that was used as a primary evacuation route. Prior to identifying the chemical, the fire department/EMS notified the nearest hospital about the mass casualty hazmat incident and asked them to notify other local hospitals and to assess their capacity. There was a delay in activation of the emergency operations center (EOC), and the health department was not informed until at least 2 hours after the incident. As a result, they were unable to take advantage of hospital preparedness preparations at the state health department, such as a radio system to assist in communication and translators.

About 170 people were taken to hospital with treatment times ranging from 25 minutes to 3 days.

The internal communication in the hospitals functioned as planned during drills, training and exercises for emergencies. However, there was a lack of communication between the fire department and the hospitals with details of the contaminant and methods of decontamination. The state health department was not notified and hospitals had to find their own sources of guidance.

This incident highlights the use of after-action reviews for emergency recovery and learning. In this case, a series of interviews particularly helped in reconstructing the incident and assessing the effectiveness of the emergency response.

4.6.5 The Southern Red Sea and the Solent, England

The Southern Red Sea incident is summarised in the MAIB (2018a) report as follows:

At 1625 on 8 June 2016, while the roll on, roll off (ro-ro) cargo vessel Eddystone was in the Southern Red Sea on passage to Duqm, Oman, the fixed fire-extinguishing system's CO₂ release alarm sounded. The engine room had been changed over to

unmanned machinery space watchkeeping mode but the second engineer, who was on duty that day, was in the engine room at the time, attending to a purifier alarm. He telephoned the chief engineer to apprise him of the situation and remained in the engine control room, which was separated from the engine room. The main engine, generators and engine room vent fans all continued to operate normally.

The chief engineer and the electrotechnical officer inspected the remote CO₂ release station and saw that it was undisturbed. They then went to the door of the CO₂ room, where they heard a loud hissing noise from within. The chief engineer informed the master, who sent the chief officer to assist them.

The chief engineer and chief officer donned breathing apparatus and entered the upper level of the CO₂ room, which contained the 65 CO₂ cylinders that comprised bank A [Eddystone's CO₂ cylinders were stored in two independent banks A and B] of the vessel's fixed fire-extinguishing system. A white cloud was seen forming at the far corner of the compartment and all the cylinder valves were in the open position. They then went down to the lower level, where the reserve set of 65 CO₂ cylinders comprising bank B were located. All of bank B's cylinder valves were in the closed position.

To prevent the release of CO₂ from bank B, the chief engineer disconnected the pilot activation lines to both banks of cylinders and left bank B in the manual activation mode, allowing it to be activated from within the CO₂ room if required. CO₂ gas from bank A continued to leak from a few failed cylinder outlet rubber hoses over the next 4 days, during which time most of the rubber hoses in bank A developed bulges in their outer skin.

The Solent incident is summarised in the MAIB (2018a) report as follows:

At 0420 on 17 July 2017, the ro-ro ferry Red Eagle departed East Cowes, Isle of Wight, bound for Southampton. Approximately 15 minutes after departing, the CO₂ release alarm sounded in the engine room. The chief engineer and mechanic, who were in the engine control room at the time, ran out of the space, exiting onto the vehicle deck immediately above. The CO₂ room and its remote release station were located on opposite sides of this deck.

The chief engineer inspected the remote CO₂ release station and saw that it was undisturbed. He then went to the door of the CO₂ room, where he heard a loud hissing sound from within. He opened the door to the room slightly, and through a very small opening saw a dense white cloud inside.

The chief engineer telephoned the bridge and discussed the situation with the master. They concluded that no emergency response was required other than ensuring that no one entered either the CO₂ room or the engine room. The master then telephoned Griffin Fire & Training Limited (GFT), who were contracted to maintain the CO₂ fire-extinguishing systems on the company's ro-ro ferries, and asked them to attend the vessel as soon as possible. He also informed the vessel's owners, who in turn notified the MCA [Marine and Coastguard Agency]. Red Eagle berthed at 0515 and, after disembarking the passengers and their vehicles, moved to a layby berth nearby. The vessel was taken out of service pending the restoration of the CO₂ system.

A GFT technician arrived on board at 0630 and, having donned breathing apparatus, went inside the CO₂ room to investigate. He could hear several of the cylinder valves rattling due to the back pressure in the outlet manifold, and CO₂ still leaking into the room from some of the cylinder outlet hose to manifold connections. To prevent

further discharge of gas, the technician removed all the cylinder valve actuation heads.

An MCA surveyor arrived on board later that morning. At the request of the surveyor, the GFT technician proved that neither the remote nor local release mechanism for the CO₂ system had been activated to cause the cylinders to discharge.

Further details of both incidents can be found in the MAIB report. There were no injuries as a result of these incidents. However, the MAIB comment in a Safety Bulletin (MAIB, 2018b) that between 1975 and 2000 the unintended release of carbon dioxide from fire-extinguishing systems caused 72 deaths and 145 injuries, mainly in the marine industry.

4.6.6 Fraserburgh, UK

From the MAIB (2018c) Safety Bulletin:

Sunbeam was a 56 m UK registered pelagic trawler. Its home port was Fraserburgh, Scotland, and it was typically manned by a crew of eleven. In the weeks prior to the accident, it had been fishing for herring in the North Sea and landing its catch in Lerwick, Shetland. The vessel had nine refrigerated salt water (RSW) tanks for storing its catch.

On 10 August 2018, Sunbeam arrived at Fraserburgh. It had caught and landed its seasonal quota of herring and was being prepared for a planned refit period. During the refit the vessel's owner intended to replace Sunbeam's refrigeration plant.

At about 0900 on 14 August, Sunbeam's crew arrived at the vessel's berth ready to begin work. The vessel's refrigeration plant had been shut down after landing the final catch at Lerwick, and its RSW tanks had been pumped out and tank lids opened in preparation for deep cleaning. At some time between 1200 and 1350, Sunbeam's second engineer entered the aft centre RSW tank and collapsed.

At about 1350, the second engineer was seen lying unconscious at the aft end of the tank by a crewmate, who immediately raised the alarm. Three of the vessel's crew entered the tank and tried to resuscitate the second engineer but they soon became dizzy, confused and short of breath. One of the crew managed to climb out of the tank unaided, the other two crewmen and the second engineer were recovered onto the open deck by two crewmen wearing breathing apparatus. The two crewmen made a full recovery, but the second engineer could not be resuscitated and died.

It is unclear when and why the second engineer entered the tank. However, evidence indicated that his intention was to sweep the residual seawater that had settled at the aft end of the tank forward in to the tank's bilge well. No safety procedures for entering or working in RSW tanks had been completed before he entered the tank.

Tests of the atmosphere in the tank following the accident showed that the level of oxygen at the bottom was less than 6% (normal level should be 20.9%). Further tests of both the tank atmosphere and residual water samples showed the presence of Freon R22, the refrigerant gas used in the RSW tank's refrigeration plant.

The MAIB's initial investigation identified that the refrigeration plant sea water evaporators had suffered several tube failures resulting in a number of repairs. It is likely that the refrigerant leaked through one or more failed tubes into the seawater system, and was released into the RSW tank. Freon R22 is four times heavier than air so it will displace oxygen at the bottom of an enclosed space, such as an RSW tank. It is a toxic, tasteless and mostly odourless gas. If it is deeply inhaled, it can cut off vital oxygen to blood cells and lungs.

Further details can be found in the MAIB bulletin.

4.7 Summary

The above incident review is not exhaustive, all sources of information relating to an incident have not been sought. However, it is sufficient to provide examples of common features such as substances, location, cause of the release and basic source descriptions. A summary table of many features is included in Annex I¹⁰¹.

Information recording

Some very limited analysis is presented here. This is not only because the review was not intended to be exhaustive but also because information about incidents is often disparate, incomplete and poorly recorded. Often the only quantitative information available is the financial loss and the number of fatalities and injuries. Several reports and reviews comment similarly on the lack of information, and/or the poor quality of the available data for event analyses.

Location

The locations of the example incidents listed in Sections 4.4 and 4.5 and the number of incidents occurring at those locations are shown in Figure 32. The US clearly has the largest number of examples. The high numbers in the US and UK and the lower numbers in African and South/Central American countries agree with the trend reported by Mihailidou et al. (2012) for general major accidents (i.e. not only dense gas) up to 2012. Mihailidou et al. (2012) pointed out that despite the higher incidence in more developed countries, the numbers of deaths and injuries are lower, which they attribute to better enforcement of safety regulations in more developed countries.

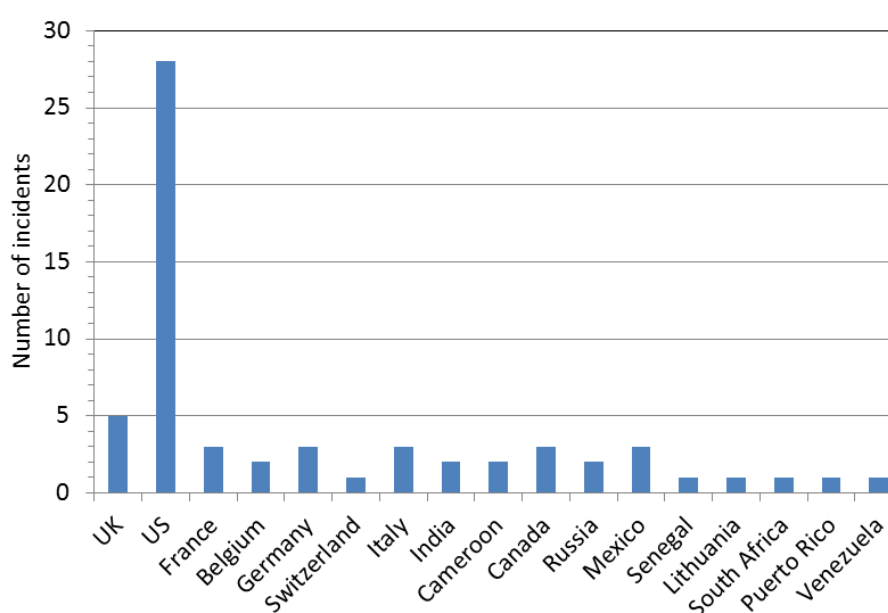


Figure 32 Locations of incidents and number of incidents at that location from Sections 4.4 and 4.5

Substance

The substances and frequency of their occurrence in the incidents summarised in Sections 4.4 and 4.5 are shown in Figure 33. The top five substances are chlorine, ammonia,

¹⁰¹ "ANNEX_I_Summary_tables_incidents_experiments.xlsx"

hydrogen sulphide, LPG and, with an equal amount, carbon dioxide, propane and gasoline. It is interesting to note that of these six substances only LPG and gasoline have been involved in the top ten incidents with death and injury listed in Mihailidou et al. (2012). This could imply that LPG and gasoline are both high frequency, high consequence substances, although the gasoline incidents in Mihailidou et al. (2012) are not likely to have occurred as a result of density effects.

Chlorine, ammonia, hydrogen sulphide and carbon dioxide could be categorised as high frequency, lower consequence substances. This means that the cumulative consequences of these events could be similar in impact to one high consequence event.

The remaining substances are relatively low frequency but may be high or low consequence. For example, there is only one Methyl Isocyanate incident listed here, Bhopal, but it still has the greatest loss of life of any major industrial incident to date.

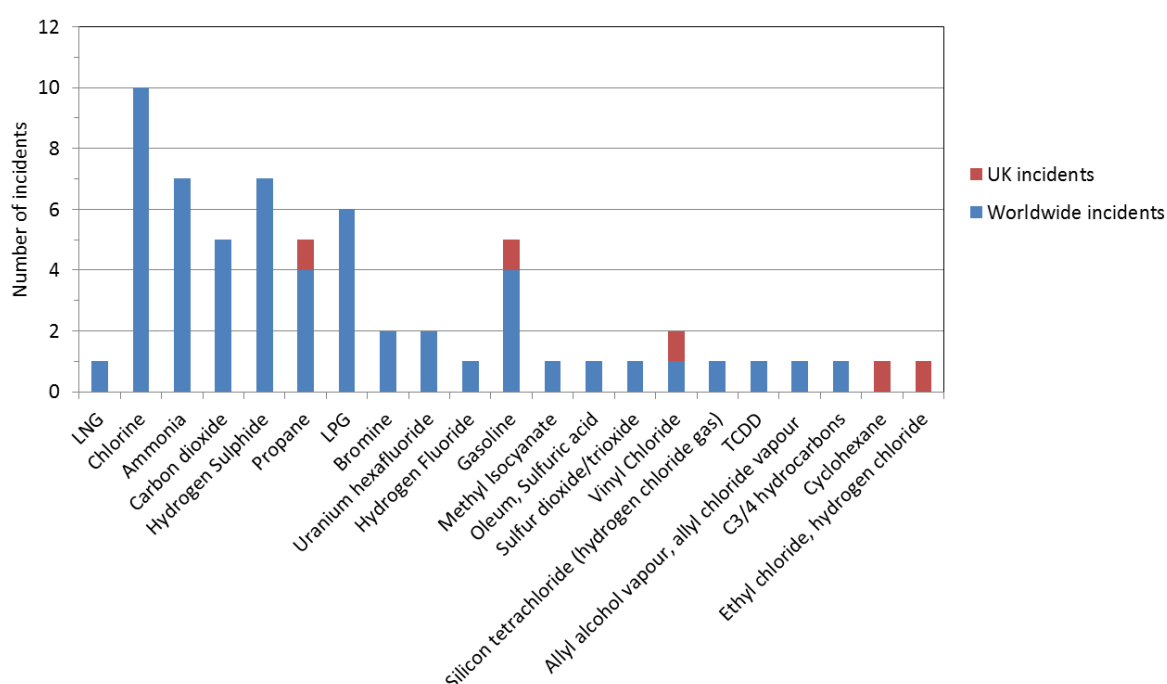


Figure 33 Substances and frequency of their occurrence in incidents listed in Sections 4.4 and 4.5. Blue bars indicate worldwide incidents, red indicates UK incidents

Figure 34 shows hazardous cloud sizes in km^2 with year for incidents where information about the cloud footprint was provided or easily approximated¹⁰². The data is not confirmed from other sources or an in depth review, it is presented to provide ball-park indication of cloud sizes. It can be seen that clouds generated from substances where the risk predominantly down to toxicity are larger and have wider range of cloud sizes than those generated when the risk is primarily due to substance flammability. Khan and Abbasi (1999) noted that the damage potential over an area is greatest for toxic releases, as compared to explosions or fires. However, the impact of explosions and fires is often more acute than toxic releases and can also result in escalation of the severity of an incident.

¹⁰² Note that to undertake a proper quantitative analysis, the method for approximating cloud size would need to be consistent

For some of the incidents, the cloud depth was also provided in the sources used. Figure 35 shows those incidents that provided both cloud area and depth. It can be seen that cloud depth generally increases with cloud area, and the clouds where the main risk is toxicity are generally larger and deeper. Note that many of these dimensions are likely based on observations on the ground, either of the cloud itself or of the discolouring of vegetation or burn marks. The deepest cloud shown in Figure 35 (about 2500 m deep) corresponds to the depth that the chlorine cloud was observed to 'boil up' to in the incident at La Barre, Louisiana.

Substances such as hydrogen sulphide are invisible and do not leave evidence of their passage. For substances such as this, measurement sensors and recording of the casualty locations can assist in incident interpretation and collection of quantitative datasets.

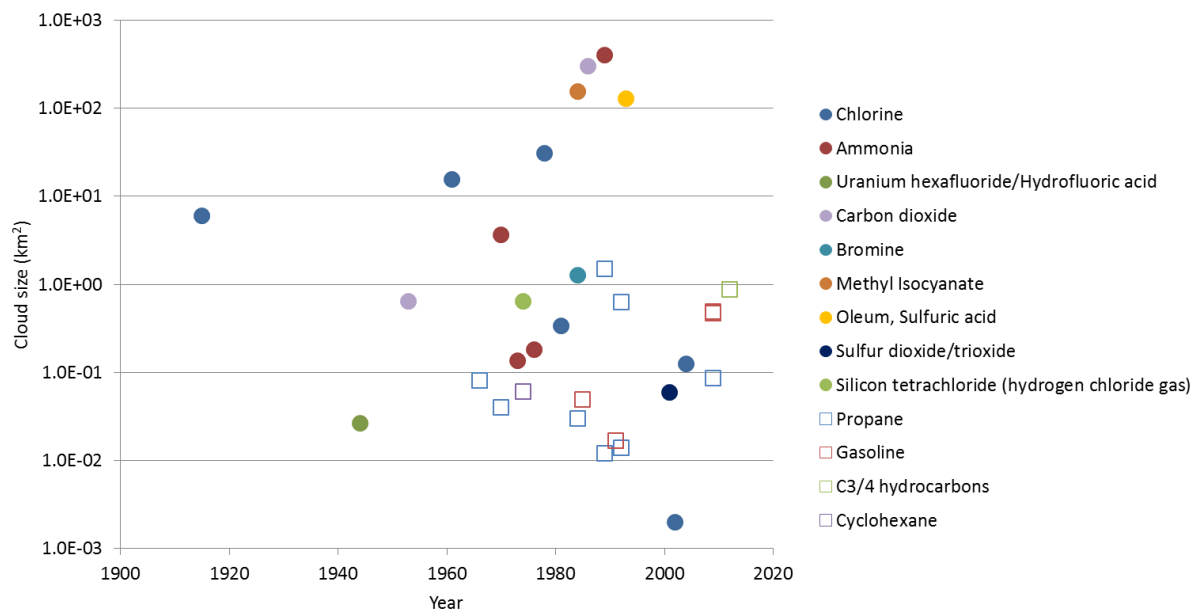


Figure 34 Cloud size for several substances shown by year. Solid circles indicate substances where the predominant risk is toxicity. Hollow squares indicate substances where the predominant risk is flammability

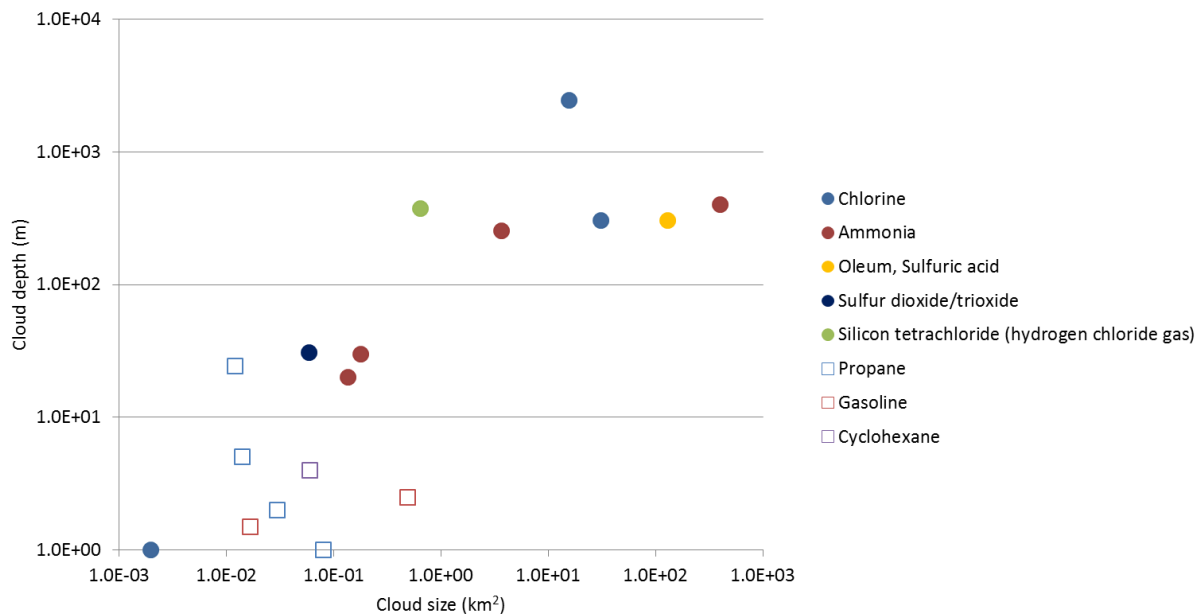


Figure 35 Cloud size and depth. Solid circles indicate substances where the predominant risk is toxicity. Hollow squares indicate substances where the predominant risk is flammability

Decade

The distribution of the decades in which the incidents listed here occurred is shown in Figure 36. As mentioned previously, this data only represents relatively few examples but it indicates a general decrease in more recent incidents. This is broadly in keeping with trends noted in reviews such as Khan and Abbasi (1999) and Mihailidou et al. (2012), but these only extend to 2012. Unfortunately, the recent report on property losses by Marsh (2020) suggests that this is not the case and that both the number and total cost of losses have increased in the last decade. Indeed, four of the losses in the last two years were among the 20 largest losses of all time. This could be because Marsh assesses property losses and focuses on the hydrocarbon industry.

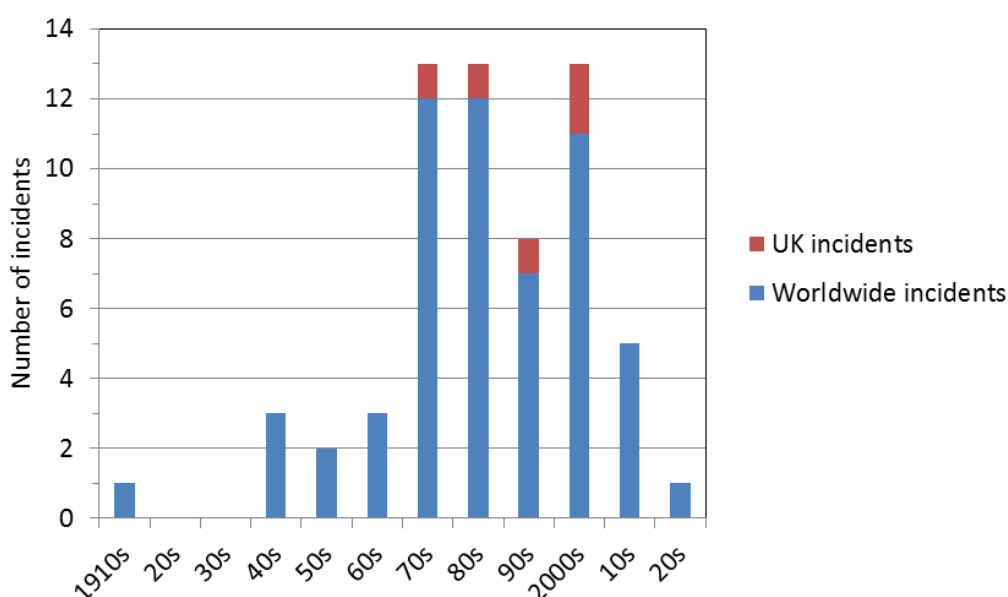


Figure 36 Decades between 1910 and 2020 and frequency of incidents occurring in a decade from those listed in Sections 4.4 and 4.5. Blue bars indicate worldwide incidents, red indicates UK incidents

Incompatible mixtures

There are five incidents, shown in Table 12, that resulted from a release of dense toxic gas as a product of a mixture of two incompatible substances. Four resulted in a hydrogen sulphide release and one in chlorine. Hydrogen sulphide is a particular risk in drains and when incompatible substances are stored in proximity to each other. Lack of knowledge about substance compatibility could be a factor in these incidents.

Table 12 Incidents in which dense gases were released as a result of mixing of other substances

Incident	Substance
Baden-Wurtemberg, Germany	Hydrogen Sulphide
Savannah, Georgia	Hydrogen Sulphide
Chicago, Illinois 1978	Hydrogen Sulphide
Pennington, Alabama	Hydrogen Sulphide
Arkansas, US	Chlorine

Effectively passive releases

There are a few incidents listed above in which the gas may have dispersed as either a dense cloud or as a neutrally-buoyant passive gas. It is difficult to assess which type of dispersion behaviour was dominant in these cases, for the following reasons:

- In Poza Rica, hydrogen sulphide was released from a 90 ft stack. With no other factors affecting it, a calculation could be undertaken to determine whether it would touch down. However, the source was complicated by a heat source from a flare. The dispersion behaviour was also affected by a low altitude temperature inversion and topography in the vicinity of the plant.
- In Glendora, a vinyl chloride monomer gas cloud formed and ignited. The release continued and then several hours later there was an explosion. It is difficult to determine whether the gases retained their density effects in the presence of the fire.

Eye-witness statements report a clinging ground fog but this could result from the atmospheric conditions.

- In Jonova, an evaporating pool of liquid ammonia formed. Under some conditions, this could be accompanied by a dense cloud of ammonia but here the liquid was stored at atmospheric pressure and the vapour above the pool ignited, so it seems that a dense gas cloud was unlikely to form. Despite this, ammonia was detected in the air up to 23 km away.
- In the incident in Richmond in 2001, the sulphur dioxide/trioxide was initially stated to be released vertically before the plume was blown over by the wind, bringing it down to ground level. Consideration could be given to whether the plume density effects contributed to the grounding of the plume.

In these incidents it is difficult to identify whether the density effects were present at all or if they could be regarded as a source feature and have negligible impact when compared to the effects of the atmospheric conditions or other factors, notably fires. It would be informative to try and calculate 'incident Richardson numbers' or some other metric to try to understand whether the density effects are important in a particular incident and also when they cease to be important, i.e. when transition occurs.

Indoor and semi-confined releases

Only a very limited set of semi-confined examples is presented here because the focus is outdoor dispersion. However, incidents such as Mönchengladbach and Geneva illustrate how indoor releases can become significant outdoor dispersion hazards.

The substances involved in the indoor or semi-confined examples were hydrogen sulphide, carbon dioxide, chlorine, freon and bromine. Several of the incidents are exacerbated by people coming to the aid of afflicted colleagues and succumbing to the hazard themselves. Some toxic/asphyxiating gases do not have a distinct odour, such as carbon dioxide, or hydrogen sulphide, for which the ability to smell the gas disappears if a hazardous concentration is reached.

To provide some indication of frequency, between 1975 and 2000, the unintended release of carbon dioxide from fire-extinguishing systems caused 72 deaths and 145 injuries, mainly in the marine industry (MAIB, 2018b). An ARIA News Flash (ARIA, 2008c), highlighted accidents due to carbon dioxide extinguisher systems. At that time, there were 11 accidents related to carbon dioxide system issues in the ARIA database. A US EPA study into the risks of carbon dioxide fire suppressing systems (US EPA, 2000) reported 62 accidents up to 1999, which resulted in 119 deaths and 152 injuries. The main cause of fatalities or injuries was accidental exposure to carbon dioxide during maintenance and testing, often resulting from inadequate personnel training on carbon dioxide risk.

There are only four indoor or semi-confined hydrogen sulphide example incidents listed here but Danielsson et al. (2009) highlighted many more incidents with hydrogen sulphide, both in confined and unconfined spaces. They suggested that most fatalities occur due to biologically-generated hydrogen sulphide releases, which they suggest is due to a lack of knowledge and experience in this sector compared with industrial sectors such as oil and gas.

Other points of interest

Some other points of interest are as follows:

- 38 out of 62 incidents listed in Sections 4.4 and 4.5 originated from industrial facilities and in 26 of these cases, the gas cloud spread off-site, impacting the surrounding population/environment

- 16 out of 62 incidents resulted from modes of transport. Of these, 11 originated from railcars, four from road tankers and one from a ship.
- Five out of 62 incidents resulted from pipeline releases
- Seven could be considered as instantaneous releases, while the rest were continuous or finite duration
- Over 40% of incidents occurred due to issues with valves or vents (15) and pipe or hose failures (12)
- 38 out of 69 incidents (including semi-confined cases in Section 4.6) involved a pressurised source
- Nearly half of the incidents (35 out of 69) occurred or escalated due to a failure in safety procedures, emergency preparedness or response

Many of the incidents at industrial facilities occurred during non-standard operating conditions such as during start-ups, pauses in production for maintenance, and during loading and unloading. This is not unique to dense gas incidents and has been observed in other studies (e.g. Khan and Abbasi, 1999; Danielsson et al. 2009). Non-standard operating conditions often means pressure/temperature changes and therefore contraction/expansion of vessels and pipe-work etc. It may also include bypasses and temporary vessels. These are occasions where human error can occur and less familiar safety procedures may be in use. They are also occasions when contractors are involved, who may be less familiar with site safety procedures.

Lists of incidents which illustrate specific factors affecting dense gas dispersion and incidents for which numerical modelling has been undertaken are given in the two sub-sections below.

4.7.1 Incidents illustrating factors that affect dense gas dispersion

Examples of incidents, which illustrate where particular factors have influenced the dispersion of the gas clouds are summarised here.

Topography

13 incidents clearly indicate that the topography at the incident location, or nearby, influenced the spread of the gas cloud. These incidents are listed in Table 13.

Table 13 Incidents where local topography influenced the dense gas dispersion

Incident	Substance
Poza Rica, Mexico	Hydrogen Sulphide
Menzengraben, Germany	Carbon dioxide
Port Hudson, Missouri	Propane
	Liquid Propane, Butane & condensate products
Mill Woods, Canada	Chlorine
Montana, Mexico	Carbon dioxide
Lake Monoun, Cameroon	Gasoline
Naples, Italy	Carbon dioxide
Lake Nyos, Cameroon	LPG
Ufa, Russia	LPG
Brenham, Texas	LPG, light naptha
La Mede, France	Oleum, Sulfuric acid
Richmond, California, 1993	Carbon dioxide & hydrogen sulphide
Yazoo County, Mississippi	

Nil or low wind conditions

There are 21 incidents that mention nil or very low wind conditions. These are listed in Table 14.

Table 14 Incidents of dense gas dispersion in nil or low wind conditions

Incident	Substance
Buncefield, UK	Gasoline
Poza Rica, Mexico	Hydrogen Sulphide
Menzengraben, Germany	Carbon dioxide
Blair, Nebraska	Ammonia
Port Hudson, Missouri	Propane
Potchefstroom, South Africa	Ammonia
Houston, Texas	Ammonia
Youngstown, Florida	Chlorine
Naples, Italy	Gasoline
Lake Nyos, Cameroon	Carbon dioxide
Jonova, Lithuania	Ammonia
Ufa, Russia	LPG
Baton Rouge, Louisiana 1989	Ethane and Propane
St Herblain, France	Gasoline
Brenham, Texas	LPG
La Mede, France	LPG, light naptha
Viareggio, Italy	LPG
Jaipur, India	Gasoline
San Juan, Puerto Rico	Gasoline
Amuay, Venezuela	C3/4 hydrocarbons
Wisconsin, US	Hydrogen sulphide

Indoor sources and ingress

In five of the incidents, the dense gas originated indoors but was not contained and had significant impact on the surrounding area. These are listed in Table 15. In 14 of the incidents ingress of gas is mentioned. These are listed in Table 16.

Table 15 Incidents of dense gas dispersion originating indoors

Incident	Substance
Geneva, Switzerland	Bromine
Baden-Wurttemberg, Germany	Hydrogen sulphide
Pennington, Alabama	Hydrogen sulphide
Monchengladbach, Germany	Carbon dioxide
Chelyabinsk, Russia	Bromine

Table 16 Incidents where the dispersing gas is reported as entering structures such as buildings

Incident	Substance	Structure
Runcorn, UK	Vinyl Chloride	Ship accommodation
Brooklyn, New York	Chlorine	Subway
Cleveland, Ohio	LNG	Sewers
Poza Rica, Mexico	Hydrogen Sulphide	Residences
La Barre, Louisiana	Chlorine	Residences
Mill Woods, Canada	Liquid Propane, Butane & condensate products	Sewers
Youngstown, Florida	Chlorine	Vehicles
Mexico City, Mexico	LPG	Residences
Gore, Oklahoma	Uranium hexafluoride/Hydrofluoric acid	Site buildings
Richmond, California, 1993	Oleum, Sulfuric acid	Residences
Dalton, Georgia	Allyl alcohol vapour, allyl chloride vapour	Vehicles
Monchengladbach, Germany	Carbon dioxide	Residences/basements
Viareggio, Italy	LPG	Residences/basements
San Juan, Puerto Rico	Gasoline	Drainage system

4.7.2 Numerical modelling of incidents

Existing modelling studies have been found for 13 of the incidents. These are listed in Table 17.

There are several incidents where there is fairly detailed qualitative information available and in some cases, quantitative measurements such as source dimensions, estimated flow rates, gas cloud sizes and concentration readings from monitors. Incidents where there is potential for use in a modelling exercise are listed in Table 18. It is possible that prior modelling for these incidents exists but has not been identified in this review.

Table 17 Incidents for which previous modelling studies have been found

Incident	Substance
Flixborough, UK	Cyclohexane
Runcorn, UK	Vinyl Chloride
Buncefield, UK	Gasoline
Menzengraben, Germany	Carbon dioxide
Potchefstroom, South Africa	Ammonia
Houston, Texas	Ammonia
Jonova, Lithuania	Ammonia
Bhopal, India	Methyl Isocyanate
Festus, Missouri	Chlorine
Dalton, Georgia	Allyl alcohol vapour, allyl chloride vapour
Macdonna, Texas	Chlorine
Graniteville, South Carolina	Chlorine
Viareggio, Italy	LPG

Table 18 Incidents where sufficient information may be available for a modelling exercise

Incident	Substance
Wealdstone	Propane
La Barre, Louisiana	Chlorine
Blair, Nebraska	Ammonia
Youngstown, Florida	Chlorine
Montana, Mexico	Chlorine
Geneva, Switzerland	Bromine
Mexico City, Mexico	LPG
Lake Nyos, Cameroon	Carbon dioxide
Ufa, Russia	LPG
Baton Rouge, Louisiana 1989	Ethane and Propane
St Herblain, France	Gasoline
Brenham, Texas	LPG
La Mede, France	LPG, light naptha
Antwerp, Belgium	Hydrogen sulphide
Jaipur, India	Gasoline
San Juan, Puerto Rico	Gasoline
Theodore, Alabama	Ammonia
Amuay, Venezuela	C3/4 hydrocarbons
Wisconsin, US	Hydrogen sulphide

5 MODELLING DENSE GAS DISPERSION

5.1 Introduction

Numerical models have the potential to play a crucial role in industrial regulation and emergency response. Broadly speaking, the purpose of modelling work can be split into three categories:

- Preparedness: Advance predictions from hazardous gas scenarios, for example for input into COMAH safety reports or land use planning zones.
- Response: During incident predictions, for example for setting safety cordons.
- Recovery: Post-event analysis and learning.

In each of these categories, the modelling approach is generally constrained by three factors:

- The models available
- The time available – time to setup and run the model and to assimilate results into a suitable format for the end-user
- The information available – for example on the source, topography, weather etc.

Advance predictions for top-tier COMAH safety reports, undertaken by the dutyholder of an industrial facility every five years, can use whichever model they choose and they also have access to detailed site information. On the other hand, the advance modelling undertaken by HSE for LUP assessments is often based on a generic set of information and assumptions (details of specific chemical inventories may not be known) and the resulting predictions are generally only undertaken once and will be applied for the duration of operations on that site, i.e. 20 – 30 years.

Emergency response modelling during incidents has the shortest time frames, on the order of minutes. It also has the least information available and ideally uses as few models as possible for speed and consistency. The end-user is more likely to be non-technical and therefore great care is required in the presentation of output. There is scope for refinement as information becomes available, for example during a longer incident, but time frames remain short.

Post-event analysis of an incident has a varying amount of information available, depending on what was recorded during the incident. Additional analysis may involve experimental and modelling studies of particular hypotheses in which case much information is available. The models can afford to be more complex and time frames for the whole analysis can be on the order of years. Post-event modelling can also be used in legal cases, in which case the time frames can be expected to be shorter.

This section covers a range of models suitable for dense gas dispersion modelling in the contexts above. Firstly, the different types of model are discussed along with some generic model assumptions and parameterisations. A summary of relevant previous model reviews, good practice documents and comments on model evaluation are included. This is followed by brief summaries of individual models for predicting dense gas dispersion outdoors and gas ingress into buildings.

5.2 Types of model

Models can be classified into types, described generically by the modelling approach or solution method for their governing equations.

Markiewicz (2012) reviewed the model classes (types), including lists of dense gas dispersion models that can be classified under various headings. A summary table of the

general attributes of models of each class is shown in Table 19. Note that even though the theory on which a particular model is based may cause it to fall into one class, many models have pragmatic modifications to ensure their utility despite their limitations. Not all models can be discretised into a particular class of model.

Table 19 Summary of general attributes of different classes of model.

Model	Simple met/ complex met	Nil wind	Topography	Obstacles	Infiltration & indoor air	User expertise	Computing power	Ease of obtaining results
Empirical / nomogram	Simple	Yes	Simple	Complex	No	Low	Low	High
Gaussian plume	Simple	No	Simple	Simple	No	Low	Low	High
Box	Simple	Yes	Simple	Simple	No	Low	Low	High
Integral plume	Simple	No	Simple	Simple	No	Low	Low	High
Shallow Layer	Complex	Yes	Complex	Complex	No	Medium	Medium	Medium
Lagrangian particle / puff	Complex	Yes	Complex	Complex	Complex	Medium	Medium	Medium
CFD	Complex	Yes	Complex	Complex	Complex	High	High	Low
Zone	Simple	No	n/a	n/a	Simple	Low	Low	High

5.2.1 Empirical models and nomograms

Empirical models are derived directly from experimental measurements. Examples of empirical models are the Britter and McQuaid (1988) workbook nomograms and the VDI 3783 Part 2 (VDI, 1990). Both used experimental data to obtain correlations for cloud centreline concentration. These sorts of models are particularly useful for providing quick 'look up' systems with few inputs for predicting dispersion.

The main benefits of empirical models and nomograms are that they are quick to use and the few inputs mean that they leave little room for user variability. The main limitation with any empirical model is its basis in experimental data means that it is only as good as the data on which it is based. The model should not be used outside of the range of this data because there is no physical basis to the model to justify this. Empirical models can be extended as further information becomes available. The limitation of nomograms is that a large amount of them are required in order to cover a reasonable range of possible conditions.

These types of model are also sometimes referred to as screening tools.

5.2.2 Gaussian plume models

Gaussian plume models are simplified analytical models. They were designed for point source releases with values for plume spread parameters, σ_y and σ_z , which depend on atmospheric stability class and terrain (Briggs, 1995). In a classic Gaussian plume model, the atmospheric transport and dispersion is independent of any chemical property, so that knowledge of the chemical is not necessary. They are used in passive gas dispersion modelling and have been well-validated in this field. Further information on classic Gaussian plume models can be found in Hanna et al. (1982).

Strictly speaking, Gaussian plume models are not applicable to dense gas dispersion, they are only applicable at the passive limit of the cloud downwind. Van Ulden (1974) compared a

Gaussian plume model to measurements from dense gas experiments and showed that the model overestimated the height of the cloud by a factor of 5 and underestimated the radius by a factor of 2.5. Despite this, Gaussian plume models have been applied to dense gas scenarios both in unmodified form and by modifying the values of dispersion coefficients (e.g. Burgess and Zabetakis, 1973).

In a sub-model comparison exercise, Thoman et al. (2006) compared the Gaussian plume sub-model in ALOHA to the dense gas sub-model in ALOHA and found that under some conditions the Gaussian plume model predicted higher concentrations and in others the dense gas model predicted higher concentrations. In a model evaluation study, Hanna et al. (1993a) found that the Gaussian plume model performed well compared with dense gas-specific models for continuous releases of dense gas. When comparing the performance of six dense gas dispersion models and a Gaussian plume model to the Festus incident, Hanna et al. (2008) observed the following:

- 0.1 – 1 km from the source: the Gaussian plume model predicted concentrations within 20% of the median of the dense gas models
- 2 – 5 km from the source: the Gaussian plume model predicted concentrations similar to the maximum of the dense gas models
- 10 – 25 km from the source: the Gaussian plume model predicted concentrations a factor of 2 to 3 larger than the dense gas models
- The Gaussian model predicted maximum downwind distances to the 400 ppm and 20 ppm concentration contours that were very similar to the median of the distances predicted by the dense gas dispersion models

The conclusion is that, in terms of accuracy of concentration predictions, Gaussian plume models might provide a reasonable prediction in some dense gas scenarios, but not in others.

If a dense gas cloud becomes effectively passive within a relatively short distance then it is easy to see why a Gaussian plume model might perform reasonably well. Model performance depends strongly on the quality and quantity of input information and also on the criteria used for acceptance of a model prediction. It is entirely possible that if there is uncertainty in the source information then a dense gas model may not be able to provide an accurate prediction. If the acceptance criteria are fairly broad, then similar agreement can be achieved with a Gaussian plume model prediction. However, this agreement may only hold for the conditions of the validation study and, in a similar fashion to an empirical model, it should not be taken as acceptable outside of the range of the study. If a Gaussian plume model is desired for wider use, a significant amount of work testing the sensitivity and uncertainty of predictions to different sets of information is required alongside comparative tests of dense gas-specific models. Even if this is undertaken, the model will never contain the appropriate physics for dense gas dispersion modelling and should be used with caution.

Gaussian plume models cannot account for complex terrain, but they can be modified to account for building effects, see for example Robins et al. (1997). Gaussian-plume models break down during very low wind speed or calm conditions. They assume that the concentration of gas at a given downwind location is inversely proportional to the wind speed, which means that concentrations become unreasonably large as wind speeds approach calm conditions. Hanna et al. (1982) suggest a minimum wind speed of 0.5 m/s. Several models avoid the problem by setting a minimum wind speed in the model.

5.2.3 Box and integral models

These types of models describe the overall behaviour of the cloud, integrated across the cloud, as opposed to models that assess the behaviour of discrete elements within the cloud.

Box models

Box models are used to describe instantaneous releases of grounded clouds. They assume that at any time, the dense gas cloud is a cylinder with uniform height and radius and uniform gas concentration throughout the cloud volume. The governing equations characterise the cloud horizontal spreading, entrainment of the ambient air into the cloud and cloud heating. They form a set of ordinary differential equations (ODEs) that are integrated with respect to time. Horizontal spreading is governed by a front velocity. The concentration is calculated based on the mass of the substance released and the box volume and is therefore an average over the cloud volume.

Entrainment at the top and edge of the cloud is usually based on empirical formulas and the Richardson number. Not all models include edge entrainment. Cloud heating and dilution with ambient air are included and it is possible to include unsteady heat transfer and other thermodynamic effects such as phase changes. Thermodynamic sub-models are normally based on the assumption of homogeneous equilibrium. It is also possible to include sub-models for chemical reactions, which are important for substances such as for hydrogen fluoride or ammonia.

Box models can account for the effect of the wind speed, surface roughness and atmospheric stability, usually using Pasquill-Gifford stability classes, atmospheric temperature, pressure and humidity. They can also model nil wind. In still air, the cloud spreads under gravity and if the wind is present the cloud is advected downwind.

When the criteria for passive dispersion are met, it is possible to model transition to passive dispersion by assuming the box model predictions act as a virtual source. Dispersion coefficients are then calculated as input into a passive dispersion model, usually a Gaussian model. Alternatively, the transition can be refined to create a continuous, seamless transition by applying profiles to the averaged variables calculated by the model, for example Gaussian or top hat profiles, which remain valid for subsequent passive dispersion.

Most box models assume flat terrain and surface roughness is used to account for obstacles. However, it is possible to include dispersion on uniform slopes and simple obstacles such as fences.

Integral models

Integral plume models involve the solution of ordinary differential equations (ODEs) expressing the integral, or bulk, properties of the cloud for continuous releases (plumes). This includes horizontal spreading, mass transfer between the plume and the ambient and heating of the plume.

Steady-state plume models are used for grounded releases. They assume that the plume has a rectangular cross-section and the plume properties are averaged over the cross-section. The plume properties are also integrated in the downwind direction. The plume is steady state and does not vary with time. Similar to box models, the average plume concentration is calculated by using the mass flow rate of the substance and the volume flow rate of the plume. Similarity profiles can be applied to redistribute the concentration across the plume cross-section to be more physically representative. For the simplest models, most other features are as for box models. Transition is normally modelled using a virtual source and calculating dispersion coefficients.

These models can be generalised using similarity profiles applied to the averaged values in order to model the spatial variation of concentrations and other plume variables. These profiles are sophisticated enough to change at different downwind distances from the source. For example, near to the source the horizontal cross-wind plume profile for concentration might be a top hat profile, which will change to a Gaussian profile further

downwind. The benefit of this approach is it ensures a continuous transition to passive dispersion.

Similar to the more sophisticated box models, the more complex plume models include unsteady heat transfer and other thermodynamic effects, such as phase changes and chemical reactions. They can be modified to model uniform slopes and the effects of simple obstacles.

Integral models are also used for continuous elevated releases, for example, Ooms and Duijm (1984) and Hoot et al. (1973). The model equations are averaged over the plume cross-section. The cross-sectional area can be assumed to be a circle, ellipse or a rectangle. Similarity profiles are again applied to the spatially averaged variables to describe the spatial variability of a variable within the plume. The elevated plume is influenced by gravity, the drag force of the ambient flow and the momentum of the entrained air. There are different entrainment mechanisms in these models compared with grounded plumes to account for turbulence of the jet and cross-flow perpendicular to the plume axis.

Plume touchdown can be simulated using integral models. If transition to passive dispersion occurs while the plume is elevated, the plume continues to be modelled as an elevated passive plume. If touchdown occurs, the elevated plume model can be linked to a grounded dense gas dispersion model.

Both box and integral models normally require relatively few inputs, computing costs are typically low and often little user expertise is required. There has been a lot of work on integral models and many have undergone significant validation efforts. They have been shown to perform reasonably well when compared with experimental measurements.

In risk analyses, where initial conditions may be unknown, it is beneficial and indeed common practice to perform as many runs as possible with different conditions. The speed of integral models makes them ideal for this. They can provide a fast, general understanding of the flow, which is sometimes difficult to extract from more complex models such as CFD, which require post-processing to obtain relatively simple information.

One limitation that results from the fundamentally one-dimensional nature of the models is the inability to cope with complex terrain. Also, continuous integral models are not valid in very low or nil wind conditions. The user should take care that the anticipated accuracy of the model is not significantly changed in this limit.

5.2.4 Shallow layer models

Shallow layer models can be one dimensional or two dimensional. The two dimensional equations are averaged over the cloud depth. The one dimensional equations are also averaged across the cloud cross-section. Shallow layer theory assumes that the pressure throughout the cloud is hydrostatic everywhere, therefore vertical motion is neglected. This is broadly aligned to the motion of dense gas clouds, except at the front edge of the cloud.

Treatment of this front edge is often where different models vary. In one method, the front is treated as a discontinuity and its velocity is calculated by applying a front condition, as for integral models of grounded plumes. The method requires tracking of this front position. This is relatively simple to achieve in a one-dimensional model but this is not simple in a two-dimensional model and not typically used in this case. An alternative method applies additional terms at the front of the gas cloud to simulate the force imposed on the front as it pushes through the ambient air. A Froude number condition is used to control this method.

The form of the equations makes it a relatively simple matter to include source terms in the model to account for features such as complex topography. It is possible to include the influence of buildings and fences, although in these cases it is more difficult to justify neglect of vertical momentum.

Most shallow layer models are single-phase models. They can include the effects of heat transfer from the ground. Most existing models model atmospheric conditions in a similar manner to integral models, i.e. static and spatially non-varying. However, it is possible to include spatially-varying meteorological information. They are also able to model nil wind.

The main benefit of these models is their ability to predict the behaviour of dense gas clouds in complex, spatially-varying terrain. Another benefit compared with integral models is that they do not rely on empirical input. A benefit over CFD models is that they are less complex and therefore more easily used and, moreover, much faster to run in terms of computing time. However, like a CFD model, they rely on solving the governing equations on a mesh of points covering the area of interest and therefore dependency on the resolution of the mesh should be checked. This makes them more computationally intensive than integral models.

Perhaps the greatest limitation of these models is their inability to model the transition to passive dispersion, which is perhaps why there are few of these models and they are nearly all no longer in use or used for research purposes only. However, they can provide initial conditions for input into passive dispersion models and they can also be used in Lagrangian approaches, for example QUIC¹⁰³ (Brambilla et al., 2009).

Their usefulness in Quantitative Risk Assessment (QRA) has been demonstrated (Hankin, 2004a,b). However, at present there is no 'operational' shallow layer model for dense gas dispersion.

There are no examples of shallow layer models being used for modelling infiltration into fixed structures.

5.2.5 Lagrangian particle and puff models

Lagrangian particle models

Most Lagrangian particle models for dense gas dispersion originated from modifications to Lagrangian models for passive dispersion. They can be used to model both grounded plumes and elevated plumes. The mass of the released dense gas is represented by particles and the transport and dispersion is simulated by particle tracking. The movement of the particle during a time step is calculated through the collective effects of the mean flow, atmospheric turbulence and the excess density (relative to the air).

The mean wind field is usually three-dimensional and is provided as an input into the model from a meteorological model. The turbulent flow properties and Lagrangian time scales are derived from the meteorological model. The impact of the negative buoyancy of the dense gas cloud is expressed in terms of a local gradient Richardson number or the density difference between the particles and the air.

It is not trivial to include dense gas effects, in particular gravitational effects, in Lagrangian particle models, because it is necessary to link the transport of individual particles to the bulk behaviour of all particles. As a result, the model relies on using other models, similar to those already discussed, to provide the required physics.

Anfossi et al. (2010) discusses different methods for implementing Lagrangian models for dense gas dispersion. These range from the simplest models where a separate integral plume model provides the final dense plume extent and only then are neutrally buoyant particles emitted, to complex models where the buoyancy of the particle is included in the stochastic equation for the particle velocity evolution.

Lagrangian particle models can account for thermodynamic processes, for example during evaporation and condensation, but it is not simple to include them. The models are able to

¹⁰³ <http://www.lanl.gov/projects/quic/> accessed 8th November 2011

take into account complex topography and fixed structures. A smooth transition to passive dispersion is readily obtained, since the Lagrangian particle model continues without the gravity effects.

Lagrangian particle tracking has been used extensively for a variety of indoor air scenarios; for example, to investigate HVAC systems and air quality. No studies have been found that simulate infiltration and indoor dispersion of dense gases with a Lagrangian particle model.

The models are relatively fast to run, typically faster than RANS CFD models but they are slower than integral models. They are fast enough that they have been incorporated into emergency response packages. Note that many general-purpose commercial CFD packages include Lagrangian particle tracking models. A limitation of these models lies in the accuracy of the approach used for modelling the bulk effects of a dense gas release with individual particles.

Lagrangian puff models

Lagrangian puff models are another type of Lagrangian model. In this approach, a series of puffs are released into the flow field which are assumed to have Gaussian concentration distributions. The concentration field of the cloud is obtained from the sum of the contributions from the puffs. For elevated releases, negatively buoyant puffs fall downward under a buoyancy forcing. For grounded releases, the effects associated with the dense gas slumping on the ground are included.

Lagrangian puff models can be used with all types of meteorological data but their reliance on Gaussian profiles means that they cannot model nil or very low wind conditions and an approach is required to deal with these conditions. They can model topography but, unlike Lagrangian particle models, they cannot easily accommodate fixed structures. As for Lagrangian particle models, inclusion of thermodynamic processes is complex.

Like Lagrangian particle models Lagrangian puff models are fast to run and are used for emergency response.

5.2.6 Computational Fluid Dynamics (CFD) models

CFD models are two or three dimensional models in which a full set of partial differential equations are solved for conservation of mass, momentum, energy and species. They can be steady state or time-dependent. These models can simulate the full range of fluid flow phenomena and can be applied to all emission scenarios, terrain and meteorological conditions.

The models can be subdivided into three sub-groups: Reynolds-Averaged Navier Stokes (RANS), Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS). RANS models are sometimes sub-divided into steady and unsteady RANS (or URANS). There are also hybrid approaches, such as Detached Eddy Simulation (DES), which apply RANS models near solid surfaces coupled to LES models in the open space.

RANS models are perhaps the most commonly used CFD model because they tend to be less computationally intensive than LES. They rely on solving the mean properties of the flow (i.e. time- or ensemble-averaged) and use models to account for the effect of unresolved turbulent fluctuations on the mean flow. There are many different RANS turbulence models, information on which can be found in text books (e.g. Pope, 2000) or in the user manuals of commercial software packages. A brief summary is given in Markiewicz (2012). The turbulence model may have a strong effect in some dense gas scenarios with terrain and obstacles, because of differences in their ability to resolve the turbulence structures in the lee of buildings. Various comparison studies of turbulence models have been undertaken (e.g. Sklavounos and Rigas, 2004). The choice of RANS turbulence model

often involves a compromise between availability, complexity, computing time and the available validation.

A limitation of RANS models for simulating atmospheric boundary layers is the treatment of flow near walls. Most RANS turbulence models in common use were originally derived for engineering applications (e.g. gas turbines), and were tuned to give good predictions for flows over flat plates, through channels and spinning disks. For rough walls, RANS models typically use an equivalent sand grain roughness, k_s , with “wall functions”, that approximate the rapid changes in velocity (and temperature) near the wall. The wall functions can cause significant issues with maintaining realistic atmospheric boundary layer profiles. The use of k_s , when combined with z_0 values, can set specific requirements on near wall mesh resolution that are difficult to achieve and sometimes incompatible with modelling dense gas dispersion (Blocken et al., 2007; Batt et al., 2018).

LES models solve Navier-Stokes equations that are filtered in space, meaning that they resolve the behaviour of large eddies and use a model to account for the effect of the smaller (unresolved) turbulent eddies on the larger scales. The size of the filter is usually related to the computational grid cell size. Using a finer mesh therefore means that the LES resolves more of the turbulent eddies and the model accounts for a smaller fraction of the turbulence energy. In the limit of a very fine mesh, the LES becomes a DNS and resolves all of the turbulent scales. LES inherently requires the calculation of the time-varying behaviour. To simulate a steady-state flow, the LES simulation needs to be run for a sufficiently long time to generate statistically reliable mean values. When simulating puff releases, each LES simulation will give one realisation and multiple simulations are needed to generate ensemble-averaged values.

LES models typically have much higher computational cost than RANS models and they require care in generating realistic turbulent eddies at the inlets to the flow domain.

RANS models still represent a good compromise between accuracy of results and computational effort. Both LES and DNS have been mainly used as research tools to improve understanding of physical processes. However, the development and use of LES is becoming more common as modern computing power increases. For example, the Parallelized Large-Eddy Simulation Model (PALM) is an LES model, which has been optimised for use on massively parallel computer systems. It was recently updated to run on Graphical Processor Units (GPUs). The use of supercomputers means that it can simulate very high resolution scenarios (down to about 1 m) on large model domains (see Maronga et al., 2015).

Appropriate meshing can be a particular difficulty for dense gas dispersion. As the dense gas spreads, it requires a fine mesh to accurately resolve the leading edge of the cloud and avoid excessive numerical diffusion in its vicinity (see Qi et al., 2010). Adaptive meshing is ideally suited to this application, where the mesh changes as the flow evolves during the calculation to maintain a fine grid just in areas where there are steep gradients in velocity or concentration. However, adaptive meshing is currently only available in just a few software packages. When simulating shallow, dense gas clouds that spread over large distances, it can be almost impossible to achieve a fine enough resolution in the cloud and a large enough mesh elsewhere, without prohibitively high computational cost (Batt et al., 2018).

General-purpose commercial CFD packages such as ANSYS CFX, Fluent and Star-CCM+, provide a basic platform on which most dense-gas dispersion scenarios can be built using a variety of models. They have many options and input parameters and therefore they require significant user expertise. This increases the importance of verifying that the sub-models selected are describing the correct physics. The level of specialism required to use the software is often a limitation of the CFD approach. Some CFD models have been built specifically for dense gas dispersion modelling with a less complicated user interface, but

they still require significant user expertise. Model comparison/evaluation studies have found significant variation in the results depending on the user. For example, Touma et al. (1995) found that in their model comparison study that model developers frequently disagreed with the method of application, choice of source terms etc. CFD software also have typically high purchase costs.

There are several issues with the use of CFD models for Land-Use Planning in the UK, which were discussed by Gant and Tucker (2018). The strength of all CFD models is in scenario reconstruction for post event analysis, when there may be a more precise idea of the initial and ambient conditions than in a risk analysis. CFD can also be usefully applied for testing mitigation measures. An essential part of setting up a CFD model is building a geometry that contains the salient features of the study area hence their advantage in reconstructing incidents. Complex three-dimensional geometries such as provided by GIS data can usually be imported into CFD models. It is also a relatively simple matter to include structures and fences.

A significant limitation of CFD is that, in some cases, creating a detailed model in CFD can over-complicate the problem. If all that is needed is a first approximation or an order of magnitude prediction, empirical or integral models offer a faster and less expensive solution. There is always a significant amount of research underway into novel, more sophisticated and higher resolution CFD approaches, particularly with ever-increasing modern computing power. However, these are of little use for dense gas dispersion if the source is unknown or cannot be reasonably approximated. Also, while CFD models are theoretically able to model any meteorological conditions, as with simpler models, low wind conditions can sometimes cause problems with CFD models, due to issues at the boundaries to the flow domain.

An alternative use of CFD models is as a databank to provide virtual measurement data for creation of simpler models. This is of particular interest in complex terrain where the simpler models are often limited. In some examples, multiple LES models are run in advance to provide data coverage of an area from which nomograms are created. The idea is to utilise the high resolution of CFD models but avoid their slow run times by creating a fast and accurate model prediction tool for use in incident response. Examples of this type of modelling system are CT-Analyst developed by the US Naval Research Laboratory¹⁰⁴ and SIRANE (Soulhac et al., 2011). It is arguable whether this sort of model is reasonable outside the limits and conditions of the specific studies with which it was validated.

Another example of relatively novel use of modern computing power is the Joint Outdoor-indoor Urban Large-Eddy Simulation (JOULES) model, which is being developed by Aeris in partnership with LBNL¹⁰⁵. Limited information is available on the Aeris website:

[JOULES is] a next-generation synthetic modeling environment generator—a GPU-based large eddy simulation (LES) model with an in-line tracer capability—that can synthesize environments with physically realistic peak/mean concentrations and spatio-temporal gradients for an urban location. The synthetic datasets are calculated up to 150x faster than those computed by a CPU-based system.

The objective is to compile a high resolution synthetic dataset using JOULES to supplement limited experimental datasets for use in validation of other, more operational, models. A difficulty with using this approach in the current context is that dense gas dispersion is highly dependent on the source conditions and therefore not easily generalised.

CFD models can be used to model infiltration scenarios but they are mainly limited to purpose-provided (known) openings. The location of adventitious openings are not likely to be known and if they are, they are likely to be of such sizes and shapes that they are difficult

¹⁰⁴ <https://www.nrl.navy.mil/lcp/ct-analyst> Accessed on 17th April 2020

¹⁰⁵ <https://aerisllc.com/item/urban-coupled-indoor-outdoor-modeling-synthetic-environments/> Accessed on 26th June 2020

to resolve with a mesh. The CFD model can model both the outdoor and indoor air flow although the mesh scales and computational cost would make this prohibitively expensive in one simulation. Bespoke CFD models have been developed for infiltration scenarios but it is more common to use one simulation to calculate the external flow field and then another for the internal flow.

In a similar manner to outdoor dispersion, the strength of CFD in internal flow modelling is in scenario reconstruction to look at a particular feature of the flow field. Otherwise, other approaches, such as multi-zone models, allow for more scenarios to be studied at much lower cost in terms of computing time and effort.

5.2.7 Zone models

Zone models are particular to indoor air flow and not applied to external flows. However, they are relevant as part of modelling infiltration into buildings.

The general principle behind them is that each zone is linked through airflow pathways to other zones or to the outside air. Zone models can be single-zone or multi-zone depending on whether the indoor area is set as a single space or broken down into multiple spaces. Each zone is assumed to be well-mixed. In the case of a multi-zone model a zone might represent a room while for a single-zone model the entire building is represented by one zone. Airflow pathways are openings such as doors, windows, cracks, fans, ducts, hallways etc.

To setup a zone model calculation, the zones and the pathways are first defined. Flow rates for each zone are determined by the pressure difference across all of the links between the zones and outside. Using these conditions and mass conservation the model calculates the air and contaminant concentrations for each zone.

Zone models can be used with time-varying inputs and boundary conditions, which means that they can model transient features such as the movement of occupants into and out of rooms and HVAC systems turning on and off. The models can output the variation of concentration in a zone with time. They cannot typically resolve flow fields within the room or variations in temperature or concentration within a room. However, it is also possible to create sub-zones to model variations within a single zone (e.g. Ren and Stewart, 2002). In this case, a room is divided into a small number (tens to hundreds) of zones, each of which is assumed to be homogeneous. The sub-zone (or zonal) models can be used to predict airflow and temperature variations within a room providing it is feasible to predict the main driving flows (Wurtz et al., 1999). For example, air jets from fans or thermal plumes from heaters.

The most limiting assumption in zone models is their use of well-mixed zones. Their lack of ability to model the details of the zone flow field and variable distributions mean that they may under or over predict exposure of occupants to contaminants within that zone. It also means that they may not provide an accurate prediction of contaminant transport to an adjacent zone. These are features that can be improved with the use of sub-zones as mentioned above but they are also modelled as standard with a CFD model.

The main advantage of zone models and multi-zone models in particular, compared with CFD, is their ability to model an entire building much more quickly. They also have the advantage that they can model many transient features in the model relatively simply compared with a CFD model.

5.3 Assumptions and parameterisations

There are some general assumptions and parameterisations that are common across some or all types of model. These are discussed in this section.

5.3.1 Source terms

For dense gas dispersion, knowledge of the source conditions is critical. The source drives the density difference between the hazardous cloud and the surrounding environment. Therefore accurate modelling of the source is critical if the dispersion is to be modelled accurately.

The review of incidents presented earlier showed that dense gases can be produced from a variety of different sources. In particular, storage conditions mean that hazardous gases are often stored in a liquid state and undergo complex physical processes on release.

Some dispersion models include the sub-models for different sources. In other cases, a separate model must be used to calculate appropriate input conditions. This could be in the form of a simple calculation, an analytical solution, a complex source term model or experimental measurements.

A good description of source terms, including flow charts for determining release processes and methods of calculating them, can be found in Section 4 of US EPA (1993a). Reviews of source term models can be found, for example in Webber et al. (2010), which focuses on LNG, but many of the models summarised are applicable across a range of substances.

A difficulty with emergency response modelling is that the details of the source can be unknown at the time and are often not established fully until the incident is over. This is one of the greatest difficulties with dispersion modelling for emergency response. For passive contaminants, a first approximation of the cloud dispersion can be gained by releasing a unit quantity of material (e.g. 1 g/s) and then scaling the results once on some measurement data is available.

A significant amount of work has been undertaken on inverse modelling, which seeks to determine the source conditions from measurements downwind (e.g. Endregard et al., 2016; Efthimiou et al., 2017). Much of this work has been focused on passive releases and is unsuitable or more complicated for dense gas releases.

5.3.2 Flat terrain

Many dense gas dispersion models assume that the terrain is flat. It is for the user to decide if this is appropriate or not and to assess the impact. When the wind is present the effects of relatively small topographical features may not be important compared with other factors. More information on topographical effects can be found in Section 3.4.7.

5.3.3 Surface roughness and fixed structures

Surface roughness can be anything from gravel to city-scape depending on the scale of the obstacle array to the scale of the contaminant cloud. Important dimensions, in addition to the size of the cloud, tend to be the height of the obstacles and the distance between the obstacles. Figure 37 helps to highlight the relevance of cloud depth compared with the average buildings depths and is discussed further below.

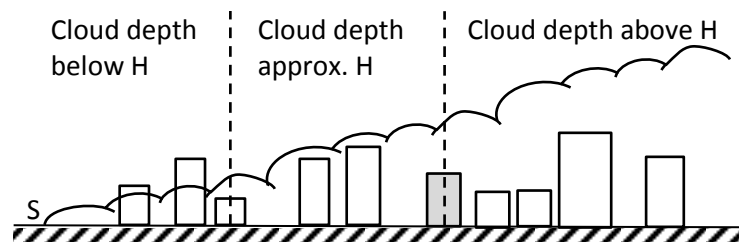


Figure 37 Schematic diagram of a contaminant cloud released from a source (S) at ground level within an obstacle array (based on Hanna and Britter, 2002). The grey obstacle represents the average building height, H

Modelling fixed structures as a roughness is appealing when the details of the interaction of a gas cloud with the obstacle array are not of interest compared with the bulk effect. This approach may be acceptable on the scale of the surface layer but it should be undertaken with caution when considering effects on dense gas dispersion. Figure 35 has shown that it is not uncommon for dense gas cloud depths to be of a similar order of magnitude to building heights, particularly for flammable clouds.

Hanna and Britter (2002) suggest criteria for defining a roughness array as 20 or more obstacles and covering a distance of greater than the maximum of ten building heights, 20 m or 20% of the total distance from the source to the point of interest in the along wind direction. They also suggest an angular coverage of greater than about 30 degrees around the source.

Aerodynamic roughness length

In many dispersion models, surface roughness is parameterised in terms of the aerodynamic roughness length, z_0 . The value of z_0 is not directly related to the height of any physical roughness elements. Instead, it is calculated by extrapolating a logarithmic velocity profile through the surface layer of the atmosphere; the height at which the velocity falls to zero is z_0 . As a rule of thumb, z_0 is about 10% of the average height of obstacles, with a factor of two uncertainty (Hanna and Britter, 2002). It is common to prescribe z_0 using tabulated values for different ground surfaces and land-uses. For example, see Table 2 in Section 3.4.4. Hanna and Britter (2002) cited the work of Auer (1978), who proposed choosing the value based on the land use with 3 km of the source.

Surface roughness is often used to account for obstacle arrays, such as groups of buildings. When the surface roughness is large, in the form of high, dense, obstacle arrays (see Table 2) the displacement depth, d , can be used to shift the effective ground level. Like z_0 , the displacement height is not simply the height of the obstacles or roughness, it is an effective parameter that requires calibration. For obstacles such as urban centres and forests this can be estimated as about 50% of the mean physical height and for less packed environments such as residential developments or industrial processing sites it can be estimated as about 10-20% of the mean height (Hanna and Britter, 2002).

The dilution of the cloud due to the presence of the roughness is modified due to its dependence on the friction velocity, u_* , which is dependent on z_0 and d . Many numerical models have been developed under the assumption that the roughness elements are small compared with the cloud size (right hand end of Figure 37) and rely on this approach. However, when the roughness elements are bigger than, or similar to, the cloud depth (middle and left hand end of Figure 37), the detailed flow around the individual obstacles can also contribute to dilution (Roberts and Hall, 1994). The Yellow Book (Van den Bosch and Weterings, 2005) says that as a rule of thumb, to use an aerodynamic roughness length approach, the height of the cloud should always exceed the roughness length by an order of magnitude, except for very near the source. Roberts and Hall (1994) (and others) have

suggested that the maximum roughness length that should be used in models of dense gas dispersion is about $z_0 = 0.5$ m.

A difficulty with specifying z_0 and d is the spatial variation of surface roughness and obstacle arrays. Contaminant clouds can disperse over very large areas and the terrain within the area of interest can change dramatically. Hanna and Britter (2002) discuss spatial variation and suggest that if z_0 changes by less than a factor of two over the cloud trajectory then an averaged value is acceptable, otherwise it should be discretised into different roughness zones. Most models do not account for spatially varying surface roughness.

The above methodologies also assume that the release occurs within an equilibrium boundary layer. In other words, they do not account for dispersion over an area where an internal boundary layer is developing, e.g. transitioning from rough to open. Hanna and Britter (2002) suggested a criterion of the maximum of ten building heights or 20 m for an equilibrium boundary layer to form.

Another difficulty with using z_0 is that this is the height at which the wind speed approaches zero but the gas cloud may disperse below this height. For modelling shallow plumes that disperse below the roughness height, z_0 , some models use a linear interpolation for the wind speed for heights less than $2z_0$, so that the wind is continuous all the way down to $z = 0$. Alternatively, Hanna and Britter (2002) proposed a model for the velocity within the obstacle 'canopy', which can be used to modify the velocity profile in a dense gas dispersion model. Alongside this is the effect on turbulence within the obstacle array. For passive releases, this is reasonably well described via u_* . Hanna and Britter (2002) suggest this approach is reasonable for dense gases until further work is undertaken to determine its validity.

A limitation of the z_0 concept is that it is only valid within the surface layer of the atmospheric boundary layer. This varies in depth depending on the atmospheric stability but can be of the order of 50-100 m. Hanna and Britter (2002) stated that this method of describing surface roughness should not be used for average building heights exceeding 25-50 m and suggest a maximum of about 20 m.

CFD models have other issues with modelling large aerodynamic surface roughness values, as discussed in Section 5.2.6.

Other obstacle array parameterisations

There is a large amount of literature on modelling a range of obstacle arrays with parameterisations, which are particularly useful for the urban and industrial environment. Good summaries can be found in Hanna and Britter (2002), Britter and Hanna (2003) and Scapergas and Hebden (2003). Most methods rely on calculating a frontal area density, or packing density, λ_f , or the planar area density λ_p (Grimmond and Oke, 1999). These are essentially ratios of average areas blocked by buildings and the total built-up area. They can be used to calculate z_0 and d .

These obstacle array densities can also be used to assess the likely flow field and decide on the model complexity required when the dense gas cloud is of similar height to, or smaller than, the obstacle array. For example, see Table 20, which is based on the interpretation of dispersion types from Scapergas and Hebden (2003).

Table 20 Obstacle model selection when the source is within the obstacle array and/or the dense gas cloud is typically of similar height or lower than the height of the fixed structures through which it is dispersing. H is the average building height, S is the average spacing between buildings and $\lambda_p = A_p/A_d$ is the plan density, where A_d is the area of the overall complex and A_p is the sum of the plan areas occupied by buildings. Based on Scapergas and Hebden (2003)

Spacing of obstacles	Conditions	Description	Modelling
Large	$\lambda_p < 10\%$, $S > 10 - 20H$	• Array of isolated obstacles • There is no wake interaction • Flow field around each obstacle is generally as if it were in isolation • BUT turbulence from upstream buildings may enhance dispersion around downstream buildings	Single building model can be implemented in simple models
Intermediate	$10\% < \lambda_p < 20\%$, $S < 10H$	• Array of interacting obstacles • Wake interference • Building wakes interact with each other and with flow above • Enhanced turbulence production within the array • Dispersion is dominated by wake to wake entrainment	An improved methodology, such as CFD or physical modelling, is advised
Skimming flow	$\lambda_p > 20\%$ $\Delta H < H/10$	• Array of interacting obstacles • Obstacle wakes merge • Flow (above) skims over buildings • Less turbulence production within the array • Dispersion is dominated by street-to-street channelling • Does not occur if the height variation is greater than 10%	An improved methodology, such as CFD or physical modelling, is advised
Small	$S < H/2$, $\Delta H < H/2$	• Closely packed array with little variation in height • No separate wakes • The entire array can be treated as one isolated obstacle • Flow field within the array is effectively stagnant	Single building model can be implemented in simple models

A limitation to using the building-density parameterisations is the inherent inhomogeneities in the urban environment, such as tall buildings and open spaces. In contrast, much of the data available for model validation tends to be for homogeneous arrays of cubes (Macdonald,

2000; Britter and Hanna, 2003). There are other parameters that influence the regimes suggested in Table 20, such as the arrangement of the obstacles (aligned or staggered), orientation to the wind and length and width of individual obstacles.

Another approach for congested areas and obstacle arrays is to use porosity values in parts of the computational domain. For example, the FLACS model¹⁰⁶ uses this approach.

Resolving fixed structures

If it is important to predict the details of the concentration distribution within the obstacle array, for example concentration downwind of a particular building, then the impact of individual buildings may need to be modelled. The approach adopted for isolated structures may vary depending on whether the obstacle has a significant volume attributed to it, such as a building, or is more two-dimensional, such as a fence. Obstacles have been modelled by imposing an increase in the cloud's width and height at the location of the obstacle rather than model the obstacle itself (Martin et al., 1994, Cleaver et al., 1995); or by imposing a pressure drop due to the presence of an obstacle and adding a term to account for increased entrainment downstream of it. This 'building effect' modelling is used in some simpler dense gas dispersion models.

Models that are capable of resolving the detailed flow field around buildings have historically been expensive, but with modern computing power the potential for this is increasing, even for real-time simulations. PALM is an example of a state of the art, high resolution LES model which can resolve buildings down to 1 m over domains of several km (Maronga et al., 2015). Street network models such as SIRANE are other examples of real-time modelling solutions. They can use multiple high fidelity simulations, performed in advance of an incident, to create a bank of representative flow fields throughout the street network of a particular city (Soulhac et al., 2011; Belcher et al., 2015). Neither PALM nor SIRANE can model dense gas dispersion.

As mentioned above, a difficulty for modellers when modelling flow within large obstacle arrays is defining an appropriate velocity profile within the array. In addition, recent work on passive gas plume dispersion suggests that atmospheric stability should be accounted for (Marucci and Carpentieri, 2020).

5.3.4 Atmospheric conditions

Static vs transient conditions

It is a common assumption in regulatory dispersion modelling to simplify the atmospheric conditions by assuming static meteorology for any one release. Much of the modelling in this context is undertaken in advance and so the conditions are unknown. It is more informative and time-efficient to conduct multiple simulations of static conditions with different wind directions and a range of atmospheric stabilities than it would be to model conditions that change over time. As a result of this, there are many models that assume static meteorology, or have this option. In an emergency response context, and sometimes in post event analysis, it is important to correctly model changes in the atmospheric conditions.

Static meteorological models tend to characterise the atmospheric conditions in terms of the Monin-Obukhov (MO) length, friction velocity, aerodynamic surface roughness length and the mixing height. Perhaps the most common way of calculating the MO length, L , is to approximate it from the atmospheric stability in terms of Pasquill-Gifford Stability class and use an aerodynamic surface roughness length. For an example of this methodology see the Yellow Book (Van den Bosch and Weterings, 2005). These parameters are used to calculate a set of profiles that describe the atmospheric flow field, including, the wind profile,

¹⁰⁶ <https://www.qexcon.com/products-services/FLACS-Software/22/en> Accessed on 14th April 2020

temperature profile and turbulence profiles. Commonly used forms for the wind profile include log profiles (e.g. Panofsky and Dutton, 1984) or power law profiles (e.g. Wheatley, 1986).

Lacome and Truchot (2013) found that the use of different approaches by different modellers to translate from the Pasquill stability class to the value of L was one of the issues responsible for significant variability in CFD results for atmospheric dispersion. Monin-Obhukov Similarity Theory (MOST) is also technically only valid in the surface layer of the atmospheric boundary layer. This is frequently not an issue because many dense gas dispersion incidents occur within the surface layer. Under neutrally stratified atmospheric conditions the surface layer is quite high. However, in stably stratified conditions the surface layer can be relatively shallow. There is a large body of work that has sought to extend the validity of MOST beyond the surface layer height (e.g., Zilitinkevich et al. 1998; Gryning et al., 2007).

In reality, atmospheric conditions are changing continually. Therefore, there is the question of whether atmospheric conditions can be modelled as static, or whether the model needs the ability to simulate the effects of changes in conditions. The Yellow Book (Van den Bosch and Weterings, 2005) suggests that the total travel time for which the static models are valid should have a maximum of about 3 hours. This can be equated to a maximum travel distance using the reference wind speed, u_{ref} as about $10^4 \times u_{ref}$ metres (e.g. for a wind speed of 2 m/s it equates to a distance of 2 km). For larger distances, the Yellow Book (Van den Bosch and Weterings, 2005) suggests that dedicated long range dispersion models are required.

Wind meander

Wind meander is the natural, low frequency lateral motion of the wind that causes a plume to snake from side to side over time. It can be an important effect for widening the area affected by the hazardous cloud.

Wind meander is often included in models. Most integral dispersion models simulate wind meander by making the lateral spreading rate depend on the averaging time, for example see Tickle and Carlisle (2013). Most RANS-based CFD models assume that the wind speed and direction remains constant over time. Whilst it is possible to impose fluctuating wind conditions (Hanna et al., 2004), this is not widely done in practice.

Nil wind, high stability conditions

Many dispersion models cannot simulate very low wind speeds (or nil wind), and very stable atmospheres, and instead they limit the wind speed to minimum value. Pasquill-Gifford stability curves, which are used by some models, are strictly only valid for wind speeds above 2 m/s (Sawyer, 2007).

Sawyer (2007) and Wannberg et al. (2010) found that for the scenarios in their studies, dispersion models tended to over-predict concentrations at low wind speeds and therefore they could at least be considered conservative.

5.3.5 The Boussinesq approximation

The Boussinesq approximation assumes that the effect of density on inertia is small and can be neglected. This means that in the governing equations the density only appears when it is multiplied by the gravitational acceleration, g (in the body force term). The approximation is valid if the difference in density between the dense gas and the environment is small compared to the density of either fluid.

The approximation is inaccurate when the dimensionless density difference, $\frac{\Delta\rho}{\rho}$, is of order one. This can occur near the source of a dense gas release. Despite this, the approximation is widely used in many dispersion models.

Several studies have examined the differences between Boussinesq and non-Boussinesq density currents using water flume laboratory studies, for example see Lowe et al. (2004).

5.3.6 Homogeneous equilibrium

Two-phase thermodynamics is frequently modelled assuming homogeneous equilibrium, e.g. DRIFT (Jones et al., 1994). Homogeneous equilibrium implies that the liquid droplets are uniformly distributed within the cloud and the liquid and gas are at a uniform temperature and in thermodynamic equilibrium. Therefore, both phases can be modelled with a single temperature and velocity field. The alternative is a more rigorous approach accounting for mass and heat transfer processes between droplets and the surrounding air/vapour mixture. Essentially, the homogeneous equilibrium model should be valid providing that these processes occur more rapidly than the dilution of the cloud by air entrainment (Britten, 1998).

Kukkonen et al. (1994) compared predictions from DRIFT, which assumes homogeneous equilibrium, and AERCLOUD, which uses a more sophisticated aerosol approach where heat transfer to droplets in the cloud are modelled explicitly. They found that the droplet heat transfer processes were indeed fast enough that there was little difference between the model predictions. In particular, they concluded that the homogeneous equilibrium model may be adequate for dense gas releases where the droplet size is smaller than 100 μm .

Similar conclusions were reached by Dixon et al. (2012), who compared the integral model FRED to two different CFD models, one of which used assumed homogeneous equilibrium and the other which used a Lagrangian particle model that allowed for non-equilibrium behaviour. The results from the two CFD models for dense-phase CO_2 jets were practically identical, and in good agreement with the measurements.

Whilst homogeneous equilibrium may be valid for pressure-liquefied gas releases that produce small droplets, for lower pressure releases (e.g. for cryogenic, temperature-liquefied gases), the homogeneous equilibrium model may not be appropriate.

5.4 Previous model reviews

5.4.1 Havens (1982)

Havens (1982) conducted a review of mathematical models for dense gas dispersion, which included some of the earlier models for dense gas dispersion on which many of the subsequent dispersion-modelling software is based. The work included reviews of the mathematical models of van Ulden (1974), Germeles and Drake (1975), Picknett (1978a), Eidsvik (1979), Cox and Carpenter (1980), Colenbrander (1980) and the k-theory model SIGMET. Particular attention is given to comparison of entrainment model parameter estimation. The models were compared to the limited experimental data available at the time for spills of LNG on water: Bureau of Mines, Gadila, API/Esso and Burro (see Section 6.5).

5.4.2 Zapert et al. (1991)

Zapert et al. (1991) published a US EPA evaluation of DEGADIS, SLAB, CHARM, AIRTOX, FOCUS, SAFEMODE and TRACE, using data from Desert Tortoise, Burro and Goldfish. The exercise was specifically for dense gas releases in which the gas was continually released for between three and ten minutes.

The experimental data was well-analysed to obtain information suitable for model input, which was tabulated and presented in a form that could be used in another model evaluation exercise. Statistical performance measures were used to evaluate model performance.

Model predictions of maximum concentration and plume half-width were compared to the data. The model performance varied with none of the models exhibiting consistently good performance across all of the experiments. However, when combined across the three experiments, all models performed to within a factor of 2.

5.4.3 Hanna and co-workers

Over the last 30 years, Steven Hanna has published extensively on atmospheric dispersion of hazardous substances. Much of this work has involved model comparison and validation exercises.

A particularly relevant study is the model evaluation of 14 dispersion models as part of the US Air Force and American Petroleum Institute model evaluation program (Hanna et al. 1993a). The models included AFTOX (passive), the Britter and McQuaid workbook, DEGADIS, INPUFF, Ocean Breeze/Dry Gulch (passive), SLAB, Gaussian Plume Model (passive), AIRTOX, CHARM, TRACE, HEGADAS, FOCUS, GASTAR and PHAST.

The models were evaluated against the following field experiments: Burro, Coyote, Desert Tortoise, Goldfish, Porton Down, Maplin sands, Thorney Island, Prairie Grass (passive) and Hanford (passive). The experimental data was thoroughly analysed to obtain information for model input. Statistical performance measures were used to assess the performance of models.

Hanna et al. (1993) found that a few of the models exhibited relatively good performance in their predictions of maximum concentrations on monitoring arcs. It was found that the Britter and McQuaid, CHARM, GASTAR, HEGADAS, HGSYSTEM, PHAST, SLAB, and TRACE models exhibited the most consistent predictions of the plume centreline concentration. Most of the models performed reasonably well in predictions of the plume width. None of the tested models were able to reproduce the observed variation of concentrations with averaging time. The predictions of concentrations were weakly sensitive to the change in roughness length.

The later Hanna et al. (1996) study included a tabulated summary of model information, gained from questionnaires to developers, on the following models: AIRTOX, ALOHA, AQPAC, CANARY, CHARM, CHEM-MIDAS, DEGADIS, DRIFT, FEM3C, GASTAR, HGSYSTEM, HOTMAC/RAPTAD, PHAST, PLM 89A, SADENZ/SACRUNCH/SAPLUME, SAFEMODE, SCIPUFF, SLAB, SUPERCHEMS EXPERT, TRACE, TSCREEN and VDI 3783. According to the information provided, all of these models can model dense gas dispersion.

Hanna et al. (1996) also included seven worked examples of applying ALOHA, DEGADIS, HGSYSTEM, INPUFF, ISC and SLAB.

Hanna et al. (2008) compared the dense gas dispersion models of TRACE, PHAST, ALOHA, HGSYSTEM, SLAB and SCIPUFF to data from three chlorine railcar incidents: Festus, Macdona and Graniteville (see Section 4.5). They also evaluated the performance of the Gaussian plume model alongside the dense gas dispersion models for Festus. Hanna et al. found that all of the models produced broadly similar downwind distances to specific concentration levels and similar corresponding plume widths and heights. They also found that accurate estimation of the source term is important since the calculated chlorine concentrations were approximately proportional to the mass release rate. All of the models consistently over-predicted the number of casualties in the incidents, by an order of magnitude or more (Hanna and Chang, 2008). Hanna et al. identified a number of uncertainties in the models that could be responsible for the errors. These included the discharge models, the effect of liquid rainout and pool formation, the atmospheric dispersion models, the effect of terrain and chemical reactions (including photolysis), dry deposition, and the toxic effects models.

5.4.4 Sykes and Lewellen (1992)

Sykes and Lewellen (1992) evaluated PLM89A, TRIAD, HGSYSTEM, ADAM and SLAB for simulating uranium hexafluoride releases. They concluded that none of the models met all of the requirements for a safety analysis model. HGSYSTEM was subsequently modified to include relevant physics specifically for uranium hexafluoride as a result of this study.

5.4.5 Liddament and Allen (1993)

Liddament and Allen (1993) published a study under the auspices of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme that aimed to assess the performance of models used to calculate hourly mean rates of air infiltration and fresh air exchange in buildings. They also sought to identify fundamental parameters required to achieve reliable results.

The work involved a model validation exercise on ten infiltration models: LEAKS, NRC Canada, ELA 4, SWIFIB, VENT, ENCORE, Gas Research Institute/Institute of Gas Technology, LBL, BRE, Reeves et al. The models tested included both simpler, single-zone models and more complex, multi-zone models. Some of the models were theoretical and others made use of whole-building pressurisation tests to determine the overall leakage rate. The study also included a review of suitable validation datasets.

Model performance was based on the consistency at which the predictions were within $\pm 25\%$ of the measured air infiltration rate. They found that, in general, there was excellent agreement between calculated and measured air infiltration rates. The important parameters identified were the external pressure distribution and the air leakage characteristics of the building. They observed that it was difficult to quantify the wind pressure distribution, particularly in the case of shielding from neighbouring buildings and because of the shape of the building itself.

5.4.6 Lazaro et al. (1997)

The model review and evaluation conducted by Lazaro et al. (1997) appears to follow on from Hanna et al. (1993,1996) studies. Codes for atmospheric dispersion were identified and then categorised into Tier I or Tier II based on a set of nine screening criteria. Tier I codes were: ADAM, ALOHA, CALPUFF, ASRAM-SC, DEGADIS, FEM3C, HGSYSTEM, MOTMAC/RAPTAD, INPUFF, SCIPUFF, SLAB, TSCREEN, VLSTRACK. Tier II codes were: AFTOX, AQPAC, CG-MATHEW/ADPIC, CTDM Plus, EMGRES, GAUSI, HARM-II, MARSS, PUFF-PLUME, RTVSM, VDI 3783 Parts 1 and 2. The Tier I codes received detailed review and evaluation, which included running test problems, while Tier II codes only received the review.

Tables in the Lazaro et al. (1997) document provide information on model developers, intended use of the model and its capabilities, as well as input information and model outputs. The scenarios studied were similar to those analysed by Hanna et al. (1996), but with a wider range of models. The study also compared passive dispersion models with dense gas dispersion models for modelling dense gas dispersion.

5.4.7 Nair et al. (1997b)

Nair et al. (1997b) conducted a review of models available for determining the consequences of uranium hexafluoride releases. They identified that HGSYSTEM was the most 'complete' model available at that time, along with a draft model for NRC (Chhibber and Kaiser, 1993). Nair et al. (1997b) also review RTM-96. This is a screening model, which involves a hand calculation procedure that was developed to predict conservative estimates of health impacts from releases of uranium hexafluoride into the atmosphere.

5.4.8 Lines et al. (2000)

Lines et al. (2000) published a review of dense gas dispersion models in low wind speed conditions. They compared HGSYSTEM, GASTAR and DRIFT to data from Burro trial 8, Lathen trial 60 and Thorney Island trial 47. All of the models performed similarly and reasonably well to limited experimental data available. They found that the model evaluation statistics for low wind speeds were comparable to those with wind. Lines et al. (2000) highlighted the lack of data available for wind speeds less than 1.5 m/s and that source definition in trials (up until 2000) was not good enough for use in typical dispersion models.

Model limitations and recommendations were discussed. They concluded that the models can be used with reasonable confidence at wind speeds at least as low as 1.5 m/s but care must be taken that the source is accurately characterised within the model and guidance is required on provision of appropriate inputs. Sensitivity to the way the user chooses to define the model was observed and this sensitivity increased at low wind speed. They suggest the greatest scope for model improvement is in better use of the existing models e.g. through better guidance, use of meteorological data.

5.4.9 Scapergas and Hebden (2003)

Scapergas and Hebden (2003) investigated source term modelling for releases within building complexes. The study provides useful information on the dispersion of dense gases within, and downwind of, building complexes. It includes a review of relevant wind tunnel experiments, CFD modelling and simpler model parameterisations for modelling the impact of fixed structures on dense gas dispersion.

5.4.10 Sohn et al. (2004)

Sohn et al. (2004) conducted a review of models that could be used for predicting dispersion of chemical and biological substances in and around buildings, including a comparison of CFD and multi-zone models for indoor air flow. They concluded that both types of model are useful tools, with CFD providing greater detail, but with the limitation that it is not able to quickly account for transient effects, such as occupants coming and going, without requiring significant computing resource.

The review included two models that are capable of modelling both inside and outside flow: AirPak and FloVENT. Other models for solely internal or external flow were also reviewed with a view to using one as input to the other. The models reviewed for outdoor flow were HPAC¹⁰⁷ and FEM3MP. The models reviewed for indoor air were CONTAM and FloVENT.

5.4.11 SMEDIS

The European Scientific Model Evaluation of dense gas DISpersion models (SMEDIS) project was set up to develop and test a framework for the scientific evaluation of models for dense gas dispersion in complex situations (Carissimo et al., 2001). The objective was to develop a protocol for the scientific evaluation of dense gas dispersion models with a particular emphasis on the complex effects of obstacles, terrain and aerosols, and to apply this protocol to dense gas dispersion models currently in use in Europe.

The models included were Britter and McQuaid (1988), VDI 3783, AEROCLOUD, DRIFT, EOLE, ESCAPE, GASTAR, HAGAR, HGSYSTEM, OHRAT, PHAST/UDM, SLAM, SLUMP, WHAZAN. Several other models (DISPLAY-1, DISPLAY-2, GReAT, SLAB, TWODEE, ADREA-HF, CFX, COBRA, MERCURE and STAR-CD. DEGADIS, FLACS, KAMELEON and FLUENT) joined the project later and were also evaluated.

¹⁰⁷ Note that HPAC development has progressed since 2004 and now includes a means to model indoor – outdoor interaction using CONTAM.

Most of the evaluation was undertaken by the model developers themselves and they were allowed to tune their models during the study. Statistical performance measures were calculated for the models. In general, the statistical performance was better for more sophisticated models.

5.4.12 Wannberg et al. (2010)

Wannberg et al. (2010) examined the capabilities of three models for simulating buoyant, passive and dense gas releases in low wind speeds. Their results highlighted that some models (ALOHA in this case) should be used with caution, since they were not designed to be used for low wind speeds, and as a result it may under-predict concentrations.

5.4.13 Hall and Spanton (2012)

The ADMLC has funded two reviews of ingress modelling. The first was undertaken by Milner et al. (2004) and the second by Hall and Spanton (2012). The latter work included an overview of building ventilation and infiltration. This was followed by a closer look at pressure patterns on building surfaces and the impact of building distribution on the pressure patterns. The spatial variation of concentration on buildings from contaminants from external sources was reviewed and differences between open terrain and urban areas were studied. The review includes a discussion of methods for estimating building infiltration and ventilation rates, and external and internal exposure to contaminants.

Existing models were reviewed, including discussion of the limitations of models and available information. The authors commented that there is a 'law of diminishing returns' in attempting more sophisticated calculations than spreadsheets, due to the increased amount of inputs required for the increasingly sophisticated models.

5.4.14 Lees Loss Prevention in the Process Industries

Lees Loss Prevention in the Process Industries (Mannan, 2012) Chapter 15, sections 15.23 – 15.36 cover dense gas dispersion models. Chapter 15.41 discusses the models and references dense gas dispersion model validation and model comparison exercises.

5.4.15 Mazzola et al. (2020)

Mazzola et al. (2020) presented the results of comparisons between the predictions of 17 dense gas dispersion models with observations from three of the Jack Rabbit II chlorine trials. The models included in the review were as follows: ADAM (EU), ALOHA, SLAB-R, Britter and McQuaid Workbook, Canadian Urban Dispersion Model, DRIFT, ESCAPE, HPAC, Integral Dense-gas Dispersion Model (IDDM), PHAST, Parallel-Micro-SWIFT-SPRAY (PMSS), Puff model of atmospheric dispersion (PUMA), RAILCAR-ALOHA, RAILCAR-QUIC, Safer Trace, SLAB-I and VDI 3783 Parts I and II. Emissions and meteorology input into the models were provided by the Jack Rabbit II scientific team.

Graphical comparisons of all models with experimental data for variables such as cloud downwind distance and cloud width are presented. Statistical analysis of the model performance, highlighting over and under-prediction are discussed. Overall, Mazzola et al. (2020) found that the performance of all 17 models was good and there were no major biases or excessive scatter.

5.5 Model evaluation

Model evaluation is required to ensure that a model is fit for purpose. This may include comparison of model predictions to experimental data and inter-model comparisons.

According to Coldrick et al. (2016), model evaluation normally contains the following elements:

- i. The underlying model must have a sound physical basis (scientific assessment)
- ii. The computer implementation of the model must be consistent with its mathematical basis (verification)
- iii. The model must represent reality to an acceptable degree (validation)
- iv. The interaction between the user and the model must be considered (user-oriented assessment)
- v. The level of uncertainty when evaluating and using the model and its effect on output must be considered (sensitivity and uncertainty analysis)

The rationale behind such a well-defined protocol is that each stage is dependent on the previous one having been carried out and there is little point continuing to the next step if the previous one has not been completed.

An important point of model evaluation that is often overlooked is that it should be an ongoing process as models are refined and updated and as new datasets / knowledge become available.

5.5.1 Model evaluation studies

A review and analysis of several model evaluation protocols was undertaken by Coldrick et al. (2016) as part of the European SAPHEDRA project. Some studies specifically aimed at developing model evaluation protocols are summarised below. The majority of these are not specifically aimed at dense gas dispersion, but the concepts behind a protocol apply more generally. Works that present results of evaluation studies are included in the review Section 5.4 or for the individual models in Section 5.7:

MEG

The Model Evaluation Group (MEG) reports (MEG, 1994a,b) were some of the earliest studies dedicated specifically to model evaluation. MEG was formed by the Commission of European Communities programme on Major Industrial Hazards. This resulted in a generic model evaluation protocol

HGDEG

The Heavy Gas Dispersion Expert Group (HGDEG) was a subgroup of MEG focussed on dense gas dispersion, with its own protocol. (Duijm et al., 1997; Mercer et al., 1996a, b)

SMEDIS

The objective of the EU-sponsored SMEDIS project was to develop a protocol for the scientific evaluation of dense gas dispersion models, with a particular emphasis on the complex effects of obstacles, terrain and aerosols (Carissimo et al., 2001, Daish et al., 2000). The project also aimed to apply this protocol to dense gas dispersion models currently in use in Europe. As part of the project, the SMEDIS database of measurement data was compiled (see Section 6.3.3) and over 20 models were reviewed.

Ivings et al. (2016)

Ivings et al. (2016) developed a comprehensive model evaluation protocol (MEP) for modelling LNG dispersion, based on a revised version of SMEDIS. As part of their work, Ivings et al. (2016) developed a database for undertaking model evaluation exercises, the 'LNG model validation database' (see Section 6.3.4). The Ivings et al. (2016) report includes an example scientific assessment of two models: DEGADIS and FEM3A.

COST 732

The European Cooperation in Science and Technology (COST) Action 732 sought to determine and improve the quality of micro-scale meteorological models for the prediction of

flow and dispersion processes in urban and industrial environments. There were three main publications from the project:

- Best practice guideline for the CFD simulation of flows in the urban environment (Franke et al., 2007)
- Model evaluation guidance and protocol (Britter and Schatzmann, 2007)
- Model evaluation case studies (Schatzmann et al., 2010)

Britter and Schatzmann (2007) provided a description of what should be involved in evaluating a model, along with suggestions for approaches for undertaking an evaluation.

COST ES1006

The European COST Action ES1006 sought to evaluate, improve and provide guidance on the use of local-scale emergency prediction and response tools for airborne hazards in built environments. It is described on the COST website¹⁰⁸ as follows:

Releases of hazardous agents in complex built environments pose a tremendous challenge to emergency first responders and authorities in charge due to the large number of casualties potentially involved. Air motions in built-up areas are very complex and adequate modelling tools have to be applied properly in order to predict the dispersion of hazardous materials with sufficient accuracy within a very short time. Different types of tools are applied; however, it is not always clear what the advantages and limitations of individual model approaches are. Therefore, it is of exceptional interest to compile a detailed inventory of the different models and methodologies currently in use, to characterize their performance and to establish strategies for their improvement. A consensus on reliable, efficient and suitable model approaches for given local threats and their scientific advancement is imperative. Consequently, the Action is aiming for a substantial improvement in the implementation of local-scale emergency response tools. By characterizing threat scenarios, compiling dedicated test cases, revealing model limitations and improving model approaches, the Action is delivering guidance for a reliable application of local-scale emergency response tools. The Action is a first cross-community initiative to join, to coordinate and to harmonize European efforts in threat assessment and reduction for local-scale airborne hazards.

The project involved a series of workshops and developed three scenarios for modellers to use in blind and non-blind exercises. It resulted in several journal publications and three reports:

- Best practice guidelines for the use of atmospheric dispersion models in emergency response tools at local-scale in case of hazmat releases into the air (COST, 2015a)
- Model evaluation protocol (COST, 2015b)
- Model evaluation case studies (COST, 2015c)

The model evaluation document proposed a method for evaluating model capabilities specific to emergency response.

US EPA (2009)

The US EPA (2009) published a general guidance document on the development, evaluation and use of models in environmental decision making. The contents of the document are designed to apply to all types of models.

¹⁰⁸ <https://www.cost.eu/actions/ES1006/#tabs|Name:overview> Accessed 26th June 2020

Oberkampf et al. (2007)

Oberkampf et al. (2007) produced an extension to the typical model evaluation protocols discussed above in the form of a Predictive Capability Maturity Model (PCMM) for computational modelling and simulation. The main elements of the evaluation process were similar but the method applied a 'maturity' level, from 0 to 3, to each element. For example, at Maturity Level 0, model validation might be by judgement only, with few (if any) comparisons to measurements. At the other end of the scale, at Maturity Level 3, there may be quantitative assessment at conditions and geometries directly relevant to the application, well-characterised experimental uncertainties and independent peer review.

Nair et al. (1997a)

As part of a review of models used for determining the consequences of uranium hexafluoride releases Nair et al. (1997b) presented the basis for the models' evaluation. This includes specific scoring and ranking techniques.

5.5.2 Statistical performance measures

A statistical approach is frequently adopted to assess model performance in the form of statistical performance measures (SPMs). SPMs provide a means of comparing measured and modelled parameters.

There are many variations in SPMs, some more appropriate than others for different applications. At least two SPMs should be used in an evaluation exercise to obtain measures of both bias and variance. A common measure used to imply acceptable model performance is 'FAC2', which assesses if the model prediction lies within a factor of two of the experimental measurements. Graphical representation is also recommended to aid interpretation of the model behaviour (Duijm et al., 1996). Further discussion on the choice of SPMs can be found in Coldrick et al. (2016) and Ivings et al. (2016). Perhaps the most frequently used set of SPMs for gas dispersion are those presented in Chang and Hanna (2004), for air quality models.

Acceptance criteria for SPMs are used to judge whether or not a model is considered acceptable for the given application. Chang and Hanna (2004) presented a set of criteria for air quality models in rural settings, which focused on passive dispersion in unobstructed, flat terrain. More recently, they have provided an update with criteria for air quality models in urban settings. Ivings et al. (2016) defined acceptance criteria for dense gas dispersion models applied to LNG releases.

Hanna and Chang (2012) acknowledged that the choice of criteria are somewhat arbitrary. It is important that the criteria are realistic and practical. For example, there is little point having such strict criteria that exclude all available models. It should also be borne in mind that the quality and the extent of the field experiment data sets will influence the results of the evaluation. These and other considerations are discussed by Chang and Hanna (2004) and Hanna and Chang (2012).

5.5.3 Sensitivity and uncertainty analysis

Sensitivity studies allow the modeller to understand the sensitivity of model predictions to the value of input parameters. Consequently, a sensitivity analysis assists in identifying when the uncertainty in the value of a parameter will impact on confidence in the model prediction.

Uncertainty can arise from:

- an incomplete understanding of the physics involved in the transport and dispersion of the hazardous materials and the resulting consequences
- limitations in the data used as input into the model or available for model validation, for example data quality and completeness or appropriateness

- limitations in the model, for example, simplifications made in the modelling to reduce costs, complexity, speed, input data requirements

Source terms are often major sources of uncertainty in dense gas dispersion models, particularly for flashing or multi-phase releases. Uncertainty also arises from the complex and time-varying nature of the atmosphere.

The presentation of uncertain dispersion model predictions to decision makers was discussed by French et al. (2014) in the context of radiological emergencies. The resulting recommendations may also apply more generally to other applications.

5.6 Guidelines and good practice guidance

There are various modelling guidelines and documents on good practice for modelling atmospheric dispersion scenarios. These are summarised briefly below for hazardous substances in general, including dense gas dispersion and also passive and buoyant gas releases.

5.6.1 CCPS

The Center for Chemical Process Safety (CCPS) published a book of guidelines for using vapour cloud dispersion models (Hanna et al., 1996). They are aimed at a range of users from students to government agencies. Therefore, the objectives of the book are broad. It provides a practical understanding of the basic physical and chemical processes, guidance on source formulation, information about models and uncertainty, and guidance on how to interpret model results.

The book steps through input data requirements, source models, dispersion models, modelling uncertainties, existing models and evaluation of models with field data. It also includes seven detailed worked examples. This book is a valuable reference for dense gas dispersion modelling.

5.6.2 US EPA

The US EPA (1993a) provided guidance on the application of dispersion models for releases of hazardous substances. Their document has methodical, almost step-by-step guidance on characterising the release, determining source terms and applying appropriate dispersion models. It applies this methodology through eight worked scenarios using the models ADAM, ALOHA, DEGADIS, HGSYSTEM and SLAB. Specific inputs are calculated, implications of choices of input are discussed and output available from the models is discussed. The document also discusses how to determine input that would result in 'worst case' conditions.

5.6.3 TNO Yellow Book

The Yellow Book (Van den Bosch and Weterings, 2005) contains many practical tools and methods for calculating the physical effects of releases of hazardous materials. Since it was published in 1979, it has become a fairly standard reference across the world. It is designed to be accessible to a range of model users from designers to the authorities. The book covers outflow and spray releases, pool evaporation, vapour cloud dispersion, vapour cloud explosion, heat flux from fires, ruptures of vessels and interfacing of models. Dense gas dispersion is included within these chapters where relevant.

5.6.4 NUREG Handbook

The NUREG Handbook (SAIC, 1998) contains a broad spectrum of information for nuclear facilities including information on atmospheric dispersion modelling, particularly for ammonia, hydrogen fluoride and uranium hexafluoride. The handbook makes significant use of the CCPS guidelines (Hanna et al., 1996), supplementing these with additional chemical and

physical processes associated with the complex reactive substances prevalent in the nuclear industry.

The handbook covers hazard evaluation, source term determination, transport within containment/confinement and atmospheric dispersion and consequence modelling. The main content is supported by extensive appendices of which Appendix B is particularly useful guideline with a summary of methods for predicting the characteristics of accidental releases of chemicals.

5.6.5 INERIS

INERIS published a good practice guide for three-dimensional modelling for atmospheric dispersion scenarios in accident situations (Lacome and Truchot, 2016), which is currently only available in French. It is a combination of reviews of good practices and a report of the results of a French national working group. It includes three case studies to illustrate some of the points and to validate the guidance. The guidance can be downloaded from the INERIS website¹⁰⁹.

5.6.6 COST ES1006

The European Cooperation in Science and Technology (COST) Action ES1006, summarised in Section 5.5.1, included development of best practice guidelines for the use of atmospheric dispersion models in emergency response at local-scale in case of hazmat releases into the air (COST, 2015a). The guidance has a strong preference for four dimensional (space and time) high-fidelity dispersion modelling, i.e. Lagrangian or CFD models, particularly for modelling the built-up environment. However, it does also state that models should be developed to meet the practical requirements of their mode of application. Unlike other documents listed here, this guidance is also aimed at first responders, decision makers and other stakeholders who could be involved in emergency preparedness or response.

5.6.7 COST 732

The COST Action 732 included development of best practice guideline for the CFD simulation of flows in the urban environment (Franke et al., 2007). The guidelines were mostly aimed at steady-state RANS modelling of flow in the urban environment (without dispersion). Therefore, there is no specific guidance on dense gas dispersion modelling.

5.6.8 Meroney et al. (2016)

The review by Meroney et al. (2016) contains summaries and references to some other international guidelines for general verification and validation of CFD models for dispersion modelling.

5.7 Models for predicting dense gas dispersion outdoors

The models summarised in this section comprise both individual tools as well as software packages, which can model dense gas dispersion. The summaries broadly cover the author and developer of the model; whether it is proprietary or freely available; the expected use and end-user; whether it is a package or one model/tool; whether it includes source term models; information about scientific assessment, verification and validation; and any other readily obtainable information such as typical outputs, meteorology etc.

5.7.1 ADAM (EU)

The Accident Damage Analysis Module (ADAM) is a modelling package compiled by Fabbri et al. (2017) at the EU Joint Research Centre (JRC). It is a software tool to undertake

¹⁰⁹ https://aida.ineris.fr/liste_documents/1/86007/0 Accessed 14th April 2020

dispersion modelling to assist industrial establishments in meeting the requirements of the Seveso Directives. The tool is freely available and aimed at assisting states that are new to the European Union that do not have expert capabilities in dispersion modelling.

ADAM includes three modules: source terms, physical effects and vulnerability. The user can assess the potential exposure or lethality of an industrial incident by calculating the physical effects and by using the appropriate vulnerability models.

ADAM can model a variety of source terms including instantaneous and continuous releases; jets and pool spreading and vaporisation. It contains physical effects models for fires and explosions. It has an automatic system to identify all possible outcomes of a scenario based on the substance, operating conditions and failure mode input by the user.

The main model for atmospheric dispersion is ADAM-SLAB, which is based on SLAB (see Section 5.7.43). ADAM-SLAB is a re-write of the SLAB model in the C++ programming language and allows for integration with the source term module. However, it is also possible to provide source term input files for the original SLAB using ADAM. ADAM-SLAB also has additional output formats allowing output to easily be visualised in GIS-based tools.

Other modifications to the original SLAB include:

- Atmospheric temperature and pressure conditions can be specified for specific scenarios, i.e. they are not hard-wired
- An alternative calculation is used for the average concentration for instantaneous releases
- Calculation of time-varying releases
- Inclusion of the contribution from pool evaporation in case of rainout
- Modification of the SLAB routine for the calculation of the plume velocity

The model typically outputs the released amount, 2D contours, effect maps and lethality maps. Data can also be output in tabular forms such as Excel.

ADAM has been extensively verified and validated, as presented in Fabbri et al. (2018). ADAM-SLAB obtained consistent results when verified against the original SLAB. It was validated against Burro, Coyote, Desert Tortoise, Goldfish, Fladis and Thorney Island, including calculation of statistic performance measures. The overall performance was very good.

5.7.2 ADAM (US)

The US Air-Force Dispersion Assessment Model (ADAM) was originally developed for the US Air Force by Raj and Morris (1987) as an extension to the Ocean Breeze/Dry Gulch model (discussed by Hanna et al., 1993). It is a modification to a box and Gaussian dispersion model to incorporate thermodynamics, chemistry, heat transfer, aerosols and dense gas effects. ADAM can model continuous and instantaneous release types, area and point sources and pressurized and unpressurized releases. It contains liquid/vapor/two-phase options. It assumes releases are at ground level and horizontal. It can model both dense and passive plumes, including transition between the two. The passive model is consistent with the AFTOX model.

ADAM contains a source term component that can be applied to calculate releases of nitrogen tetroxide, phosgene, anhydrous ammonia, chlorine, sulfur dioxide, hydrogen sulphide, fluorine and hydrogen fluoride. For these chemicals it includes models for chemical reactions, aerosols and mixing processes for up to 16 types of release. However, it contains only these eight chemicals and it does not have a simple means to add new chemicals into the model.

The inability to readily include new chemicals is the reason ADAM was not included in the model evaluation of Hanna et al. (1993). Another limitation of the model is the inability to run multiple simulations in a 'batch' mode. The model must be run one at a time with user input.

ADAM was compared with other dispersion models in the evaluation of Lazaro et al. (1997) and found to generally under-predict concentrations, relative to other models such as SLAB and HYSYSTEM. Lazaro et al. (1997) stated that ADAM was validated with Desert Tortoise field data and under-predicted by over a factor of two at 100 m and both under and over-predicted at 3 km, depending on the trial. The model developers found good agreement for the Goldfish trials.

The model was designed for consequence analysis for specific substances, not emergency response. It is listed as an EPA 'alternative' dispersion model and executables can be downloaded from the EPA website¹¹⁰.

5.7.3 ADMS-Puff

ADMS-Puff is a proprietary model developed and maintained by CERC. It is described on the CERC website¹¹¹ as follows:

ADMS-Puff uses a Lagrangian puff methodology to model the fate of dense and passive gas releases. ADMS-Puff can use temporally and spatially varying meteorological data from the WRF model, or simple surface data. ADMS-Puff can also account for the impact of complex terrain: hills and variable surface roughness.

ADMS-Puff calculates snapshots of instantaneous air concentration along with a time integrated dose. These concentrations can be compared against regulatory or other levels, including inbuilt flammability limits.

There is limited information available on the CERC website on the mathematical basis of the model, and its verification and validation. A user guide is available, which contains very limited comparison to GASTAR (CERC, 2014).

5.7.4 ADREA-HF

ADREA-HF is a proprietary model of the National Centre for Scientific Research "Demokritos", Greece. It is a dense-gas specific CFD model initially developed by Bartzis (1991). The code is designed to predict dispersion of contaminants in complex geometry at local scales for consequence assessment of incidents under realistic conditions.

ADREA-HF solves 3D, time-dependent equations for dense, neutral or buoyant releases. It can model ideal multi-component mixtures, instantaneous and time-varying continuous releases, subsonic and sonic jets, single and two-phase releases and pool formation and spread. Solid structures and obstacles are modelled with a porosity model.

ADREA-HF has been used in several model evaluation studies. It was one of the models applied in the EMU project (Hall, 1997b) and it was also included in the SMEDIS project. It has subsequently been applied to releases of gaseous and liquid hydrogen (Venetsanos and Bartzis, 2007; Venetsanos et al., 2010; Gianissi et al., 2011).

A more detailed summary of the model and a list of validation exercises and other references can be found on the Demokritos website¹¹².

¹¹⁰ <https://www.epa.gov/scram/air-quality-dispersion-modeling-alternative-models> Accessed on 14th April 2020

¹¹¹ <https://www.cerc.co.uk/environmental-software/ADMS-Puff-model.html> Accessed on 26th June 2020

¹¹² <http://www2.ipta.demokritos.gr/pages/ADREA-HF.html> Accessed on 14th April 2020

5.7.5 Aeolus (QUIC-CFD¹¹³)

Aeolus is a proprietary CFD model developed by LLNL to provide high resolution simulations of dense gas dispersion through buildings and over complex terrain. It has been used to develop emergency response planning guidance and is one of very few CFD models that is aimed at use in operational emergency response applications undertaken by the National Atmospheric Release Advisory Centre (NARAC) at LLNL. With this in mind, the model has two simulation modes: A RANS model that has been optimised for speed of modelling a 2 km x 2 km urban area in minutes; and an LES model that can provide detailed turbulence analysis for investigating complex scenarios. They can both be run on a laptop but the latter requires several hours. The model has rapid grid generation and is able to create a 2 km x 2 km urban area from shapefiles which are available for 133 US cities. There is a built-in Lagrangian particle model for dispersion of neutrally buoyant, dense gas, buoyant releases and particulates.

The model outputs include 3D concentration fields, deposition patterns on the ground and on building surfaces, and dose calculations. It also outputs pressure patterns on building surfaces, which can be used as input into indoor infiltration models such as CONTAM.

Aeolus has been extensively validated against the Joint Urban 2003 data (Gowardhan and Brown, 2012). In particular, the model demonstrated its ability to capture building effects, such as channelling and reversed flow. More recently, the model has been used for dense gas applications.

Further information can be found on the LLNL website¹¹⁴, Gowardhan (2014) and Gowardhan et al. (2017).

5.7.6 ALOHA

The Areal Locations of Hazardous Atmospheres (ALOHA) model was developed by the National Atmospheric and Oceanic Administration (NOAA) in collaboration with the EPA to provide emergency response personnel with estimates of the spatial extent of common hazards associated with chemical spills. Technical documentation for version 5.4.4 can be found in Jones et al. (2013). ALOHA forms part of the CAMEO (Computer-Aided Management of Emergency Operations) software, which facilitates the management of emergency operations.

ALOHA provides estimates of the spatial extent of some of the hazards associated with relatively short-term accidental releases of volatile and flammable chemicals. For example, scales typical of transportation accidents, where the threat may range from 100 m to 10,000 m with durations of up to an hour. It specifically addresses human health hazards associated with inhalation of toxic chemical vapours, thermal radiation from chemical fires and the impact of pressure waves from VCEs.

ALOHA output is based on the user selecting three toxic levels of concern, such as ERPGs or AEGLs, when modelling a toxic chemical release, to generate a threat zone estimate. Yellow, orange, and red zones indicate areas where those values were predicted to be exceeded at some point in time. The software includes ERPG and AEGL information for substances, where it is available.

The model has a graphical user interface for input and output information and it can run quickly on small computers. It was designed to provide an assessment of the threat zones from information commonly available to emergency responders. User input is checked for

¹¹³ The referencing of Aeolus points at posters and papers that do not mention the name Aeolus but refer to QUIC-CFD. Therefore it is assumed that Aeolus evolved from QUIC-CFD

¹¹⁴ <https://narac.llnl.gov/research-and-development/urban-dispersion-modeling> and <https://narac.llnl.gov/research-and-development/dense-gas-transport-in-complex-environment> Accessed on 14th April 2020

consistency and reasonableness. It is used by most fire departments and emergency responders in the US (according to Hanna et al., 2008). This wide range of user modelling abilities means that many modelling options are hard-wired and allow for only limited user interaction.

ALOHA includes source term models and dispersion models for passive and dense gases. A Richardson number criterion is used to determine when the release is effectively passive. The dense gas dispersion model is based on DEGADIS but with some modifications. For example, it is limited to releases at ground level and does not account for the initial momentum in jet releases. Other differences are discussed in Jones et al. (2013). The ALOHA-DEGADIS model has been verified against the DEGADIS model and found to be generally more conservative with peak concentrations estimates at a point on average about 10% bigger than those predicted by DEGADIS (Jones et al., 2013).

ALOHA contains a simple infiltration model with an effective leakage area based on a fraction of 0.00059 times the area of the house for an average house floor area of 160 m², a ceiling height of 2.5 m and a building height of 5 m for a two-storey building (Jones et al., 2013). The indoor temperature is assumed to be 20°C. The model assumes that leakage occurs evenly over the building and there is no difference between floor or ceiling leakage, indoor and outdoor concentrations are uniform and environmental conditions do not change with time. There are different infiltration coefficients for a sheltered or unsheltered building.

ALOHA has been extensively validated. It was evaluated in the studies of Zapert et al. (1991) and Lazaro et al. (1997). Wannberg et al. (2010) assessed its performance in low wind conditions. ALOHA was compared with chlorine incidents by Hanna et al. (2008; 2009) and also compared with HPAC for the Graniteville incident (Jani et al., 2016).

ALOHA is limited in its ability to account for the effects of terrain and buildings. The wind field only varies with elevation, it does not vary with time or horizontal position. It is only valid for wind speeds greater than 1 m/s and risks under-predicting concentrations in lower wind speeds (Wannberg et al., 2010). It cannot model the effects of thermal energy from fires, nor chemical reactions, and it cannot model particulates.

Fairly recently, ALOHA has been interfaced with the HYSPLIT model (see Section 5.7.30) to provide HYSPLIT with access to improved source term models and ALOHA with a web-based system (Rolph, 2014). However, little additional information is available on this new feature.

5.7.7 ANSYS-CFX and ANSYS-FLUENT

ANSYS-CFX and ANSYS-FLUENT are general-purpose CFD software developed by ANSYS¹¹⁵¹¹⁶. The two codes were previously independent pieces of software known as CFX and FLUENT, but both are now owned by ANSYS and have been merged into the same software interface. They are proprietary codes that are commercially available under a paid licence agreement. As general purpose models, they contain many options and require significant user expertise. ANSYS-CFX and ANSYS-FLUENT are not suitable for use in emergency response.

ANSYS-CFX has been used previously to model dense gas scenarios. For example McBride et al. (2001), Scargiali et al. (2005), Sklavounos and Rigas (2004; 2005; 2006), Cormier et al. (2009), Qi et al., (2010). Gant and Atkinson (2011) illustrate the use of ANSYS-CFX in scenario reconstruction for the Buncefield incident. Mishra (2015) used CFX to simulate the Bhopal incident. For indoor applications, Riccardi et al. (2008) undertook a comparison

¹¹⁵ <https://www.ansys.com/products/fluids/ansys-cfx> Accessed on 14th April 2020

¹¹⁶ <https://www.ansys.com/products/fluids/ansys-fluent> Accessed on 14th April 2020

between CFX and experimental tests on a dense gas released inside a ventilated room and found that it performed reasonably well.

Several studies have used FLUENT for dense gas dispersion scenarios. For example, Schmidt et al. (1999), Gavelli et al. (2008; 2010), Pontiggia et al. (2009; 2011), Tauseef et al., (2011b) and Hall (2012). The interest in LNG is such that an LNG-specific front end was created for FLUENT for the US DOE (Meroney, 2010). Both CFX and FLUENT were evaluated as part of SMEDIS.

ANSYS-CFX and ANSYS-FLUENT, and most general purpose commercially available CFD software, undergo regular rigorous verification and validation exercises as part of the quality assurance provided by the code developers.

5.7.8 ARIA Technologies

ARIA Technologies provide a series of packages for different spatial and temporal scale events. Each package contains the relevant models for the context and scale. Information can be found on the website¹¹⁷. ARIA Risk and ARIA Local are marketed as modelling dense gas dispersion.

ARIA Risk is described on the website as follows:

ARIA Risk is a 3D software for the evaluation of industrial risks linked to the airborne dispersion of toxic releases (storage accidents, pipe failure, fire clouds). The software outputs maps of instantaneous or integrated concentration and deposition, it also enables the determination of safety limits and zones of threshold exposure and IDLH. ARIA Risk can be incorporated in an alert system.

ARIA Risk is built with modules using 3D calculation of meteorology and dispersion (puff or particle model) and takes into account arbitrarily complex topography, the effect of buildings on the flow, and very low wind conditions.

The meteorology model is SWIFT and the dispersion model is TRAMES, a three dimensional Lagrangian puff model which can take into account dense gas dispersion. The model is designed to be used on scales of 500 m to 50 km.

ARIA Local is described on the website as follows:

ARIA Local models air pollution conditions down to a very small scale in industrial and urban environments for continuous or accidental emissions by taking into account detailed data on obstacles (buildings, topography...). The software can also be used for micro-meteorological applications such as wind power plants, construction works or indoor air quality assessments.

ARIA Local is based on a CFD (Computational Fluid Dynamics) model dedicated to the atmospheric environment, including a 3D non-stationary modelling of multi-phase flows, turbulence and atmospheric dispersion.

This package uses the models MERCURE (see Section 5.7.34) and GEDEON to model the complete flow field, i.e. meteorology and dispersion for scales from 100 m to 5 km, including obstacles on a 3D mesh with topography. It can model instantaneous and continuous releases of dense gases from a variety of sources.

The ARIA City and ARIA Impact 3D packages contain the MicroSwiftSpray (MSS) model (see Section 5.7.35) and should therefore also be able to model dense gas dispersion. However, they are mainly aimed at modelling air quality.

¹¹⁷ http://www.aria.fr/aria_risk.php Accessed on 14th April 2020

The ARIA website suggests that the Local package can be used to investigate ventilation in buildings. However, they also provide ARIA Indoor, which is based on the CFAST model (see Section 5.8.8) and has the potential to be coupled to an atmospheric dispersion model to investigate infiltration.

5.7.9 Britter and McQuaid Workbook

The Britter and McQuaid (1988) Workbook is a publically available document, which contains a set of nomograms (i.e. graphs) describing the concentration profile with distance downwind for releases from a continuous source and from an instantaneous source. The nomograms were derived from field test data (from Porton Down and Thorney Island) and from wind tunnel data.

The model determines the gross properties of the dispersing dense gas from empirical correlations. It requires nine input parameters: initial cloud volume, or initial plume volume flux, wind speed at 10 m, duration of release, downwind distance, initial gas density, ambient gas density, initial buoyancy term and characteristic source dimension. Atmospheric stability is not required, the representative stability class is about C or D. The roughness length is equivalent to a flat, grassy surface and for continuous plumes a representative averaging time would be about 3 to 10 minutes.

The Workbook provides criteria for when the cloud should be treated as dense and when it is effectively passive (see Section 3.2.2). It also includes a method for finite duration releases, when it is not clear whether an instantaneous or continuous release is more appropriate.

The aim of the Workbook was to enable non-specialists to obtain estimates of the dispersion of contaminant gas emissions at ground level. For continuous releases, average concentration levels along the plume axis can be predicted. For instantaneous releases, the maximum concentration level along the cloud path is output.

The Workbook is relatively simple and its reliance on empirical data means that it is restricted in its applicability. It is often referred to as a 'screening' model. As such, it is included in the Yellow Book (Van den Bosch and Weterings, 2005) and in the US screening model TSCREEN (US EPA, 1993b). The Workbook includes validation exercises with Lyme Bay, Burro and Maplin Sands and was included in the evaluation of Hanna et al. (1993) and in SMEDIS. The Workbook also includes an illustration of the use of the model for the Potchefstroom incident.

The model cannot provide source terms and cannot model terrain types outside of those used in deriving it. It should not be used outside its range of validity. Therefore, it would be inappropriate to use the Workbook for urban areas or heavily industrialised areas. Other limitations are summarised in the Workbook itself.

Recently, Hanna (2020a) demonstrated use of the workbook to analyse the Jack Rabbit II chlorine trials and found that its performance was roughly in the middle of 17 other models tested (see also Mazzola et al., 2020).

5.7.10 CANARY

CANARY is a commercially-available consequence analysis software package developed by Quest Consultants¹¹⁸ for process safety applications. The package contains a database of over 250 components and can model the thermodynamics for mixtures of up to 10 components. It can model source processes such as two-phase flashing jets, aerosol formation and liquid rainout. Pool spreading and vaporisation effects can be modelled, including heat transfer and containment. The website says the following:

¹¹⁸ <https://www.questconsult.com/software/canary/> Accessed on 14th April 2020

The base models in CANARY are derived from models in the public domain. Some models, such as DEGADIS and SLAB, can be obtained as source code. Others, such as the fire radiation models, are described in detail in articles published in scientific journals. This ensures the models have been peer reviewed.

Some of the data incorporated into the models are derived from Quest-directed in-house tests in which hazardous fluids were released to the atmosphere. Much of this information is not available in the public domain, but is incorporated into the models in CANARY.

There is limited information on validation of the model, but it is assumed to derive from the FOCUS model, a previous Quest model. FOCUS was evaluated against experimental data by Hanna et al. (1993).

5.7.11 CHARM

The Complex Hazardous Air Release Model (CHARM) is a proprietary model maintained and developed by Dr Mark Eltgroth. There are two versions of the model, which have come about due to advances in computing power. Technical documents can be downloaded from the CHARM website¹¹⁹.

The original model was a Lagrangian puff model which calculated release from a single source in flat terrain. The model is fast and the developer suggests that it could be used as a screening model. The alternative model is a 3D complex terrain version, which is not based on puffs. Along with complex terrain, it can also be used to model flow in and around buildings, particle dynamics and air chemistry.

The model website¹²⁰ indicates that both versions of the model can estimate impacts from releases of weaponised chemicals and the more advanced version can also model impact from biological releases. The advanced version can also model impacts of nuclear radiation.

Both models can model dense, passive and two-phase instantaneous or continuous releases of liquid or gas. The models contain an extensive chemical database to which custom chemicals can be added. Both models contain sub-models for thermodynamics from reactions, such as between hydrogen fluoride and moist air.

CHARM can calculate source terms. In the original version, the source term calculation assumed that no water vapour or air mixed with the puff, although there was an entrainment algorithm for jet releases. This version reduces to a standard Gaussian model for neutrally buoyant releases. The effects of wind meander are not simulated.

The original model was evaluated by Zapert et al. (1991) and Hanna et al. (1993). Version 6.1 was found to be one of six models that produced the most consistent performance for mean bias and variance when it was evaluated against the MDA by Hanna et al. (1993). There is a validation report for the new 3D version (Eltgroth et al., 2005) which includes comparison of the model predictions with measurements from the Burro, Desert Tortoise, Goldfish and Lillestrom experiments (the last of these comprised sulfur hexafluoride tracer gas releases in Norway in 1987). There does not appear to be any published validation of use of the model in complex terrain to date.

5.7.12 Code Saturne

Code Saturne is summarised on the EDF website¹²¹ as follows:

¹¹⁹ <http://www.charmmodel.com/downloads.aspx> Accessed on 14th April 2020

¹²⁰ <http://www.charmmodel.com/index.aspx> Accessed on 14th April 2020

¹²¹ <https://www.code-saturne.org/cms/> Accessed on 24th April 2020

Code_Saturne is the free, open-source software developed and released by EDF to solve computational fluid dynamics (CFD) applications.

It solves the Navier-Stokes equations for 2D, 2D-axisymmetric and 3D flows, steady or unsteady, laminar or turbulent, incompressible or weakly dilatable, isothermal or not, with scalars transport if required.

Several turbulence models are available, from Reynolds-Averaged models to Large-Eddy Simulation models. In addition, a number of specific physical models are also available as modules: gas, coal and heavy-fuel oil combustion, semi-transparent radiative transfer, particle-tracking with Lagrangian modeling, Joule effect, electric arcs, weakly compressible flows, atmospheric flows, rotor/stator interaction for hydraulic machines.

The model is available to download from the website along with up-to-date documentation, including theory, user guides and some tutorials and basic best-practice guidance. Code Saturne requires a pre- and post-processing platform for which open source software, SALOME, is available.

Code Saturne was used in the MODITIC project to perform RANS simulations of dense gas dispersion in urban environments (Burkhart et al., 2016a).

EDF have also produced the model NEPTUNE_CFD, which is a multiphase flow solver. However, this model is not open source. It is described as follows:

NEPTUNE_CFD can simulate a wide variety of multiphase flows: free-surface flows (adiabatic or not) ; dispersed flows (boiling flows, bubbly flows, particle-laden flows, droplet-laden flows) with closures to model the inter-phase transfers (momentum, mass, energy). Dedicated models are also available to simulate regime transitions of two-phase flows (from dispersed to stratified two-phase flows).

5.7.13 DENZ and CRUNCH

The DENZ and CRUNCH models resulted from the work of Fryer and Kaiser (1979) and Jagger (1983). They were developed by AEA consultancy services, initially for HSE, but have been used extensively worldwide. HSE no longer uses these models, they have been superseded by DRIFT (see Section 5.7.15).

DENZ and CRUNCH were both developed to model the dispersion of dense gases in the atmosphere. DENZ is an instantaneous release model and CRUNCH is a continuous release model. DENZ and CRUNCH cannot model processes such as buoyant lift-off, momentum driven jets, finite duration or time varying releases, and multi-component thermodynamics. These are all now modelled with DRIFT.

CRUNCH is compared with some of the Lyme Bay chlorine trials and other similar models in Wheatley et al. (1988). A comparison of DENZ with an early DRIFT model and the Britter and McQuaid Workbook can be found in Jones et al. (1993). Other validation studies were not published.

The NUREG Handbook (SAIC, 1998) noted that nuclear-specific versions of DENZ and CRUNCH have been funded by the US NRC to model the thermodynamic properties of releases of mixtures of substances such as uranium hexafluoride and moist air, and hydrogen fluoride and moist air. The modified versions are called NRCRUNCH and NRCDENZ¹²².

¹²² There is also NRCPLUME, which is a modified jet model

5.7.14 DEGADIS

The Dense Gas DISpersion Model (DEGADIS) is a publically available integral/box model developed by Havens and Spicer (1985). It is an adaptation of HEGADAS and was originally developed for LNG spills from tankers, but is now used extensively across the world for atmospheric dispersion calculations. DEGADIS is listed by the US EPA as an alternative model for use in regulatory applications on a case-by-case basis. The model itself, official documentation, recent update information and test cases are available from the US EPA website¹²³.

DEGADIS simulates the dispersion over flat, level terrain of dense gas (or aerosol) clouds, released with zero momentum from an area source at ground-level. The model simulates the dispersion processes which accompany the gravity-driven flow and entrainment of the gas. It can simulate the transition from dense to passive dispersion. DEGADIS does not have sub-models for calculating source terms, it requires the mass of the substance released to be provided.

DEGADIS has a model for initial gravity-driven spreading of dense gas clouds that is based on the rate at which source material is taken up by the atmosphere. If the release rate is low then the model assumes that the gas is dispersed downwind. If the release rate exceeds this rate, the model assumes that the gas spreads as a shallow cylindrical volume or 'blanket' around the source as a density current. This initial spreading of the cloud includes top entrainment due to wind shear and air entrainment into the front edge. The gas continues to spread until the atmospheric take up from the top of the cylinder is balanced by the entrainment rate. The centre of the spreading cylinder of dense gas remains fixed over the source until the cloud stops growing. Once the gas cloud stops growing, the model treats the cloud as a secondary source, in the form of an area source from which downwind dispersion is calculated. The model assumes that the cloud horizontal concentration profiles are homogeneous at the centre with Gaussian profiles at the edge of the cloud.

There are 'bolt on' models to DEGADIS, for example, for the dispersion of gas released from vertical jets perpendicular to the mean wind direction (Havens and Spicer, 1988a,b). This is a front end model that initialises DEGADIS if the cloud calculated by the jet model is dense. If it is not dense then the jet model continues as a Gaussian plume model.

DEGADIS has been assessed in many model evaluation studies. For example, Blewitt, et al. (1987a), Hanna et al. (1993, 2008), Zapert et al. (1991), Lazaro et al. (1997) and SMEDIS. Version 2.1 of DEGADIS was partially assessed against the LNG model evaluation protocol by Ivings et al. (2007). The completed assessment can be found in the report by FERC (2010). DEGADIS has also been frequently used over the last decade as a reference model for other models. In particular, for CFD models (e.g. Ohba et al., 2004; Sklavounos and Rigas, 2006).

5.7.15 DRIFT

The Dense Releases Involving Flammables and Toxics (DRIFT) model is a commercially-available integral dispersion model produced by ESR Technology that is used by HSE for its regulatory work in the UK. The model originates from the Safety and Reliability Directorate (SRD) of the UK Atomic Energy Authority (UKAEA), but much of its development over the last 15 years has been led by HSE. Whilst DRIFT was originally conceived as a dense-gas dispersion model, it has subsequently been adapted to model dispersion of passive and buoyant sources. The software is designed to be relatively easy and quick to use so that multiple scenarios can be run in a short period of time, for example for multiple wind directions. It assumes flat terrain.

¹²³ <https://www.epa.gov/scram/air-quality-dispersion-modeling-alternative-models#degadis> Accessed on 14th April 2020

The original version of DRIFT did not contain source models. The later version, DRIFT 2, superseded the DENZ and CRUNCH dense gas dispersion models. It was still based on the theory in those models, which included using a box model for instantaneous releases and an integral model for continuous releases. DRIFT 3 is the latest major update of the model. It is able to model transition to passive dispersion, buoyant lift off and rise, momentum jets (single- and two-phase), finite duration and time-varying releases and thermodynamics of multi-component mixtures (including condensation of water vapour into cold jets and associated latent heat effects). The model can read in outputs from the pool spreading and vaporisation model GASP (Cruse et al., 2017). Source conditions can also be input by the user.

DRIFT 3 has been through a full model evaluation, based on the MEG (1994b), and a Model Evaluation Report for DRIFT 3.6.4 was produced by Coldrick and Webber (2017). Some of the verification and validation of the original DRIFT model can be found in Jones et al. (1993). Tickle (2011) includes comparison of DRIFT 2 and DRIFT 3 with experimental datasets, Tickle et al. (2012) compared DRIFT 3 to the URAHFREP experiments and found reasonable agreement. Recently, DRIFT was used by HSE to model the the Jack Rabbit II chlorine trials (McKenna et al., 2016; McKenna et al., 2017b; Gant et al., 2018; Hanna et al., 2019).

5.7.16 DISPLAY-2

DISPLAY-2 (Venetsanos et al., 2003) is a two-dimensional shallow layer model for dense gas dispersion. The model is a proprietary model and does not appear to be widely used. It has the ability to include thermal effects, obstacles and slopes. It has been well validated and was tested in both MEG (MEG, 1994a, b) and SMEDIS (Carissimo et al., 2001). Despite the model performing reasonably well in the validation exercises there are a number of issues within the model (Webber, pers. comm.).

A limitation of the model is its solution times are of the order of hours. This is typically longer than most other shallow layer models and it undermines one of the particular strengths of the shallow layer method, namely fast computing times.

Note that there was also DISPLAY-1 (Wurtz et al., 1996), which was a 1D shallow layer model, also evaluated in SMEDIS, which is no longer in use.

5.7.17 EFFECTS

EFFECTS is a proprietary model developed at TNO and marketed by Gexcon. General information can be found on the Gexcon website¹²⁴ where the model is summarised as follows:

A loss-of-containment scenario in the (petro)chemical industry can be devastating, for both property and human life. EFFECTS is easy-to-use, affordable software that helps safety professionals calculate and analyse the effects of these scenarios and develop the right prevention or containment protocols. In just a few easy clicks, you can determine the precise consequences of any scenario, and share your findings with all relevant stakeholders.

With EFFECTS, you can model the behaviour of toxic or flammable gases, liquefied gases or liquids from initial release to effects kilometres away. You'll be able to simulate the effects of accidental releases under all process conditions and weather types.

EFFECTS calculates heat radiation from fire, over-pressures from explosions, toxic concentrations and toxic doses from dispersion, and much more. Of course,

¹²⁴ <https://www.gexcon.com/products-services/EFFECTS/31/en> Accessed on 15th April 2020

EFFECTS also allows you to calculate the consequence to human life (lethality) and structure damage.

The model contains more than 2200 chemical components and allows the user to define custom chemicals and mixtures. Created from the models in the Yellow Book (Van Den Bosch and Weterings, 2005) and the Green Book (1992), there are more than 70 sub-models which can model scenarios such as leaks and ruptures in pipelines, pressure valves, vessels and storage tanks; confined gas explosions; BLEVEs; drifting toxic clouds; and jet, pool, rim, bund or rooftop fires.

EFFECTS also has the ability to link to online maps to visualise results or for the user to import their own maps or diagrams. It can integrate with GIS software.

There is no validation or verification of EFFECTS readily available online. The models in the Yellow Book and Green Book are generally well-used and well-documented models (e.g. SLAB).

5.7.18 ERG

The US Emergency Response Guidebook (ERG, 2020) was developed by Transport Canada, US DOT, and the Secretariat of Communications of Mexico with collaboration from the Centro de Informacion Quimica para Emergencias of Argentina. It is available from the US Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA) website¹²⁵ as an electronic pdf file or it can be installed as an app on mobile devices. It is updated approximately every 4 years. It is a 'look up' methodology for use by first responders to establish potential hazards, public safety information and emergency response guidance and activities for different types of incident and first aid. It is aimed mainly at incidents occurring on roads or railways and may have limited value for large incidents at static sites.

The guide provides a three-step lookup system based on identifying the substance released, identifying the three digit number associated with the material and looking up the guide associated with that number. There are various methods for identifying the substance or what to do if this is not possible. For example, placard identification and identification of road tanker and railcar type.

The guide is colour-coded into yellow, blue, green and orange pages. The yellow pages are an index of goods listed by ID number with corresponding three digit guide number; the blue pages are an index of the goods listed by substance with corresponding three digit guide number; the green pages are an index of materials that represent a toxic inhalation hazard including chemical warfare agents and water-reactive substances listed by ID with recommended safe distances; and the orange pages are the guides associated with the three digit numbers. Substances that have entries in the green pages are highlighted in the blue and yellow pages.

The orange pages comprise 63 guides, each of which comprises two pages of information. The left page contains potential hazards and public safety information and the right page contains emergency response guidance and activities for different types of incident and first aid. Each guide covers a group of materials which possess similar chemical and toxicological characteristics.

The orange pages contain isolation distances for the generic group of substances covered in that number guide. If a substance is highlighted in the blue and yellow pages it is referred to the green pages for substance-specific recommended distances. An example is shown in

¹²⁵ <https://www.phmsa.dot.gov/hazmat/erg/emergency-response-guidebook-erg> Accessed on 24th April 2020

Figure 38. The safe distances in the green pages provide two different types of recommendation:

- Initial isolation distances are radii around the release and create a circular zone within which evacuation should be considered, as illustrated in Figure 39
- Protective action distances define a square downwind zone within which protective action should be considered, also illustrated in Figure 39. Protective actions are aimed at ensuring the health and safety of the public and emergency responder and include actions like shelter-in-place or evacuation. There are two sets of recommended protective action distances, for day and night, in recognition of the differences in their characteristic atmospheric conditions.

The recommendations are also split into size of spill. Small spills are approximately 208 litres (55 US gallons) or less and large spills are more than 208 litres. The distances are designed to represent potentially affected areas in the first 30 minutes after release.

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TABLE 1 - INITIAL ISOLATION AND PROTECTIVE ACTION DISTANCES										
ID No. Guide NAME OF MATERIAL			SMALL SPILLS (From a small package or small leak from a large package)				LARGE SPILLS (From a large package or from many small packages)			
			First ISOLATE in all Directions		Then PROTECT persons Downwind during		First ISOLATE in all Directions		Then PROTECT persons Downwind during	
					DAY	NIGHT			DAY	NIGHT
			Meters (Feet)	Kilometers (Miles)	Kilometers (Miles)	Meters (Feet)	Kilometers (Miles)	Kilometers (Miles)		
—	153	Soman (when used as a weapon)	60 m (200 ft)	0.4 km (0.3 mi)	0.7 km (0.5 mi)	300 m (1000 ft)	1.8 km (1.1 mi)	2.7 km (1.7 mi)		
—	153	Tabun (when used as a weapon)	30 m (100 ft)	0.2 km (0.1 mi)	0.2 km (0.1 mi)	100 m (300 ft)	0.5 km (0.4 mi)	0.6 km (0.4 mi)		
—	153	Thickened GD (when used as a weapon)	60 m (200 ft)	0.4 km (0.3 mi)	0.7 km (0.5 mi)	300 m (1000 ft)	1.8 km (1.1 mi)	2.7 km (1.7 mi)		
—	153	VX (when used as a weapon)	30 m (100 ft)	0.1 km (0.1 mi)	0.1 km (0.1 mi)	60 m (200 ft)	0.4 km (0.2 mi)	0.3 km (0.2 mi)		
1005	125	Ammonia, anhydrous	30 m (100 ft)	0.1 km (0.1 mi)	0.2 km (0.1 mi)	Refer to table 3				
1005	125	Anhydrous ammonia								
1008	125	Boron trifluoride	30 m (100 ft)	0.2 km (0.1 mi)	0.7 km (0.5 mi)	100 m (300 ft)	0.5 km (0.4 mi)	0.6 km (0.4 mi)		

Figure 38 Excerpt from the green pages of the ERG

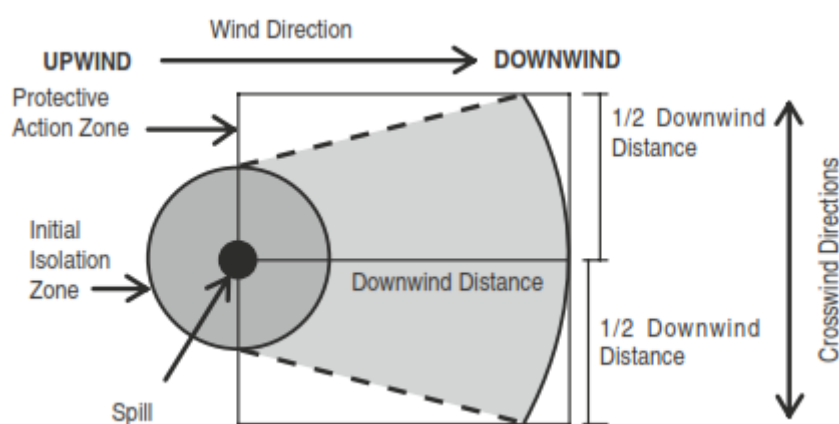


Figure 39 Illustration of zones generated by safe distances recommended in the ERG green pages

There are six substances that have a separate table of initial isolation and protective action distances for large spills, based on transport container sizes. These materials are anhydrous ammonia, chlorine, ethylene oxide, anhydrous or refrigerated liquid hydrogen chloride, anhydrous hydrogen fluoride and sulfur dioxide. As in Figure 38, the safe distances depend on night or day but also on estimates of low, medium or high wind speed. Guidance is provided on estimating wind speed from environmental clues.

The methodology applied to calculate the recommended distances is described in the ERG (2020, page 292). It is based on statistical analysis of predictions from emission rate and dispersion models; statistical release rate data from the US DOT Hazardous Materials Incident Reporting System; five years of meteorological data from over 120 locations in the US, Canada and Mexico; and current toxicological exposure guidelines. Thousands of hypothetical releases were modelled for each chemical to account for statistical variation in released amount and atmospheric conditions. The protective action distances for each chemical are based on the 90% percentile.

The emission modelling included releases of vapour directly into the air or due to pool evaporation, or both, including flash vaporisation. It accounted for emission of toxic vapour due to spills of water-reactive substances onto water. The dispersion modelling accounted for time-dependent emission rates and the density of the vapour and the effects of atmospheric conditions, including night time and day time.

The input required to use the guide is knowledge of the substance, the wind direction, whether it is day or night and whether the release is smaller or larger than 200 litres.

The guide states that first responders should be trained in the use of the guidebook. Also, it highlights that it is for first-response purposes and further information about a substance should be sought at the earliest possibility, because information from contacting appropriate emergency response agencies may be more specific and more accurate.

The ERG was developed for use in North America (USA, Canada and Mexico) and it may need to be reevaluated for use elsewhere in the world, where different bulk containers are used and the meteorology may differ.

5.7.19 ESCAPE

ESCAPE is an integral model developed by the Finnish Meteorological Institute. Information and references are available on the Finnish Meteorological Institute website¹²⁶, where the model is summarised as follows:

Consequences of chemical accidents in air quality can be estimated by dispersion models developed in Finnish Meteorological Institute. The dispersion model ESCAPE (Expert System for Consequence Analysis and Preparing for Emergencies) is a validated assessment tool for consequence analysis of accidents involving hazardous materials. The model can be used for evaluating releases, the formation of source terms, atmospheric dispersion and consequences of hazardous materials. The model is applicable to evaluate both continuous and instantaneous ground-level releases of toxic and flammable gases into the atmosphere.

A graphical user interface for the ESCAPE model based on web-browser technology has been developed for the needs of the Finnish emergency authorities to be readily applicable for rescue service in operational cases. Its primary purpose is to provide estimates of the spatial extent of some common hazards associated with chemical spills for emergency response personnel.

The software has been designed to utilize directly and in real-time the meteorological data produced by numerical weather prediction (NWP) models. Direct utilization of e.g. NWP-model products simplifies the data a user has to provide while providing more reliable and accurate predictions. The user only needs to specify input data regarding the characteristics of the release and the environment (the type of release and its associated details, the location and time of the accident, and the contaminant).

¹²⁶ <https://en.ilmatieteenlaitos.fi/chemical-accident-model> Accessed on 14th April 2020

The model is not designed for evaluating the dispersion of buoyant plumes originating from, for example fires. A separate model (BUOYANT) can be used to estimate the dispersion of pollutants emitted from warehouse and wind-land fires. The ESCAPE model is limited in its ability to account for the detailed effects associated with complex terrain, buildings and other obstacles. Further, time-varying releases are outside of the scope of the model.

A more detailed description of the current version of ESCAPE can be found in the recent publication of Kukkonen et al. (2017). In particular, the model has been adapted to be able to automatically use the real time predictions and forecasts of the High Resolution Limited Area Model (HIRLAM¹²⁷), which is a numerical weather prediction model. The dense gas dispersion model is based on a modified version of DRIFT.

The original ESCAPE model was evaluated as part of the SMEDIS project and the more recent version has been evaluated against six field trials, including Thorney Island and Desert Tortoise. The results for the latter were presented by Kukkonen et al. (2017). Further validation with Kit Fox and Jack Rabbit is intended.

5.7.20 FDS

The Fire Dynamics Simulator (FDS) is an LES CFD model developed by the US National Institute of Standards and Technology (NIST)¹²⁸. It is freely available along with a post-processor, Smokeview. FDS can also be coupled to CFAST to model evacuation.

While FDS is primarily aimed at fire-driven flows and smoke movement, it can be used for wider ranging applications, including dense gas dispersion. FDS has been used for dispersion of vapour from LNG spills and in this context it has been evaluated using the model validation database (see Section 6.3.4) by Kohout (2011).

5.7.21 FEM3C

FEM3C is a three-dimensional, finite element model for dense and neutrally buoyant gas dispersion. It is a proprietary model developed at LLNL (Chan, 1994).

FEM3C can model multiple simultaneous sources of instantaneous, steady continuous and finite-duration releases. It can model the effects of obstructions to the flow and complex terrain. Phase change between liquid and vapour state can be modelled assuming local thermodynamic equilibrium. FEM3 has primarily been used in LNG applications and is well validated, although there has been no recent published activity. It has been used to model the Burro 8 test with and without terrain effects and under low wind conditions (Morgan et al., 1984) and it was evaluated in the study of Lazaro et al. (1997).

A limitation is that source terms such as pressurised jets and time-varying emissions cannot be modelled. As with CFD codes, FEM3C also requires significant post-processing in order to obtain concentration values at specific locations and averaging times, which makes it more suitable for applications such as scenario reconstruction than emergency preparedness or response.

Information on the current status of FEM3C on the LLNL website is limited and it seems likely that this model has been superseded by FEM3MP or Aeolus.

5.7.22 FEM3MP

FEM3MP is a state of the art three-dimensional, CFD model run on a parallel array computing platform. It is a proprietary model developed at NARAC, LLNL.

¹²⁷ <https://en.ilmatieteenlaitos.fi/numerical-weather-prediction> Accessed on 14th April 2020

¹²⁸ <https://www.nist.gov/services-resources/software/fds-and-smokeview> Accessed on 14th April 2020

The model is designed to be used for modelling urban applications and it has been validated with various (passive) urban experimental datasets, for example Chan and Leach (2007). It has also been validated against the Burro dense gas experiments (Kosovic and Mirocha, 2008).

The use of FEM3MP, and other models, is outlined in Sugiyama et al. (2010) in the context of NARAC's capabilities for US homeland security. It is difficult to find more recent information on FEM3MP on the NARAC website¹²⁹ and it appears that the model has been superseded by Aeolus.

5.7.23 FLACS

FLACS is a CFD package developed and distributed by Gexcon. Information can be found on their website¹³⁰, where the model is summarised as follows:

FLACS is a comprehensive, yet easy to use, software tool for modelling (dispersion, fire and explosion) consequences in full 3D for all typical flammable and toxic release scenarios. It is used extensively in the oil and gas and process industries and also increasingly in the nuclear industry, in facilities with dust explosion potential and many other fields. By modelling with CFD (Computational Fluid Dynamics) in full 3D, it is possible to predict consequences much more accurately and to include the effect of all contributing and mitigating effects (such as confinement and congestion due to real geometry, ventilation, deluge).

There have been various validation studies on the model, many of which can be found in the publications on the Gexcon website¹³¹. For dense gas dispersion, for example, it was evaluated as part of the SMEDIS project. It was compared with Kit Fox (Hanna et al., 2004) and was used by Hanna et al. (2009) to model dispersion of chlorine in the Festus incident and another hypothetical incident. FLACS was evaluated using the LNG model validation database (Hansen et al., 2010, see Section 6.3.4). The dispersion modelling capabilities of FLACS version 9.0 were reviewed by HSE (Gant and Hoyes, 2009).

5.7.24 FLUIDYN-PANACHE

Fluidyn-PANACHE is a suite of proprietary models, developed by Transoft International, of which Fluidyn-PANACHE is designed for accidental releases of dense gases. The website¹³² describes the model as follows:

It is a self-contained, fully 3-D Computational Fluid Dynamics (CFD) software package designed to simulate atmospheric flow and pollutant dispersion in complex environments i.e. with topography, buildings, land covers and usages.

All modules use the same interface, called fluidyn-PANACHE, designed by default numerical values, for modelling related atmospheric physics – air flow, pollution transportation. All modelling information such as boundary layer or turbulence models, meshing, solvers etc are inbuilt and automatic and used according to the problem described by the user.

The model is designed to provide fast response estimation of plume dispersion in the case of accidents. There are various references, including the use of the model in dense gas dispersion scenarios, on their website.

¹²⁹ <https://narac.llnl.gov/research-and-development/dense-gas-transport-in-complex-environments> Accessed on 14th April 2020

¹³⁰ <https://www.gexcon.com/products-services/FLACS-Software/22/en> Accessed on 14th April 2020

¹³¹ <https://www.gexcon.com/page/Publications/en> Accessed on 14th April 2020

¹³² <https://www.fluidyn.com/fluidyn/panache> Accessed on 14th April 2020

5.7.25 FRED

FRED is a proprietary consequence modelling tool originally developed by Shell and now available through Gexcon. General information can be found on the Gexcon website¹³³ where the model is summarised as follows:

The FRED software gathers in one tool state-of-the-art Fire, Release, Explosion and Dispersion models that predict consequences of accidental and design releases of products from process, storage, transport and distribution operations.

Its ease of use allows the user to rapidly comprehend the consequence prediction related to incidents for facilities and operations. It provides the user with an at-a-glance overview of the extent of blast waves, gas contours and heat radiation directly on site plan.

FRED has been continuously developed and validated by Shell since the 1980s, and has been extensively used by oil, gas and petrochemical operating companies, engineering contractors, insurers and regulators throughout the world. The integrated models rely on an extensive and unique programme of large-scale experiments, combined with validated scientific research, that assure the reliability and consistency of the results.

According to Dixon et al., (2012) the dense gas dispersion model within the FRED tool is HEGADAS (see Section 5.7.28). The model is designed to be used for emergency planning and preparation of safety cases but it can also be used for accident investigation and for Quantified Risk Assessments (QRA) with Shepherd (also available from Gexcon).

FRED was used in a model validation exercise for pressurised releases of carbon dioxide by Gant et al. (2014) and Dixon et al. (2012).

5.7.26 GASTAR

The GASEous Transport from Accidental Releases (GASTAR) model is a proprietary model developed and sold by Cambridge Environmental Research Consultants (CERC). A significant amount of information on the model is available on the CERC website¹³⁴. It is summarised as follows:

GASTAR is a dense gas dispersion model developed by CERC ideally suited to modelling accident and emergency response scenarios or investigating site safety involving releases of flammable and/or toxic materials from a variety of industrial accidents such as cryogenic spills, catastrophic tank failure, pipe fractures and multi-phase jets.

GASTAR is used for:

- risk assessment,
- land-use planning,
- emergency response planning,
- management and training.

GASTAR is an integral (or box) model. Using a combination of conservation laws applied to the cloud, supplemented by semi-empirical relations derived from dispersion research, it calculates spatially-averaged properties of the cloud, and their variation with distance downwind, and then applies profiles to give the concentration at any point. Novel features, such as slopes and obstacles, are incorporated into the

¹³³ <https://www.gexcon.com/products-services/FRED-Software/26/en> Accessed on 15th April 2020

¹³⁴ <https://www.cerc.co.uk/environmental-software/GASTAR-model.html> Accessed on 14th April 2020

integral formulation. Efficient solution algorithms require only seconds to solve a typical problem.

The model can simulate cloud evolution from dense to effectively passive and it can model instantaneous, steady and time-varying continuous releases. It includes a two phase jet source model and contains sub-models for slopes and obstacles. There is an averaging time option to account for plume meander. The jet model can simulate a jet of any orientation. GASTAR can model aerosol releases if the aerosol fraction is specified by the user. There is a method to model releases in calm wind conditions.

The model outputs cloud properties along the centreline such as distance travelled, concentration, width, height and temperature. For instantaneous releases, it outputs the locations of the leading and trailing edges of the cloud and the downwind and crosswind dimensions. Dose, toxic load and flammable limits can also be output. The model is very fast to run and can be run either in batch mode or interactive mode.

GASTAR was evaluated by Hanna et al. (1993a) and as part of SMEDIS.

5.7.27 HEGADAS and HEGABOX

See HGSYSTEM.

5.7.28 HGSYSTEM

The Heavy Gas System (HGSYSTEM) package is a publically available suite of programs for assessing dispersion from gas, liquid or two-phase releases. It was developed by Shell Research Ltd with support and sponsorship of industry groups and is available from Shell, US EPA and US API. It was first compiled to model the release of hydrogen fluoride and ideal gases and was then extended to include multi-component mixtures. A version of HGSYSTEM was also developed to model dispersion of uranium hexafluoride, under the sponsorship of the US Department of Energy. HGSYSTEM is listed by the US EPA as an alternative model for regulatory use on a case-by-case basis.

User guides and manuals are available for HGSYSTEM, published by McFarlane et al. (1990), Witlox et al. (1990), Witlox (1991) and Hanna et al. (1994). The uranium hexafluoride version, HGSYSTEM/UF₆, was described by Hanna et al. (1998). There is a website¹³⁵ with detailed information about HGSYSTEM, including technical documentation for each of the models included in the package.

HGSYSTEM contains models to simulate the evolution of a dense gas cloud from source through to passive dispersion. The package can model dense, neutrally buoyant and buoyant gases. Physical and thermodynamic properties for 30 chemicals are incorporated in the substance database. The package can simulate ground-based transient releases of single or multi-component liquid or vapour jets; near-source jet and elevated plume dispersion; pool evaporation of single or multi-component vapours; hydrogen fluoride chemistry and thermodynamics; and ground-based steady or transient continuous dense gas dispersion and instantaneous dense gas releases. The main dense gas dispersion models are HEGADAS and HEGABOX. HEGADAS is an integral model for use modelling continuous dense or passive gas releases and HEGABOX is the instantaneous box model. The technical documentation on the website includes many references to publications on development of these models and the other modelling components of the package.

HGSYSTEM was evaluated by Zapert et al. (1991) Hanna et al. (1993), Lazaro et al. (1997) and SMEDIS. The first two of these studies only evaluated the continuous release model, HEGADAS. The original HEGADAS and updated version were compared to Kit Fox trials by

¹³⁵ <http://www.hgssystem.com/hqweb.html> Accessed on 14th April 2020

Hanna and Chang (2001). HGSYSTEM was compared to chlorine railcar incidents and other models by Hanna et al. (2008, 2009).

5.7.29 HPAC

The Hazard Predication and Assessment Capability (HPAC) is a tool produced by the US Defense Threat Reduction Agency (DTRA). It is made available to agencies on a case-by-case basis (in the UK, HPAC is used by Dstl). The tool is designed to be easy to use and fast to run. HPAC contains a suite of models for various modes of release of radiological, chemical and biological agents. It generates interpolated meteorological data fields based on input meteorology and models the subsequent dispersion. The meteorological model is SWIFT. The main dispersion model is SCIPUFF (see Section 5.7.42) but MicroSWIFTSPRAY (see Section 5.7.35) is also available. HPAC incorporates the Dstl Urban Dispersion Model (UDM, see Section 5.7.47).

The HPAC tool has been validated with several passive datasets (see for example, Warner et al., 2006). It has been used to model the Graniteville chlorine railcar incident and compared with ALOHA (Jani et al., 2016). Mazzola et al. (2020) presented HPAC results for the Jack Rabbit II chlorine trials. The dispersion models themselves (SCIPUFF and MSS) have also been validated independently of HPAC.

HPAC has the capability to model infiltration into buildings and egress from buildings through coupling the dispersion model results with the IBH model and CONTAM (see Sections 5.8.6 and 5.8.10 and Wolski, 2016). Dstl also developed the Building Ventilation and Infiltration Model (BVIM), which is a simple box model that can be used to simulate infiltration in HPAC (Parker et al., 2015).

5.7.30 HYSPLIT

The HYSPLIT model has been developed by the Air Resources Lab of NOAA. A large amount of information on the model can be found on the website¹³⁶, including an up to date list of model updates, publications, limitations and areas of research. The website describes the model as follows:

The HYSPLIT model is a complete system for computing simple air parcel trajectories, as well as complex transport, dispersion, chemical transformation, and deposition simulations. HYSPLIT continues to be one of the most extensively used atmospheric transport and dispersion models in the atmospheric sciences community. A common application is a back trajectory analysis to determine the origin of air masses and establish source-receptor relationships. HYSPLIT has also been used in a variety of simulations describing the atmospheric transport, dispersion, and deposition of pollutants and hazardous materials. Some examples of the applications include tracking and forecasting the release of radioactive material, wildfire smoke, windblown dust, pollutants from various stationary and mobile emission sources, allergens and volcanic ash.

The model calculation method is a hybrid between the Lagrangian approach, using a moving frame of reference for the advection and diffusion calculations as the trajectories or air parcels move from their initial location, and the Eulerian methodology, which uses a fixed three-dimensional grid as a frame of reference to compute pollutant air concentrations...

The dispersion of a pollutant is calculated by assuming either puff or particle dispersion. In the puff model, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into several

¹³⁶ <https://www.arl.noaa.gov/hysplit/hysplit/> accessed on 15th April 2020

new puffs, each with its share of the pollutant mass. In the particle model, a fixed number of particles are advected about the model domain by the mean wind field and spread by a turbulent component. The model's default configuration assumes a 3-dimensional particle distribution (horizontal and vertical).

A history of the evolution of the model can be found in Stein et al. (2015) with some examples of its use. There are two versions of the model: a PC version and a web version for fast response (Real-time Environmental Applications and Display - READY). At present, the model does not include dense gas dispersion, chemical reactions, by-products from fires, explosions, or chemical reactions, gases released that are not neutrally-buoyant, deposition (unless the user enters appropriate wet and dry deposition parameters), particulate transport (unless the user enters information about the particle), complex terrain (other than what is resolved by the meteorological model's terrain), varying emission rate with time or height (except for in particular scenarios). NOAA recommends the use of ALOHA for scales less than 1 km.

Fairly recently, HYSPLIT and ALOHA have been integrated to provide HYSPLIT with access to improved source term models and ALOHA with a web-based system. It appears that this integration results in a model that can account for dense gas dispersion (Rolph, 2014). However, little additional information is available.

5.7.31 JEM

The Joint Effects Model (JEM) has been developed by the US Department of Defense (DOD). The package is mentioned in Hanna and Chang (2012) where it is described as a package intended to be used throughout the US DOD agencies for atmospheric hazard assessments. It is intended to provide near real-time hazard information before, during and after incidents to influence and minimise effects on operations. It is capable of providing hazard areas and effects for chemical, biological, radiological, nuclear and toxic industrial chemicals or materials. It can model incidents, high-altitude releases, urban environments, building interiors and human performance degradation. JEM can interface and communicate with other packages, weather and intelligence systems and databases.

JEM includes similar atmospheric dispersion models to HPAC, namely SCIPUFF, UDM, SWIFT and MC-SCIPUFF, which is a mass-consistent wind-field module of SCIPUFF (Chang and Hanna, 2016).

Chang and Hanna (2016) provide a summary of validation for JEM "Increment 2" using passive dispersion datasets. This includes evaluation using statistical performance measures, in particular, an assessment of the capabilities of SCIPUFF's urban canopy model compared with the UDM model. There is some information on the model's capabilities in Wolski (2016), with regards to modelling infiltration and exfiltration. In this regards, the model is based on HPAC.

There appears to be no comprehensive technical documents or other information that is publically available.

5.7.32 KAMELEON FireEx (KFX)

Kameleon FireEx (KFX) is a CFD model aimed at simulating gas dispersion and fires and explosions in heavily congested areas such as industrial sites. It is owned and sold by DNVGL. Information can be found on the DNVGL website¹³⁷ where the model is described as follows:

¹³⁷ <https://www.dnvgl.com/services/fire-simulation-software-cfd-simulation-kameleon-fireex-kfx-110598> Accessed on 15th April 2020

Kameleon FireEx - KFX® represents the state-of-the-art CFD tools for simulation of dispersion, fires and explosions in congested areas. It offers simulation of conventional jet and pool fires, complex multiphase spray fires with rainout, well-ventilated and under-ventilated fires, LNG leaks with pool spreading, gas dispersion and fires, water-based fire mitigation by deluge, monitors, mist and water curtains in complex systems, optimization of passive fire protection, flare analysis, as well as turbulent flow, gas dispersion and smoke analysis in general, all in congested areas taking all weather effects into account.

Objects smaller than the grid size are taken in to account using a porosity model. It also has an interface with their finite element code for fluid-structure interactions. The software includes Lagrangian models for fire mitigation and extinction with water systems.

KFX was evaluated as part of the SMEDIS project.

5.7.33 LODI

The Lagrangian Operational Dispersion Integrator (LODI) model is used for emergency response scenarios by NARAC. Information can be found on the NARAC website¹³⁸ where the model is summarised as follows:

NARAC's primary dispersion model, the Lagrangian Operational Dispersion Integrator (LODI), uses wind, turbulence, and other gridded meteorological fields generated by NARAC's ADAPT meteorological data assimilation model to predict 2-D and 3-D gridded concentrations of hazardous material released into the atmosphere. LODI outputs time series of instantaneous and time-integrated air concentrations and ground deposition.

LODI uses a stochastic (Monte Carlo) particle diffusion method to solve the 3-D advection-diffusion equation by calculating possible trajectories of fluid "particles" in a turbulent flow. These "particles" can represent radiological, chemical, or biological materials in gaseous, liquid, or solid form. Multiple hazardous material sources can be modeled in a single LODI run using point, line, area, sphere, or Gaussian-shaped source geometries, moving as well as static sources, and time-varying emission rates.

There is a user guide available (Leone et al., 2001) but there is little other information publically available. The model was designed for passive and buoyant gases but it can also simulate dense gases, although no information is available on the dense gas sub-model in the user guide. The output is post-processed to provide maps showing air or ground contamination, dose and health effects resulting from the release of hazardous materials.

LODI was compared with HPAC for a passive release by Warner et al. (2006). The use of LODI, and other models, was outlined by Sugiyama et al. (2010) in the context of NARAC's capabilities for US homeland security. Little evidence of model evaluation of LODI is publically available.

5.7.34 MERCURE-GL

MERCURE-GL (Gaz Lourd - heavy gas) is a CFD model developed by Electricité de France (EDF) and owned by ARIA Technologies. The model forms part of the ARIA Technologies package ARIA Local (see Section 5.7.8). Very little recent information on the model is publically available. Riou (1987) compared the model with wind tunnel trials and Thorney Island field scale data, and it was evaluated as part of SMEDIS.

¹³⁸ <https://narac.llnl.gov/tools/operational-modeling/dispersion-model-lodi> Accessed on 15th April 2020

5.7.35 MicroSWIFTSPRAY

MicroSWIFTSPRAY (MSS) is a Lagrangian particle model used to predict the transport and dispersion of contaminants in urban environments. It is developed by ARIA Technologies and forms part of the ARIA City and ARIA Impact 3D packages (see Section 5.7.8). It is also included in HPAC (see Section 5.7.29). A description of the model can be found in Anfossi et al. (2010).

The SWIFT portion of this model predicts a mass-consistent wind field that considers terrain; buildings; recirculation, edge, and rooftop separation; and background and locally generated turbulence. SPRAY simulates the dispersion of passive gases, dense gases, and particulates. The model takes into account complex situations, such as the presence of breeze cycles, strong meteorological inhomogeneities and non-stationary, low wind calm conditions and recirculating flow. It can model complex terrain and obstacles, including dispersion under generalized geometries like arches, tunnels and walkways. Simulations can cover a wide range of scales from very local (less than one kilometre) to regional (hundreds of kilometres). SPRAY can also account for plume buoyancy effects, wet and dry deposition, including dry deposition on the ground, on roofs and on lateral faces of obstacles. Microscale pressure fields for integration with building models can be simulated. Both ground and elevated releases can be modelled, but it does not have the means to account for liquid-vapour phase changes.

The model has been validated using well-known experiments from the MDA and REDIPHEN databases and Kit Fox (Anfossi et al., 2010). A parallel version was used as an operational model in the MODITIC project, but only compared with the experimental data for passive releases, the dense gas modules were not included (Endregard et al., 2016).

5.7.36 PHAST

The Process Hazard Analysis Tool (PHAST) is a proprietary model distributed by DNVGL. Information about the model can be found on the DNVGL website¹³⁹ and summarised in Witlox (2010). It forms part of the SAFETI package (see Section 5.7.41).

PHAST contains source term sub-models and a dispersion model based on integral and box models called the Unified Dispersion Model (UDM, Witlox and Holt, 2007). The model continues to be actively developed, see for example Witlox et al. (2016).

PHAST has been extensively validated. It was evaluated by Hanna et al. (1993a) and as part of SMEDIS. It was compared with the ammonia experiments of Bouet (1999), chlorine railcar releases in Hanna et al. (2008, 2009), with Kit Fox by Witlox et al. (2014) and Jack Rabbit II by Gant et al. (2018). The model has been evaluated for LNG using the model evaluation protocol of Ivings et al. (2016) and the associate model validation database (Stewart et al., 2016). This work was also summarised by Witlox et al. (2013). PHAST was used by HSE as part of an investigation for MAIB (Brownless, 2005).

5.7.37 PHOENICS

PHOENICS is a commercial CFD model developed and owned by CHAM. Documentation about the model is available on the CHAM website¹⁴⁰ along with several case studies, including some that demonstrate the model's use for outdoor-indoor flow coupling.

According to Burkhart et al. (2016a, b) PHOENICS was used in the MODITIC project to perform RANS simulations of dense gas dispersion in urban environments. However, there

¹³⁹ <https://www.dnvgl.com/services/process-hazard-analysis-software-phast-1675> Accessed on 15th April 2020

¹⁴⁰ <http://www.cham.co.uk/phoenics.php> Accessed on 26th June 2020

were no results from PHOENICS presented by Burkhart et al. (2016a, b) nor were any presented in other MODITIC reports.

5.7.38 QUIC

The QUIC model is developed by Los Alamos National Laboratory (LANL). Information can be found on the LANL website¹⁴¹ including a selection of theory and user guides and other references. The model is summarised on the website as follows:

The Quick Urban & Industrial Complex (QUIC) Dispersion Modeling System is a fast response urban dispersion model that runs on a laptop. QUIC is comprised of a 3D wind field model called QUIC-URB, a transport and dispersion model called QUIC-PLUME, a pressure solver, QUIC-PRESSURE, and graphical user interface called QUIC-GUI. Chemical, biological, and radiological (CBR) agent dispersion can be computed on building to neighborhood scales in tens of seconds to tens of minutes. QUIC will never give perfect answers, but it will account for the effects of buildings in an approximate way and provide more realism than non-building aware dispersion models.

The dispersion module, QUIC-PLUME is described as follows:

QUIC-PLUME is a Lagrangian random-walk dispersion model for computing concentration fields around buildings. It has been adapted to work in the inhomogeneous environment of cities. It includes more terms than the normal random-walk model in order to account for the 3D gradients in turbulent and mean flow fields. It includes reflection terms for building and street surfaces. The dispersion of aerosols and gases can be simulated, including deposition, gravitational settling and health properties.

QUIC can simulate radiological dispersal devices with buoyant rise; dense gas dispersion with topographical effects and two-phase droplet thermodynamics; pool evaporation and spread; multi-size particle biological agent dispersion; evaporating droplet dispersion; two-phase droplet/vapour mixture dispersion including secondary evaporation from surfaces; inhalation (to estimate amount of agent in the respiratory tract); toxic load; line, area, volume and moving point sources; vegetative canopies and more. QUIC can assimilate meteorological data and it has a nested grid capability so that detail such as buildings can be resolved on the inner grid and not on the outer grid.

QUIC has models for building infiltration and exfiltration. It can model the pressure distribution on buildings, deposition on building surfaces and it can calculate indoor concentrations inside a single zone building.

Run times for QUIC are stated to be as little as tens of seconds, up to about 30 minutes for larger problems of half a million or more particles.

QUIC has been validated against several large datasets for passive dispersion and flow fields in urban environments. Some information on validation for dense gas dispersion can be found in Williams et al. (2005). QUIC was used as an operational urban dispersion model in the MODITIC project (Endregard et al., 2016).

5.7.39 RASCAL

The Radiological Assessment System for Consequence AnaLysis (RASCAL) model is developed and used by the US Nuclear Regulatory Commission (NRC) for making dose projections for atmospheric releases during radiological emergencies. It is designed to be used by response personnel to conduct independent evaluations of dose and consequence

¹⁴¹ <https://www.lanl.gov/projects/quic/> Accessed on 15th April 2020

projections, and for training and drills. Documentation can be found on the NRC website¹⁴² including the latest documentation of the model and methods (Ramsdell et al., 2012, 2015). The current version of the model is 4.3 but a general summary of the model is given on the website for version 3.0.5 of the model as follows:

RASCAL 3.0.5 evaluates releases from: nuclear power plants, spent fuel storage pools and casks, fuel cycle facilities, and radioactive material handling facilities.

While RASCAL 3.0.5 operates as a single piece of software, it is really a set of inter-linked modules each with a different function. These are:

1. Source term: this module calculates a time-dependent source term, which for nuclear power plants, is composed of about 50 radionuclides including parents and daughters. This module is unique in the world for its ability to model a wide variety of accidents based on plant conditions for many different facility types.
2. Meteorological data processor: this module inputs weather observations and forecasts along with local topography to generate time-dependent wind fields that will transport the plume.
3. Atmospheric transport and diffusion: this module uses the wind fields with a two-dimensional Gaussian puff model to transport the plume downwind and to calculate concentrations of each radionuclide as a function of time and location.
4. Dose calculator: this module calculates various types of doses resulting from airborne releases (TEDE, thyroid, acute, etc.) to individuals at each location from three dose pathways - inhalation, cloudshine, and groundshine. It also calculates the longer-term intermediate phase doses from deposited radionuclides. The calculations are completely consistent with the EPA protective action guide manual and the methods adopted by the Federal Radiological Monitoring and Assessment Center (FRMAC).
5. Display of results: this module allows the user to display a wide variety of calculated results as either a picture of the plume footprint on a map background for each of the result types or as numeric table.
6. Uranium hexafluoride module: for uranium hexafluoride releases, RASCAL contains a heavy gas model to account for the exothermic reaction with air and gravitational slumping of the plume.

There is limited validation presented in the above documentation, only a brief reference to comparison with experiments and models in Nair et al. (1997).

5.7.40 SAFER Systems

Systematic Approach For Emergency Response (SAFER) Systems is a proprietary suite of models for real-time chemical emergency response designed for use by the chemical processing industry. Information can be found on the website¹⁴³ but it is very sparse. There are three products available:

- SAFER One which is aimed at contributing to site safety
- SAFER One HR which is aimed at contributing to emergency response for hazmat responders
- SAFER TRACE which is aimed at contributing to consequence assessments

¹⁴² <https://www.nrc.gov/> Accessed on 15th April 2020

¹⁴³ <https://www.safersystem.com/> Accessed 15th April 2020

The software uses cloud computing to run in real-time and incorporates live traffic and weather data. It can display results on google maps and has the US ERG limits integrated into it, among other features.

SAFER TRACE model is based on the TRACE model (see Section 5.7.45).

5.7.41 SAFETI

The Software for the Assessment of Flammable, Explosive and Toxic Impact (SAFETI) package was originally developed by Technica and is now developed and maintained by DNVGL. High level information can be found on the DNVGL website¹⁴⁴. An old description of the original model can be found in Mannan (2012). It is marketed as a quantitative risk assessment package incorporating Phast (see Section 5.7.36).

5.7.42 SCIPUFF

SCIPUFF is a Lagrangian second order closure integrated puff dispersion model and forms the basis for the dispersion modelling in HPAC. A description of the model and some documentation can be found on the SCIPUFF website¹⁴⁵. The dense gas dispersion model was described by Sykes et al. (1999). The website outlines the model as follows:

SCIPUFF uses a collection of Gaussian puffs to represent an arbitrary three-dimensional, time-dependent concentration field, and incorporates an efficient scheme for splitting and merging puffs. Wind shear effects are accurately modeled, and puffs are split when they grow too large for single point meteorology to be representative. These techniques allow the puff model to describe complex flow effects on dispersion, such as terrain-driven circulations.

SCIPUFF has been developed with a flexible interface, to describe many types of source geometry and material properties. The model also uses several types of meteorological input, including surface and upper air observations or three-dimensional grid data. Planetary boundary layer turbulence is represented explicitly in terms of surface heat flux and shear stress using parameterized profile shapes.

SCIPUFF can model the transport of gases, liquid and particles and includes dynamic effects associated with buoyant and dense gases. It can be used for a variety of release types such as instantaneous, continuous, moving, jet, stack or point sources.

The model has been validated against passive dispersion datasets at various scales (see the website). It was evaluated by Lazaro et al. (1997). It was used to model chlorine railcar incidents in Hanna et al. (2008, 2009).

SCIPUFF is listed by the US EPA as an alternative model for use in regulatory applications with case-by-case justification.

5.7.43 SEVEX

The SEVeso Expert (SEVEX) model simulates dispersion over complex three-dimensional terrain. It is a proprietary model available in the form of “SEVEX View” from ATM Pro. A large amount of information, including technical details, is available from the ATM Pro website¹⁴⁶.

The software was designed to be used for emergency response planning and preparedness. It aims to produce realistic and ready-to-use risk zones and maps. It is designed to be used for scales on the order of one to a few tens of km.

¹⁴⁴ <https://www.dnvgl.com/services/quantitative-risk-analysis-software-safeti-1715> Accessed on 14th April 2020

¹⁴⁵ <http://www.scipuff.org/about/> Accessed on 15th April 2020

¹⁴⁶ http://www.atmpro.be/support.php?item=technotes&onqlet=sevex_techsummary Accessed on 15th April 2020

The model simulates accidental releases of toxic and/or flammable substances over flat or complex terrain. It is made up for three modules:

- SEVEX-Meso – a complex three-dimensional terrain and meteorological model
- SEVEX-Toxic – a three-dimensional Lagrangian dispersion model for passive transport and dispersion of toxic and flammable material
- SEVEX-Source – a source term model

SEVEX-Source releases can be instantaneous, steady or time-varying continuous. SEVEX can include multiple pipe or vessel sources; gaseous, liquid and two-phase flows; jet dispersion; aerosol vaporisation; pool formation and evaporation; dense gas dispersion; unconfined vapour cloud explosion (UVCE) and fireball thermal radiation (BLEVE). The model cannot account for multi-component substances or chemical transformations. The source calculations can be coupled to SEVEX-Toxic or to a simpler Gaussian plume model.

There is some validation of the model with the Desert Tortoise and Lathen experimental trials demonstrated on the website. The model has been evaluated following model evaluation guidelines and a list of reports is provided on the website.

5.7.44 SLAB

SLAB is a publically available model developed at LLNL (Ermak, 1990). It was designed for dense gas dispersion scenarios but can also be used for buoyant and non-buoyant releases. It is based on the one-dimensional shallow layer equations and is one of the long-standing models used by the US authorities. It is listed as a US EPA alternative model and is available from the EPA website¹⁴⁷ along with a user guide. It is also a recommended model in the Yellow Book (Van den Bosch and Weterings, 2005) and has been used as the basis for other models such as ADAM (EU, see Section 5.7.1).

SLAB can model continuous, finite duration and instantaneous gas releases from ground level area sources and jet flows. For finite duration releases, SLAB starts with the continuous release model and transitions to the instantaneous release model once the continuous release has stopped, i.e. once the source is no longer active.

The model includes a pool source, vertical (upwards) jet and horizontal jet and an instantaneous or short duration evaporating pool. The pool source is a finite-duration fixed radius pool releasing a steady state plume of vapour. The horizontal jet is an area source perpendicular to the flow which can release a single-component source that can be part liquid, part vapour. SLAB can account for evaporation of droplets. Releases from height can be modelled. The vertical source can also model multi-phase releases from height using the model of Hoot et al. (1973) to provide initial conditions for the shallow layer model of SLAB.

The model has entrainment at the top of the dense gas cloud and cross-wind and down-wind entrainment at the sides of the cloud. The time-averaged volume concentration includes the effects of lateral cloud meander. SLAB assumes flat terrain and cannot model topography or fixed structures.

SLAB can be run in batch mode so that multiple predictions can be obtained in a short period of time.

The model has been extensively evaluated. It was evaluated against experiments and other models in the work of Zapert et al. (1991), Hanna et al. (1993), Lazaro et al. (1997) and SMEDIS. Blewitt, et al. (1987) compared SLAB and DEGADIS to hydrogen fluoride spill data. It was compared to other models for chlorine railcar incidents by Hanna et al. (2008) and compared to Jack Rabbit I by Hanna et al. (2012) and Jack Rabbit II by Mazzola et al. (2020).

¹⁴⁷ <https://www.epa.gov/scram/air-quality-dispersion-modeling-alternative-models#slab> Accessed on 15th April 2020

5.7.45 TRACE

Toxic Release Analysis of Chemical Emissions (TRACE) is a proprietary model developed by SAFER Systems and sold as the product SAFER TRACE¹⁴⁸. It is widely used in the chemical processing industry. It is described briefly on the SAFER Systems website as follows:

SAFER TRACE is a set of consequence assessment solutions that allow rapid visualization of a potential failure involving airborne hazardous material. It allows engineers to study how incremental mitigation techniques may improve safety and help them focus on what must be put in place to mitigate the hazard.

It is difficult to obtain any information from the website without submitting requests to SAFER Systems. The current version of TRACE appears to be 10.2. The following information is mainly based on previous versions of TRACE.

The model was originally developed to evaluate the potential impact of chemical spills. It can model instantaneous and steady continuous and transient releases. It includes models for dense, passive and positively buoyant releases. The dense gas model has a transition to a Gaussian plume phase when the density difference between the cloud and the ambient air is less than a specified ratio and/or the rate of change of the cloud dimensions is comparable to the rate of change of the crosswind Gaussian dispersion coefficient.

TRACE can model sources from pool evaporation, liquid release, flashing and aerosol formation. It will calculate the fraction of liquid that flashes to vapour and the temperature of the resulting cloud. It can calculate the aerosol content of the release. In the case of a multi-component liquid spill, the model treats the spill as an ideal liquid solution, the evaporation rate is obtained by summing the rates of each component. The properties of over 100 chemicals are included in the model's database, which can be easily extended by the user.

Model output includes concentration isopleths and various cloud parameters as a function of time after release. The model provides time-averaged concentrations at both user-specified and model generated receptor positions.

The model is still actively being developed. The SAFER Systems website highlights a new exfiltration model for indoor accidental releases, which is able to calculate how long the toxicity is expected to remain at harmful levels throughout an indoor chemical release event. The model is based on information provided about the room size, temperature, and ventilation type and rate. It determines the toxic or explosive concentration and the exposure curve from the point of release over the duration of the event until safe levels are reached.

TRACE is mentioned in the Yellow Book (Van den Bosch and Weterings, 2005). Early versions of the model were evaluated by Zapert et al. (1991) and against the MDA by Hanna et al. (1993a). TRACE version 8.0 was compared with Chlorine incidents by Hanna et al. (2008). SAFER TRACE was compared with Jack Rabbit II measurements in Mazzola et al. (2020).

5.7.46 TWODEE and TWODEE-2

TWODEE is a publically available two-dimensional shallow layer code for dense gas dispersion, originally developed by the Health and Safety Laboratory for HSE (Hankin and Britter, 1999a-c). It was evaluated as part of SMEDIS. However, it was never used by HSE because it was demonstrated at HSE that there were flaws in the coding of TWODEE, in particular in the entrainment and friction models. It was highlighted that the entrainment model lacked edge entrainment (Webber, HSL, 1999, Pers. Comm.). This is particularly

¹⁴⁸ <https://www.safersystem.com/products/safer-trace/> Accessed April 15th 2020

important under low wind speeds, since top entrainment becomes significantly reduced and the importance of edge entrainment increases.

TWODEE-2 is a research code developed by Folch et al., (2009) from TWODEE. TWODEE-2 was modified to include obstacles and used by Brambilla and Manca (2010) to investigate the Viareggio railcar incident. However, it does not appear that the faults from TWODEE have been modified in TWODEE-2.

Results presented by Folch et al. (2009) showed TWODEE-2 apparently producing turbulent oscillatory behaviour. However, the governing equations of TWODEE suggest no such turbulent solutions. Correct solutions would smooth out any such turbulent behaviour (Webber, HSL, 2011, Pers. Comm.). Therefore, the oscillations may be an indication of numerical instability.

5.7.47 UDM (Dstl)

The Urban Dispersion Model is a Gaussian puff model developed for Dstl by Hall et al. (2001) for modelling dispersion in the urban environment. It has been incorporated into HPAC as a dispersion modelling option with SCIPUFF and no longer exists as a standalone code. It is designed for fast dispersion predictions at scales in the range of 10 m to 25 km. Puffs can be single or multiple, time-dependent or continuous, static or moving, by releasing a succession of timed puffs.

UDM contains sub-models for gases, particulates and liquids. There are three calculation modes for the urban setting, which are selected automatically: a single building, an urban array and open terrain. In open terrain, the puff is large compared with the scales of individual obstacles and an aerodynamic roughness length approach is used. If an obstacle is considered small relative to a puff then it is effectively ignored. When buildings are present, they are modelled via an area density specification. If the building area density is >5% then the rate of puff expansion is simply enhanced using empirical relationships determined from wind tunnel experiments on block arrays. If the area density is <5% then it will treat the buildings as isolated and puffs will split around them and the building wake(s) will be modelled. In addition, if the area density is >5%, but a single very large building is found and single building interactions are 'on' then the puffs will split to go around it and the wake will be modelled.

The model was designed so that it is modular and can be relatively easily modified. Hall et al. (2001) said that the original model was developed to provide rapid predictions for urban areas using new experimental data; to provide a GUI; and to extend its range of application to complex terrain using a wind field calculation model. The passive UDM model has been validated with field and wind tunnel experimental measurements (see, for example, Brook et al., 2003).

A dense gas model has been developed for the UDM, based on HEGADAS and DEGADIS (Herring and Ratcliffe, 2010). The model is able to account for uniform sloping terrain, interaction with obstacles and overlap of multiple puffs.

5.7.48 VDI Guideline 3783 Part 2

The VDI Guideline 3783 contains a dispersion model for passive gases (Part 1) and dense gases (Part 2). The Guideline is based on wind tunnel experiments for 25 configurations, including different fixed structures in the flow field. It can be described as a screening model in a similar way to Britter and McQuaid (1988). However, it continues to be developed (see, for example, Rauchegeger et al., 2015).

The guideline is a method for estimating dispersion of heavy gases from industrial accidents within the framework of a safety study. Results are given for mean and worst case concentrations or dose. It is not designed for use for actual incidents or reconstruction.

Results are presented in terms of normalised values for four types of release and five types of dispersion area, for both instantaneous and continuous releases. The substances are either subject to the safety criteria for flammable heavy gases or toxic heavy gases.

The four release types are:

- A. General gases – gas flowing out of a container at initial working temperature and ambient pressure
- B. Non-pressurised liquefied gases – gases that are liquefied without pressure cooled to or below boiling point
- C. Pressure-liquefied gases – gases which expand to ambient pressure and will be at boiling temperature on release
- D. Pressurised and liquefied ammonia and other gases with similar behaviour

The five dispersion area types are:

- i. Flat terrain, no obstacles
- ii. Flat terrain, hemispherical release next to a straight wall parallel to the wind direction.
- iii. Flat terrain, release in a canyon parallel to the wind direction.
- iv. Flat terrain, very large hemispherical wall downwind of the source.
- v. Flat terrain, very large hemispherical wall downwind of the source. The wall is closer than for Type IV.

For toxic heavy gases, the approach for passive gas dispersion is used with the initial conditions of the model modified to account for heavy gas near the source (tables of information are provided for each of the five types of dispersion area). In these scenarios, the quantities evaluated are the maximum temporal concentration and dose values at fixed receptor points downwind of the source for the mean and worst case dispersion situations. However, if the concentrations exceed 1%, the method used for flammable gases is used with transition to the passive model.

The existing model does not predict the height and the width of the dense gas cloud, which is required input for the intended coupling to a more advanced passive gas model (AUSTAL2000, a Lagrangian particle model). Rauchegger et al. (2015) undertook experiments to determine cloud lengths, widths and heights and also to extend the applicability of the model to elevated releases. They successfully correlated their results to provide expressions to extend the applicability of the VDI Guideline 3783 Part 2 model. According to Meroney et al. (2016) an updated version of the VDI Guideline 3783 is under consultation.

The model was evaluated as part of the SMEDIS project and by Lazaro et al. (1997). As with Britter and McQuaid (1988), the VDI Guideline should not be used to model scenarios outside the set of conditions from which the model was derived.

5.7.49 VLSTRACK

The Vapor, Liquid and Solid Tracking (VLSTRACK) model was developed by the US Naval Surface Warfare Centre Dahlgren Division. It was designed for military use to estimate the effects of chemical and biological weapons. According to Bauer (2013):

VLSTRACK represents single or multi-phase instantaneous or plume releases with Gaussian puffs that transport and diffuse according to standard empirical planetary boundary layer algorithms for open terrain. VLSTRACK was developed to predict hazards resulting from dissemination of chemical and biological warfare agents, including dense-gas forming compounds chlorine, phosgene, and hydrogen cyanide. VLSTRACK addresses settling of dense gases but not stratification; the methodology is appropriate for the mild dense gas effects of the Jack Rabbit area vapor sources. VLSTRACK generates the broadest range and most easily manipulated set of output

files among freely available ATD [Atmospheric Transport and Dispersion] models. The model has been extensively validated against chemical and biological agent and simulant field trial and tracer release data.

Typical outputs from VLSTRACK are simple and informative graphics of the hazard footprint for agent deposition, dosage and concentration. VLSTRACK can output cumulative hazard from the time of release or a periodic hazard for set time periods. It can accumulate output from many source locations to represent multiple munitions. It is able to accommodate variable meteorology but cannot model chemical reactions and the effects of fixed structures.

VLSTRACK was evaluated in the model review of Lazaro et al. (1997) in which it is omitted from comparison of the ranges across all models because its predictions were often in disagreement with the other models. Bauer (2013) used VLSTRACK to model chlorine and ammonia releases in Jack Rabbit I.

5.8 Models for predicting ingress of dense gases into structures

A significant amount of research has been conducted over the last 50 years on modelling infiltration into buildings. This has been driven by the need to understand the thermal efficiency of buildings, indoor air quality and the build-up of contaminants in buildings during toxic dispersion incidents and fires. However, relatively little work has been done that focuses specifically on infiltration of dense gases into buildings (including basements and tunnels). Experimental data for dense gases is also limited.

The following section briefly reviews models for infiltration into buildings and structures. Note that some of the models listed in the previous section on atmospheric dispersion models also have the ability to model infiltration.

5.8.1 Liddament (1986) and AIDA

Liddament (1986) described a model aimed at calculation of air infiltration into buildings. It consists of a relatively simple continuity equation that depends on the volume of the enclosure, the rate of chemical or physical decay of the pollutant, an empirical mixing factor, the internal and external concentrations of the pollutant, the ventilation rate and the total rate of emission of the pollutant from all (internal) sources.

The Air Infiltration Development Algorithm, AIDA, (Liddament, 1989) is a single zone network model based on the theory in Liddament (1986). The user defines the number of openings and provides a flow coefficient and exponent for each opening. If these are unknown they can be looked up in widely available tabulated data for standard components. The user supplies the weather conditions and the model calculates an air change rate.

5.8.2 Green book

The Green Book (1992) contains a simple method for infiltration, which in general terms proceeds as follows:

- Identify building type and average ventilation rate
- Determine if the contaminant release is continuous or instantaneous
- Calculate concentration outside the building using a dispersion model
- Calculate the maximum indoor concentration for the appropriate source type.

Expressions or calculation methods are provided for each of the stages of the process. The model does not explicitly account for dense gas effects.

5.8.3 SHELTER

SHELTER is a simple numerical model devised by Wilson (1990) for calculating internal exposure. SHELTER provides the mean internal concentration for a well-mixed internal

space under conditions of natural and mechanical ventilation for a time-varying external concentration. It requires the start time, the initial internal concentration and the characteristic time response of the building ventilation.

5.8.4 Lyons et al. (2015)

The Lyons et al. (2015) model was developed for carbon dioxide as part of the COOLTRANS project (Allason et al., 2016). It is based on principles of natural building ventilation (Etheridge and Sandberg, 1996) and the work of Brighton (1986).

The model comprises a single zone with openings to represent doors, windows and adventitious openings. Flow between the indoor and outdoor spaces is driven by pressure difference across the openings in the building envelope that are caused by to wind or internal buoyancy effects.

The model assumes that there is a normal background level of carbon dioxide initially inside the building and a carbon dioxide pipeline release occurs outside. The concentration inside the building is assumed to be uniform. The concentration of carbon dioxide in the external atmosphere is time-varying and so is the concentration of carbon dioxide within the building.

The wind pressure and buoyancy pressure are calculated using the method described by Etheridge and Sandberg (1996). Pressure on the surface of the building is adjusted for the angle of the wind. Pressure differences are modified to take into account the density of carbon dioxide. The influence of the external temperature due to the contaminant cloud is also modelled.

The main input data required for the model is the time-varying concentration of carbon dioxide and the ambient temperature outside the building, which could be provided from a dense gas dispersion model.

The model compares reasonably well with the measurements from the COOLTRANS experiments (Cleaver et al., 2016) and a case study is also presented in the paper illustrating the use of the model for calculating toxic dose.

5.8.5 INGRESS

The INGRESS tool predicts indoor concentrations based on past Building Research Establishment (BRE) wind tunnel dispersion experiments and ingress calculations. It requires information about building types, weather and source-term data (or monitored concentrations). An example of the tool can be seen in the presentation by Stewart-Evans (2020). It is under development and has not yet been used in operational work (a validation programme is required to compare predictions to other models and empirical data).

5.8.6 IBH

Internal Building Hazards (IBH) model (Wolski, 2016) is part of HPAC and JEM. It provides a source term for chemical and biological releases from within a building, and it incorporates the CONTAM model. IBH has parameters for different types of building: detached house, attached house, manufactured home, apartment, medium office building, and box model. It has instantaneous and continuous release types available, which are called burst (instantaneous), spray (finite duration) and pool (evaporation of liquid chemical agents). It also has an 'external challenge' model which models dosage or concentration with optional meteorology. The burst and spray options have the addition of a possible secondary evaporative release from liquid chemicals. The model output consists of the mass leaving the building and the dosage in the zone(s). Contamination around the building is assumed to be uniform.

There is little information on validation of the model and it appears that the JOULES model may be used to generate synthetic datasets for model comparison exercises¹⁴⁹.

5.8.7 COMIS

Conjunction of Multizone Infiltration Specialists or COMIS (Feustel, 1998) is a multi-zone network model developed by LBNL. The model represents a building as a number of nodes interconnected by flow paths which may include purpose-provided and adventitious openings along with mechanical ventilation systems. It can model features such as ducts, fans, doors, windows, including their transient activity. COMIS predicts flow induced by wind, thermal buoyancy, and mechanical ventilation. Air is assumed incompressible, and airflow through pathways is calculated by balancing pressure differences between the zones.

COMIS can be used to model contaminant infiltration. It assumes well-mixed zones and cannot model concentration density gradients within a room. The software has been applied to predict airflow and gas transport in multi-storey, low- and high-rise residences. It has been used coupled with an indoor particle model by Sohn et al. (2007) to provide the airflow to transport the particles.

There appears to have been little recent development of COMIS and it does not appear on the LBNL website, so it is possible that it no longer under development or supported.

5.8.8 CFAST

The Consolidated model of Fire And Smoke Transport (CFAST) is a freely available, open-source, multi-zone model developed by NIST. It is an amalgamation of two older models FAST and CCFM. The model and documentation can be obtained from the NIST website¹⁵⁰. The model is included here because while it is designed for fire and smoke transport, its use for contaminant dispersion could also be investigated.

The model allows the user to take into account the non-uniform distribution of temperatures, pressures and concentrations of species in the different parts (zones) of a building. CFAST can also be coupled to the FDS CFD dispersion model to simulate evacuation.

CFAST is used in the ARIA Technologies package ARIA Indoor¹⁵¹.

5.8.9 FloVENT

FloVENT is maintained and marketed by Mentor Graphics. General information can be found on the Mentor website¹⁵² where the model is summarised as follows:

FloVENT is powerful computational fluid dynamics (CFD) software that predicts 3D airflow, heat transfer, contamination distribution and comfort indices in and around buildings of all types and sizes. FloVENT's fast and easy-to-use menu system is designed specifically for engineers involved in the design and optimization of heating, ventilating and air conditioning (HVAC) systems.

FloVENT was described in more detail by Sohn et al. (2004), who also compared it with CONTAM for internal dispersion modelling. The obvious benefit of the software is detailed visualisation of the flow field, including visualising released particles. The main limitation of this type of model is the time to set it up compared with zone models such as CONTAM. Also, FloVENT cannot easily model transient effects such as occupants entering and leaving rooms, HVAC turning on and off, wind direction and magnitude changes and varying contamination sources.

¹⁴⁹ <https://aerisllc.com/item/urban-coupled-indoor-outdoor-modeling-synthetic-environments/> Accessed on 26th June 2020

¹⁵⁰ <https://pages.nist.gov/cfast/index.html> Accessed on 16th April, 2020

¹⁵¹ http://www.aria.fr/aria_indoor.php Accessed on 16th April 2020.

¹⁵² <https://www.mentor.com/products/mechanical/flovent/> Accessed on 16th April 2020

5.8.10 CONTAM

CONTAM is a multi-zone network model developed by NIST (Dols and Walton, 2002). It is similar to COMIS and can be used to model ventilation and contaminant infiltration. As for COMIS, the model assumes well-mixed zones and it cannot model concentration density gradients within a room. However, unlike COMIS, CONTAM can model spatially varying external contaminants, wind pressures and deposition (Hall and Spanton, 2012). CONTAM can also simulate one internal zone using CFD so that this zone can have a variable temperature and contaminant concentration.

Sohn et al. (2004) compared CONTAM with FloVENT and highlighted that the benefit of CONTAM is the ability to handle large, complicated buildings, which would be prohibitive with a CFD model because of the amount of time to set it up and run the calculation. CONTAM is also capable of modelling transient effects like occupants coming and going.

CONTAM and COMIS were both reviewed by Lorenzetti (2002). CONTAM was compared with the Jack Rabbit II infiltration data by Sohn et al. (2016). The model was found to perform well for predicting indoor concentrations of chlorine for the ground floor and first floor, but not so well on the higher second floor.

5.8.11 MELCOR

MELCOR is a severe accident code developed by US NRC (Summers et al. 1991). It was originally designed to simulate accident conditions and provide source terms for nuclear reactors but it is general enough to use for ventilation systems (SAIC, 1998). It is a multi-zone model able to simulate aerosols and vapour transport in buildings, and has been benchmarked against other models (see, for example, Kim et al., 1995, 1997).

5.8.12 Deru and Burns (2003)

Deru and Burns (2003) presented a multi-zone air infiltration model that incorporates measurements of a building's leakage from experimental tests and measured weather data. It uses a measured effective leakage area which the user divides amongst the surfaces enclosing each zone. The model can take into account terrain and building shielding effects. However, it does not include models for contaminant infiltration.

5.9 Other models in frequent use for atmospheric dispersion modelling

The following models are used by UK authorities for atmospheric dispersion modelling. They do not contain the necessary physics to model dense gas dispersion, but are included here because of their use in UK regulatory and emergency response applications. There are currently no dense gas dispersion models in operational use in the UK for real-time modelling during response to a civil emergency.

5.9.1 NAME

The Numerical Atmospheric-dispersion Modelling Environment (NAME) is an atmospheric dispersion model developed and maintained by the Met Office. Further information can be found on the Met Office website¹⁵³, where the model is introduced as follows:

NAME is used by the Met Office to model a wide range of atmospheric dispersion events including nuclear accidents, volcanic eruptions, chemical accidents, smoke from fires, odours, airborne animal diseases, as well as the provision of routine air quality forecasts. In inverse mode the model is used to investigate emissions of

¹⁵³ <https://www.metoffice.gov.uk/research/approach/modelling-systems/dispersion-model> Accessed on 26th June 2020

greenhouse gases and other atmospheric pollutants. The model is used for research activities and for emergency air pollution forecasts.

NAME uses the Unified Model¹⁵⁴ and ECMWF Numerical Weather Prediction (NWP) meteorology data. Both forecast and archived data are available, enabling forecasts out to 10 days and historic studies back to 1957. There is no limitation to the duration of a pollutant release or the time period covered by a NAME simulation. It is therefore possible to predict dispersion over distances ranging from a few kilometres to the whole globe and for time periods of minutes to decades.

NAME was originally developed as a Lagrangian particle model, which calculates the dispersion by tracking model 'particles' through the modelled atmosphere. These particles move with the resolved wind described by the meteorology, which can vary in space and time. The particles' motion also has a random component to represent the effects of atmospheric turbulence. A consequence of this is that no assumptions need to be made for the shape of the concentration distribution, such as are required in Gaussian plume models. Pollutants can also be removed from the model atmosphere by several processes: (i) fall out due to gravity, (ii) impaction with the surface, (iii) washout where the pollutant is 'swept out' by falling precipitation, and (iv) "rainout" where the pollutant is absorbed directly into cloud droplets as they form. In addition each model 'particle' can have its own characteristics; for example particles can represent different compounds or chemicals, and particles can have real particulate sizes.

NAME also includes an Eulerian model: here a model field representing the concentration of different chemical species is advected and diffused through the atmosphere. Advantages of this approach include direct calculation of the concentration rather than indirectly as is the case for the Lagrangian model. The Eulerian model is also better suited to smoothly varying quantities such as ozone which makes the Eulerian model a computationally cheaper model for applications such as air quality modelling. However, the Eulerian framework is not well suited to modelling dispersion from small sources such as a power station chimney. NAME combines the best of both Eulerian and Lagrangian approaches by releasing material on particles initially and then transferring the mass on those particles to fields after a specified time which can be controlled by the user.

The Lagrangian model in NAME is not a purely Lagrangian particle approach, it is a hybrid Lagrangian particle-puff approach. NAME typically uses a Lagrangian puff approach for shorter range applications and reverts to a Lagrangian particle approach at longer range. This was described further by Jones et al. (2007), who also provided some details of verification and model comparison studies. The current version is NAME III.

NAME is available for external research use under licence. A number of UK universities and government agencies use NAME in collaboration with the Met Office for research purposes. NAME is used by Met Office and by PHE (in collaboration with the Met Office) for emergency response.

5.9.2 ADMS 5

ADMS 5 is an atmospheric dispersion model developed and maintained by CERC. A large amount of information on the model, including user guides, verification and validation is available to view or download on the CERC website¹⁵⁵. The model is described by CERC as follows:

¹⁵⁴ <https://www.metoffice.gov.uk/research/approach/modelling-systems/unified-model/index> Accessed on 26th June 2020

¹⁵⁵ <https://www.cerc.co.uk/environmental-software/ADMS-model.html> Accessed on 26th June 2020

ADMS 5 is an advanced dispersion model used to model the air quality impact of existing and proposed industrial installations. Its many features include allowance for the impacts of buildings, complex terrain, coastlines and variations in surface roughness; dry and wet deposition; NO_x chemistry schemes; short term releases (puffs); calculation of fluctuations of concentration on short timescales, odours and condensed plume visibility; and allowance for radioactive decay including γ -ray dose.

Typical applications include:

- assessment of modelled air pollution concentrations against air quality standards and limit values including those from WHO, EU, UK, USA and China
- planning/permitting under IED/EPR,
- stack height determination,
- odour modelling,
- environmental impact assessments and
- safety and emergency planning.

ADMS is used worldwide by regulatory authorities and independent companies. The model is a state-of-the-art Gaussian plume air dispersion model. It contains a built-in meteorological pre-processor that allows it to process meteorological data in flexible formats. It contains an integrated mapping tool and can interface with GIS software.

5.9.3 R91

The R91, or NRPB-R91, is a Gaussian plume model developed by the National Radiation Protection Board for short and medium range dispersion of radionuclides released into the atmosphere. Information on the original model can be found in Clarke (1979). PHE use a model based on R91 in their emergency response tool (Bedwell et al., 2011).

The model was designed for modelling atmospheric dispersion of a neutrally buoyant plume over land from an isolated stack. It was valid for dispersion distances up to 100 km from the source, under the assumption that the meteorological and topographical conditions remain approximately constant for the plume duration. The model can account for atmospheric stability, surface roughness, wet and dry deposition.

R91 and NAME III were compared by Bedwell et al. (2011) to investigate differences in the model predictions for use in emergency response. R91 was shown to predict time integrated activity concentrations in air that were generally more conservative than NAME. Comparisons of R91 with ADMS and wind tunnel studies can be found in Hill et al. (2001).

5.10 Summary

The previous sections have reviewed the physics of different classes of dense gas dispersion model, their common assumptions, and work that has been undertaken to validate the models. High level information for 64 models or software packages has been summarised.

Due to the wide-ranging nature of this review, it has not been possible to go into significant detail with all the modelling approaches. As Britter (1998) noted, the limitations of models are often not well known or clearly declared. For example, even when a model states that it has the ability to simulate nil wind, this might simply mean that the model can produce predictions under those conditions, not that it gives accurate results. CFD models are often held up as the gold standard, but the difficulties they have, for example in maintaining realistic atmospheric boundary layers, are often not widely acknowledged outside of specialist CFD publications.

Dense gas dispersion modelling forms an important part of regulatory work in the UK, such as COMAH and Land-Use Planning (LUP). At present, most dense gas modelling is undertaken with integral models for industrial regulation, risk assessment and emergency preparedness. CFD codes are typically used for understanding incidents and research, although they are sometimes used by site duty holders in COMAH assessments where obstructions or sloping terrain needs to be taken into account.

Studies such as the COST Action ES1006 recommend that regulators and emergency planners move away from using integral models and adopt high-fidelity models (e.g. CFD). However, while it might seem that integral models are not sophisticated compared with high fidelity models, particularly in terms of resolving obstacles and terrain, they often include advanced models for complex sources, physics and chemistry. Moreover, they have often been more extensively validated than CFD models. The cost of CFD models also needs to be considered carefully, particularly for LUP or Quantified Risk Assessment (QRA), where hundreds of scenarios may need to be modelled.

A variety of different models are used in different countries for emergency response. Models that are designed or marketed as having the capability of running in real-time (or faster than real time) are summarised in Table 21.

Table 21 Models listed in this study that are designed or marketed as being suitable for use in emergency response

Model name	Type of model
Aeolus	CFD
ALOHA	Integral / box
ERG	Empirical
FLUIDYN-PANACHE	CFD
JEM	See HPAC models
LODI	Lagrangian particle
MicroSWIFTSPRAY (HPAC)	Lagrangian particle
QUIC	Lagrangian particle
RASCAL	Gaussian plume
SAFER SYSTEMS	Unknown
SCIPUFF (HPAC)	Lagrangian puff
UDM (HPAC)	Gaussian plume

HPAC/JEM perhaps offers the most sophisticated package for dense gas dispersion in current operational use. However, the package is primarily designed for defense and homeland security applications and is not freely available. In the UK, the main operational models for civil emergency response are NAME and R91, which do not account for dense gas dispersion.

For emergency response, there is the central problem that the source conditions will probably be unknown at first. Therefore, it is arguable where there is any benefit in using a high-fidelity dense gas model initially, although the predicted interaction of the dense gas with topography and obstructions would be informative.

A look-up system, like the US ERG (ERG,2020), is an alternative solution for the initial stages of emergency response. Care is needed to ensure that the guidance is appropriate for the UK. For example, the size of railcars and road tankers may differ between North America and the UK. For prolonged events, it would be important to seek an improved prediction as soon as possible. In the UK, this would currently involve a CHEMET from the Met Office, which would not take into account dense gas effects.

One solution to account for dense gas effects could be to couple a fast-running dense gas model for the near field with a passive atmospheric dispersion model for the far field. This approach was suggested by Britter (1998) for toxic substances. Examples of this type of coupled approach include ALOHA-HYSPLIT and VDI3783-AUSTAL2000. However, while this approach gives some recognition to the importance of the dense gas behaviour in the near field, work would be needed to ensure efficient coupling of the two models, given that calculation time is critical in emergency response. One of the benefits of models like HPAC is that they are valid across all scales, with source models included in the software to enable results to be generated quickly for scenarios like a release from a road tanker.

In the future, high fidelity models such as LES may provide databanks of information and potentially act as synthetic validation datasets, as intended with JOULES. However, they are still mostly research tools at present.

For prediction of ingress of dense gases into structures, there are very few models developed specifically for dense gases. Model development in this area is hampered by the limited availability of experimental data for model validation.

5.10.1 When is a specific dense gas model required?

One of the questions faced when needing to predict the extent of a hazardous dense gas cloud is whether a dense gas dispersion model is required at all, or whether a sufficiently accurate answer could be obtained using a passive dispersion model. The criteria for when a release need to be treated as dense were discussed in Section 3.2.2. The choice of model may be driven by the time and resources available, and whether the source conditions are clearly defined or not. If conditions are uncertain, a quick answer is needed and only a passive model is available at short notice, then that may control the decision taken.

In the model evaluation study of Hanna et al. (1993a), they found that in two of the three data groups, the “best” model was one which was not originally developed for that scenario. The Gaussian Plume Model performed the best for the continuous dense gas releases and the dense gas dispersion model SLAB performed best for the continuous passive gas releases. Lazaro et al. (1997) evaluated several models including two passive dispersion models (INPUFF and CALPUFF) alongside dense gas-specific models. They found that the passive dispersion model predictions were generally within a similar range to the dense gas-specific predictions. In some cases, this was because the gas released in the experiment became effectively passive fairly quickly and in other cases because the dense gas models did not have the correct physics for the source. A notable conclusion of Lazaro et al. (1997) was that the use of a dense gas model was essential for dense gas releases from vertically upward pointing jets, in order to reasonably accurately capture the touch-down of the gas cloud. Herring and Huq (2016) advocated using a simple Gaussian model in all future model evaluation exercises as a means of benchmarking the performance of more complex models.

The findings of the present study indicate that if source information is available, and resources allow for it, then a dense gas model should be used. However, the studies by Hanna et al. (1993a) and Lazaro et al. (1997) indicate that if the information is not available

then a passive model may provide a reasonable approximation if the model can accurately capture meteorological conditions¹⁵⁶.

It would be useful in the future to investigate the feasibility of coupling a near-field dense-gas dispersion model with the NAME dispersion model used by the Met Office for CHEMETs. In parallel, it would be useful to explore whether HPAC could be used more widely in the UK, outside its current uses for defense and counter-terrorism. Future work could also include a modelling exercise to understand the capabilities and limitations of NAME for simulating dense gas dispersion.

¹⁵⁶ It must be noted that good model performance compared to experimental data, as assessed in the studies by Hanna et al. (1993a) and Lazaro et al. (1997), would not be sufficient for model acceptance in a thorough model evaluation. Comparison with experimental data only forms one component of model evaluation (see Section 5.4.14). Scientific assessment of the model is another important component of evaluating a model for use in a particular context and a truly passive model applied to a dense gas context cannot satisfy this requirement. This is discussed further by Coldrick et al. (2016).

6 DENSE GAS DISPERSION EXPERIMENTS

6.1 Introduction

This chapter covers experimental studies of releases that result in dense gas dispersion. The factors that make an experimental dataset suitable for model evaluation are briefly discussed before providing summaries of existing experimental compilations, in the form of databases and reviews. Finally, features of previous individual experimental trials are described and any knowledge gaps are noted.

6.2 Suitability of datasets for model evaluation

Not all measurement data is suitable for model validation. Historically, many previous experimental studies on dense gases have been undertaken in order to gain insight into the physics of particular aspects of a release, with model validation being a secondary consideration, and consequently have provided insufficient information for model validation. Ivings et al. (2016) summarised the suitability criteria for model validation datasets as follows:

- The quality of the data must be fit for purpose, i.e. model evaluation. Nielsen and Ott (1996a) discuss the meaning of data quality in this context and describe methods of screening and checking the quality of data for model evaluation.
- The test conditions must be known, including source configuration, atmospheric conditions, surface roughness etc. Duijm and Carissimo (2002) stress the importance of reliable information about the source term and release rate.
- The time-averaging applied to the data must be specified. For flammables, such as LNG, data should be available for short time-averages.
- Scale factors should be within acceptable ranges (see section 6.2.1).
- The data must be available and in suitable formats.

An additional significant factor to note is that the majority of models produce an output that is essentially an ensemble-mean. An ideal dataset will consist of repeat experiments so that ensemble-mean values can be calculated. In reality, this is rarely the case, especially for field trials. Even for wind tunnel trials, multiple repeats of an instantaneous release of a dense gas under nominally identical conditions are needed to produce a reliable ensemble mean. Davies (1987) found that concentrations at the same downstream locations varied by roughly a factor of two in repeated tests. If repeated tests are not conducted, an ensemble-mean model prediction should not be expected to produce exact agreement with the experimental dataset.

The main parameters of interest in evaluating dense gas dispersion models are the maximum concentration, the time-integrated concentration (or dose), the average concentration over the cloud and the cloud width and height, all as a function of downwind distance (Hanna et al., 1993a).

6.2.1 Scale

Physical experiments on dense gas dispersion can be split into field experiments, which can be either at full- or reduced-scale, and wind or water tunnel models.

Full-scale field experiments are ideal in theory because they provide the best opportunity for a direct replica of the release conditions and consequences. In reality, they are expensive, time-consuming and present logistical difficulties, amongst other issues. Scaled-down models can have significant benefits in terms of cost, time and logistics. Smaller scales can also allow for more experiments both for additional insight and for repeat tests, which improve the range and quality of the data. The main downside to scaled-down models is ensuring that the parameters of the model are scaled appropriately to replicate full-scale characteristics.

Wind and water tunnel experiments take this one step further and provide a model with similar benefits to a scaled-down field trial but with improved control over the scaling and, in particular, without the difficulties associated with outdoor testing (e.g. variable weather conditions and difficulty locating sensors in the downwind direction). However, indoor tests are usually constrained to use inert (non-flammable, non-toxic) gases and cannot therefore replicate some of the complex physics associated with chemical reactions and evaporating sources (e.g. for HF or LNG). Their applicability also starts to fail for studies that require modelling of the atmospheric boundary layer beyond the surface layer and for the final phases of dense gas dispersion when the cloud is very large. This is more of an issue for toxic gases since the area over which vapour concentrations are hazardous is typically orders of magnitude larger than for flammable gases. A summary of the benefits of wind tunnel modelling can be found in the work by Hall (1997).

Generally speaking, the ideal study would have full-scale experiments, wind tunnel and numerical models all designed to complement and validate each other, to maximise the breadth of information obtained. For example, Figure 40 shows a comparison of images from the Porton Down small-scale field trials compared with 1/25 wind tunnel tests from experiments undertaken by Hall (1982).

In order for a wind tunnel model to be considered representative of the full scale it is crucial that scaling effects are considered in the design and reporting of wind tunnel experiments. The parameters for which similarity should be ensured are as follows (e.g. McBride et al., 2001):

Flow Reynolds number: $Re = LU\rho_a / \mu$

Richardson number: $Ri = g(\Delta\rho / \rho_a)(L / U^2)$

Or, densimetric Froude number: $Fr = U / \sqrt{[(\Delta\rho / \rho_a)gL]}$

Froude number: $Fr = U / \sqrt{gL}$

Initial density: ρ_g / ρ_a

In practice not all of these values can be matched, mainly due to the maximum/minimum running constraints of wind tunnels, and so some flexibility is required. This is acceptable if the differences do not significantly affect the representativeness of the wind tunnel experiment. The question of appropriate scaling in order to retain the full-scale characteristics of a dense gas release is covered in depth by Hall and co-workers through their experience of setting up wind tunnel models for multiple studies starting with Hall et al. (1975).

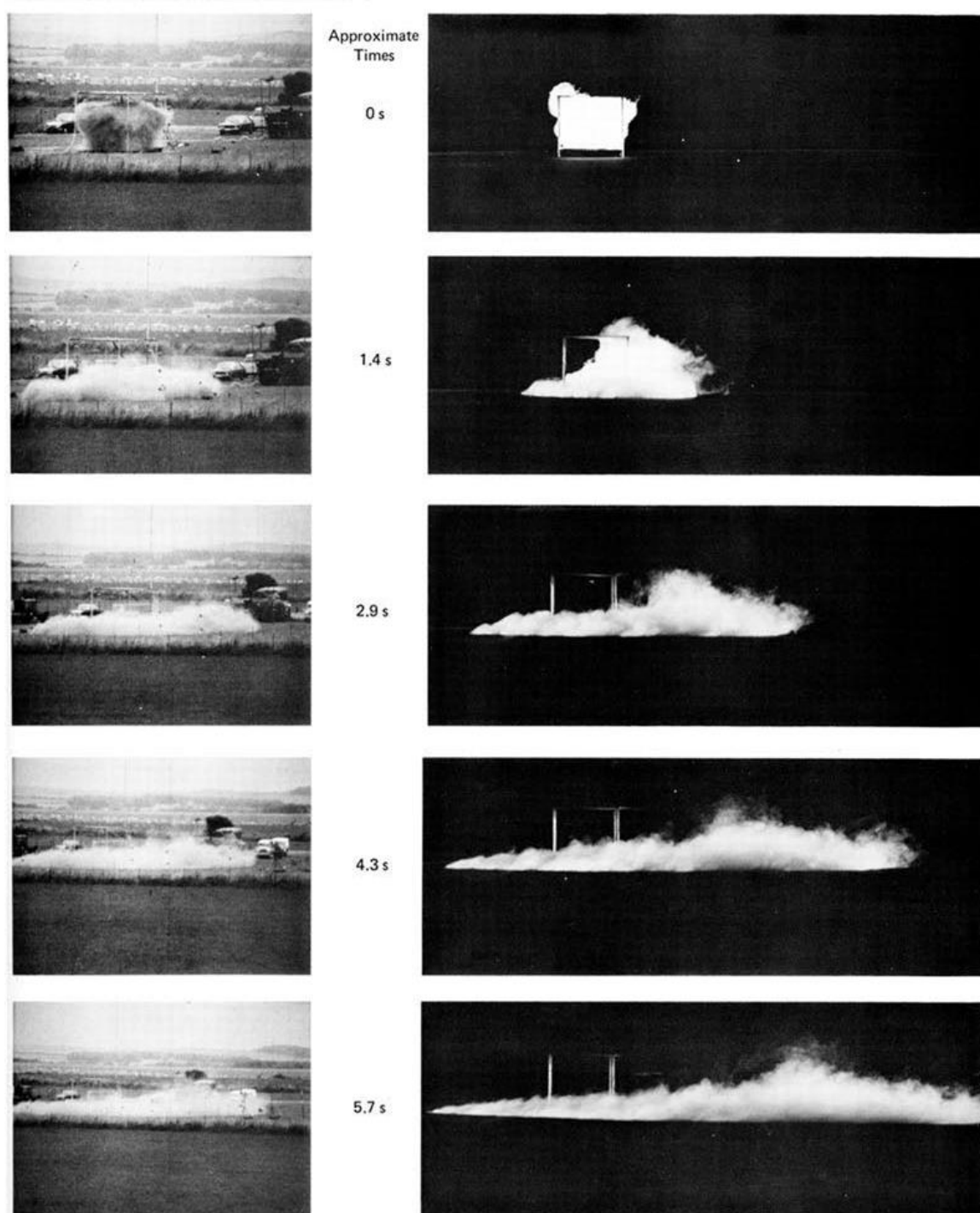


Figure 40 Comparison between 1/25 scale Froude number based model and Trial No. 29. Image from Hall (1982). Note that the scale and viewing angle vary slightly in the field trial images

Experiments involving low wind speeds can be particularly problematic. In wind tunnels, scaling issues mean that wind tunnel velocities required to simulate a low atmospheric wind speed can be unfeasibly small. To maintain their similarity when wind speeds become too low for the wind tunnel, the source gas density is sometimes increased in order to justify use of higher wind speeds (Schatzmann et al., 1991). It also becomes difficult to maintain a turbulent boundary layer over the working section at low wind speeds, and the flow in the

wind tunnel can laminarise. In the field trials, low wind speeds mean that samplers may need to cover all wind directions, the dense cloud may be more affected by topography, good quality meteorological data is required and more time may be required to shed light on variability in results (Lines and Deaves, 1997).

When it comes to validating models using reduced-scale experiments, the modeller has the option to compare simulations directly to the reduced-scale tests, or to run simulations for the full-scale scenario and compare to scaled-up data. Stewart et al. (2016) recommended the former approach, to reduce sources of uncertainty due to scaling.

6.3 Model validation databases

6.3.1 Modelers Data Archive (MDA)

The Modelers Data Archive (MDA) was compiled to evaluate the performance of hazard-response models used for calculating concentrations of hazardous chemicals in the atmosphere. A complete description of the database can be found in Hanna et al. (1993a).

The experimental datasets comprised both dense and neutrally buoyant gas release trials. The dense gas trials included Burro, Coyote, Desert Tortoise, Goldfish, Maplin Sands and Thorney Island. All of these involved continuous releases, except for Thorney Island, which provided both instantaneous and continuous releases of gas. These dense gas trials are described individually in Section 6.5 below. The continuous neutrally-buoyant gas release datasets were from the Prairie Grass (Barad, 1958) and Hanford (Nickola, 1970) trials. The Hanford trials also provided data for instantaneous neutrally-buoyant releases.

Three more datasets for dense gas releases were identified but not used in the MDA: Porton Down, Eagle and Falcon. Porton Down was omitted due to the measurements being in the form of dosage rather than concentration. Eagle and Falcon were not used because of the complicated test conditions, which involved obstructions. Further details about these trials are given in Section 6.5.

The datasets were used to evaluate 14 gas dispersion models (Britten and McQuaid, SLAB, HEDADAS, CHARM, PHAST, Gaussian Plume model (GPM), AFTOX, DEGADIS, INPUFF, OB/DG, AIRTOX, FOCUS, GASTAR, PHAST, TRACE) with performance assessed using SPMs and residual plots (see Hanna et al., 1993a, b).

Over the last 30 years, the MDA has been periodically updated. Chang and Hanna (2010) reported that at that time (ten years ago) it contained 50 datasets.

6.3.2 REDIPHEM

A validation database for dense gas models was constructed during the 'REview and Dissemination of PHysical Effect Models' (REDIPHEM) project (1992 – 1995), which was funded by the European Commission. It is a valuable resource for the evaluation of dense gas dispersion models, comprising measurements from a significant number of field trials and wind tunnel experiments. A complete description of the database can be found in Nielsen and Ott (1996a), including useful illustrations of test and source configurations for most of the trials. The database is freely available from the Risø National Laboratory, Denmark.

The REDIPHEM data base contains 14 projects. These are labelled as: BMT Edon Liddard Vince LTD (Piper Alpha, UK), Burro (LNG, China Lake, US), Burro version 2 (as amended by HSE), Coyote (LNG, China Lake, US), Eagle (N₂O₄, Nevada, US), ETH¹⁵⁷ Zürich (various tests, wind tunnel), FLADIS¹⁵⁸ (NH₃, Landskrona, Denmark), Hamburg (SF₆, wind tunnel),

¹⁵⁷ Eidgenössische Technische Hochschule (ETH) Zürich, or in English, Swiss Federal Institute of Technology in Zürich

¹⁵⁸ The full name of FLADIS is "Research on the dispersion of two-phase flashing releases"

Lathen (C₃H₈, Denmark), HSE (Freon, Thorney Island), TNO (SF₆, Apeldoorn, Netherlands), Desert Tortoise (NH₃, Nevada, US), Warren Springs Laboratory (various tests, Stevenage, UK), Warren Springs Laboratory (reduced data set). All of these trials are described individually in Section 6.5.

Experimental details including release and atmospheric conditions, sensor positions, and time-series of measured parameters are provided in the database. The time series are typically at 1 s intervals for the field trials. These time-series can be visualized, processed and exported using the REDIPHEM data browser.

Most of these datasets are included in the more recent LNG model validation database (Stewart et al. 2016) described in Section 6.3.4.

6.3.3 SMEDIS

The European Scientific Model Evaluation of dense gas DISpersion models (SMEDIS) project was set up to develop and test a framework for the scientific evaluation of models for dense gas dispersion in complex situations. In particular, in the presence of obstacles, terrain and aerosols.

The work included a review of 41 experimental datasets suitable for model validation. The datasets that were considered suitable for model validation in the SMEDIS project were: Prairie Grass, Desert Tortoise, FLADIS, BA-Propane, BA-Hamburg, BA-TNO, Thorney Island and EMU-Enflo, most of which can also be found in the REDIPHEM database and are described individually in Section 6.5. The review highlighted that there was limited experimental data for scenarios featuring complex effects on dense gas dispersion at that time. A description of the experimental database and the validation exercise can be found in Carissimo et al. (2001).

There were about 28 models evaluated as part of the study.

6.3.4 LNG model validation database

The LNG model validation database was compiled by HSE for the US Fire Protection Research Foundation (FPRF) to provide a single repository of data to evaluate gas dispersion models for safety analysis of LNG facilities. It includes five field scale experiments, four with LNG (Maplin Sands, Burro, Coyote and Falcon) and one with Freon (Thorney Island). In addition to this, it includes three wind-tunnel experiments: the CO₂ experiments at the Chemical Hazards Research Centre (Arkansas University) and SF₆ BA-Hamburg and BA-TNO experiments. In total, 33 trials were selected including both obstructed and unobstructed tests, and some with topography. Wind tunnel measurements are provided at both wind-tunnel scale and equivalent full-scale.

The database produced by HSE was designed to facilitate model evaluation. Model output data can be input into the spreadsheet, which automatically calculates Statistical Performance Measures (SPMs). Model predictions are compared to experimental data using point-wise concentrations, maximum arc-wise concentrations, cloud widths, predicted distances to the measured maximum arc-wise concentrations, distances to LFL concentration and predicted concentration at the measured distance to LFL. The database provides a collection of scatter plots showing measured against predicted arc-wise gas concentration.

A guide to the database can be found in Stewart et al. (2016) and further information is available in the associated report (Ivings et al. 2016). These documents are updates of the original database (Coldrick et al., 2010) and associated report (Ivings et al., 2007). An audit trail of the revisions between the versions can be found in the latest report (Ivings et al.,

2016). The database itself is currently Version 12 and is available free of charge from the FPRF¹⁵⁹ in a Microsoft Excel 2010 spreadsheet or as plain ASCII text.

The LNG model validation database is used by the US Pipelines and Hazardous Materials Safety Administration to approve models for use in LNG facility siting studies. Examples of the submissions for approval of FLACS and Phast can be found on the regulations.gov website¹⁶⁰.

6.4 Existing experimental reviews

Reviews of dense gas dispersion datasets were undertaken by Hanna et al. (1993), Nielsen and Ott (1996), Carissimo et al. (2001) and Stewart et al. (2016) when compiling the above databases. Therefore, these works provide good sources of information on the trials they cover and notes on topics such as uncertainties for model validation purposes. The following are a collection of additional review documents intended to cover additional experiments not found in the above.

6.4.1 Bouet (1999)

Bouet (1999) produced a review of ammonia releases undertaken by INERIS with the objective of providing information on safety parameters such as hazard distances. The work includes details about the characteristics of ammonia releases and dispersion, and a summary of experimental trials on ammonia. The following trials are included: Resplandy, Desert Tortoise, University van Kunstmest Fabrieken, Ecoles des Mines d'Ales, Imperial Chemicals, FLADIS and Landskrona. Individual details of several of these studies are provided in Section 6.5.

Large-scale work undertaken by INERIS as part of the study is also reported.

The report includes discussion aimed at identifying whether datasets are suitable for use in model validation exercises and some validation of the model Phast version 4.2 is presented.

6.4.2 Cleaver et al. (2006)

Cleaver et al. (2006) produced a summary of the experimental tests on LNG releases undertaken by Advantica (and previously British Gas Research) over the last 30 or so years, including those on dense gas dispersion. The review includes both instantaneous and continuous releases of LNG. Most of the results are not publicly available. The objective of the review was to complement the review of publically-available information by Luketa-Hanlin (2006).

The review covers a wide scope including data available for LNG outflow, liquid spread and boil-off, dense gas dispersion, pressurised releases, LNG pool fires, LNG vapour cloud explosions, rapid phase transitions and rollover. Modelling issues associated with these topics are discussed.

6.4.3 Ermak et al. (1988)

Ermak et al. (1988) produced a collection of 26 benchmark field experiments selected from Burro, Coyote, Eagle, Desert Tortoise, Maplin Sands and Thorney Island. The experiments were reviewed and specifically chosen for their use in model validation. Only continuous releases were selected, as they were considered to better represent typical accidental releases from a storage vessel or transport vehicle.

¹⁵⁹ <https://www.nfpa.org/News-and-Research/Data-research-and-tools/Hazardous-Materials/LNG-model-evaluation-protocol-and-validation-database-update> Accessed on 2nd September 2020

¹⁶⁰ <https://beta.regulations.gov/document/PHMSA-2011-0101-0005> and <https://beta.regulations.gov/docket/PHMSA-2011-0075> Accessed on 5th January 2021.

This work presents input data that would be required by models to simulate the experiments along with measured concentrations and cloud parameters for comparison with model predictions.

6.4.4 Havens (1992)

Havens (1992) produced a summary of field experiments on dense gas dispersion. Datasets included were Burro, Coyote, Maplin Sands, Thorney Island, Desert Tortoise, Goldfish and Eagle (31 tests in total). The objective was to review the test programmes, identify gaps in the knowledge at that time and make recommendations for further studies. The review was accompanied by a discussion of the suitability of the tests for model evaluation purposes, using DEGADIS as the example model.

Havens provided comments on uncertainties in the tests that complicate their use for model validation. He suggests that a set of experimental trials should be designed to provide dispersion data in ideal conditions, with no aerosol complications and accurately determined source conditions. They should be conducted on flat terrain with no obstacles and low surface roughness and should include a range of release rates and wind speeds in order to span a range of Richardson numbers (Ri based on release conditions, see Spicer and Havens, 1989, and Havens and Spicer, 1990).

Havens also proposed that much could be learnt from well controlled laboratory or wind tunnel experiments on dense gas dispersion in terrain and under the influence of obstacles. Field scale experiments could then be used primarily for demonstration purposes since they cannot be as well controlled for providing suitable datasets for numerical model evaluation when terrain or obstacles are present.

6.4.5 Lees' Loss Prevention in the Process Industries

The Lees Loss Prevention in the Process Industries book (Mannan, 2012) discusses experiments involving dense gas dispersion. Chapter 15 contains summaries of the following dense gas dispersion experiments: Bureau of mines, Esso/API, Gaz de France, Gadila, Dutch Freon (Van Ulden), AGA/Batelle, Porton down, China lake, Avocet, Burro, Coyote, Maplin Sands, Thorney Island, Desert tortoise, Eagle, Goldfish, Hawk (ICHMAP).

6.4.6 Lines et al. (2000)

Lines et al. (2000) provided a summary of low wind speed trials with and without obstructions. The objective was to identify experiments that could be used for model validation.

The main criteria for defining a test as low wind speed is a wind speed of 2.4 m/s or lower. The field experiments included were Lathen, Burro, Porton Down, Thorney Island, FLADIS, Maplin Sands and EnFlo wind tunnel experiment. Useful tables of parameters for relevant tests from each trial were presented. Three models: HGSYSTSTEM, GASTAR and DRIFT, were compared to the experiments.

Lines et al. suggested that more effort should be made to obtain measurements from experiments of integral plume parameters, such as the width and height, since these are a common feature of model output. They highlighted the lack of data in very low wind conditions. Most of the datasets they extracted for their validation study were in the range 1.5 – 2.5 m/s, with only two tests at wind speeds lower than 1.5 m/s. They noted that wind tunnel models cannot easily fill this gap because the scales were not practicable for wind tunnel operation.

6.4.7 Luketa-Hanlin (2006)

Luketa-Hanlin (2006) reviewed information in the public domain relating to vapour dispersion from unconfined LNG releases onto water, LNG pool fires and vapour cloud fires, and LNG

deflagration and detonation experiments. The datasets included those from the Esso, Shell, Maplin Sands, Burro and Falcon trials.

The work was motivated by the need to predict possible hazards resulting from the storage and transportation of LNG by ship. In terms of LNG vapour dispersion, the focus was on pool and cloud sizes and distances to the LFL.

The review included a discussion of the state of current knowledge and recommendations for future work. One of the difficulties mentioned was in undertaking experiments at the scales required to simulate a real hazard. Spill volumes from a single ship's tank are on the order of 10,000 m³. Smaller-scale field trials were recommended combined with complementary studies with numerical models. Luketa-Hanlin noted that spills of approximately 100 m³ - 200 m³ were feasible at current test sites and would help with understanding scale effects.

Luketa-Hanlin also noted that there was very limited experimental data of any scale on the effects of waves and currents on substances spilled on the water surface, and limited experimental data or model predictions of spills from breaches of ship's tanks above and below the water surface. It was suggested that underwater releases could result in more buoyant clouds than releases onto the water surface.

6.4.8 Prince (1983) and Thyer (2003)

The two reviews by Prince (1983) and Thyer (2003) provide a fairly comprehensive summary of datasets on pressure-liquefied and cryogenic liquid spills. Thyer (2003) in particular focusses on the availability of datasets on spreading and vaporisation rates from such spills and their suitability for use in evaluating models. These reviews are primarily aimed at source models, not dispersion models but they provide a useful body of references.

6.4.9 Liddament and Allen (1983)

The work by Liddament and Allen (1983) was undertaken as part of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme. The objective of the study was to assess the performance of models used to calculate hourly mean rates of air infiltration and fresh air exchange in buildings.

The study also included a review of suitable validation datasets for air infiltration. There were 14 experimental datasets identified, which comprise dwellings in Canada, Netherlands, UK, Switzerland and US. They identify three of these datasets as particularly suitable for model validation: Maugwil (Switzerland), Mark XI test house (Canada) and Runcorn (UK). These are summarised in the following section.

6.5 Individual experiments

This section lists several dense gas trials. For each trial a summary is provided with salient information and references where further details can be obtained. The trials are listed in alphabetical order.

6.5.1 AGA

In the early 1970's, the American Gas Association (AGA) sponsored a set of 42 LNG release trials, in which up to 51 m³ of LNG was released into bunds up to 24 m in diameter at the TRW Capistrano Test Site in San Clemente, California. The work was undertaken by Battelle Columbus Laboratories and detailed information can be found in AGA (1974).

The area of the site used for the trials was flat with a mainly silt-clay substrate over an area approximately 200 m long and 90 m wide. Of the 42 trials, 28 were aimed at measuring dispersion and 14 were ignited. 17 of the dispersion trials were in a 2 m bund, nine were within a 6 m bund and two within a 24 m bund. The bund height was also varied. The

bunded area was filled to approximately 0.15 m deep, which took 20-30 s and so the trials were approximately instantaneous.

Methane concentrations and temperatures were measured at up to 36 locations in up to four straight lines parallel to a line through the centre of the release, which was perpendicular to the typical wind direction. Sensors were placed at up to five heights. The data also provided measurements of pool spreading rates and vaporisation rates. The depth of the pool was monitored and thermocouples placed in the ground measured substrate temperatures at various depths.

The AGA trials also used a number of identical substrates to those of Drake and Reid (1975) and Reid (1980), who examined vaporisation rates for LNG spilled on a range of dike floor materials including concrete, soils and sand in dry and wet conditions.

Mannan (2012) suggested that the quality of the trials may be unreliable due to a tendency for the LNG to spill outside of the bund. However, trials T40 and T44 were considered of suitable quality for use in the recent model evaluation study of ANSYS Fluent by Eberwein et al. (2020).

6.5.2 API / Esso

A series of 17 unconfined spills of LNG onto water were undertaken by Esso Research and Engineering Company at Matagorda Bay, Texas in 1971. Details can be found in the report by Feldbauer et al. (1972). The objective of the work was to measure downwind concentrations and determine the distance required to dilute the cloud to concentrations below the LFL.

The spill volumes were in the range of 0.95 m³ to 9.5 m³. Nitrogen under pressure was used to force the LNG out of the storage tank. This method was used to fix the release rate at 320 l/s. LNG was discharged through a nozzle of 0.18 m diameter at a height of 7.5 m above the water surface and directed 30° upwards. This resulted in a discharge velocity of about 13 m/s.

Hydrocarbon sensors were used to measure the concentrations downwind and calculate the maximum distance to LFL. In some cases the cloud exceeded the sensor array so the distance to LFL could not be calculated from the measurements, but a visible fog could be observed. The longest distance to the last visible fog from the spill site was 1,372 m for a spill size 8.37 m³ and wind speed of 4 m/s. Meteorological data and the bulk water temperature were recorded.

This dataset has been used for model evaluation of both source term models (Webber et al. 2010) and dispersion models (e.g. Havens, 1982).

6.5.3 Atkinson and Coldrick (2012)

A series of 14 large-scale field experiments of hexane releases were sponsored and undertaken by HSE following the Buncefield Incident (Atkinson and Coldrick, 2012).

The objective was to determine the character of a vapour cloud resulting from overfilling of an atmospheric storage tank with a volatile liquid.

The experiments were designed to represent a short section of storage tank wall, with a cascade of hexane released from the top to simulate overfilling. Flow rates were between 7 and 21 kg/s. The width of the release (at the tank rim) was 1.5 m and the release height was 10 m. The cascades were approximately 0.35 – 0.4 m wide. The experiments captured the initial liquid discharge and fragmentation and the development of a liquid cascade. The impact zone, where the cascade touches down, the subsequent splash evaporation zone and near-field dispersion were also investigated.

Temperature measurements of the vapour cloud were obtained out to a distance of about 16 m from the tank wall. A large amount of video footage was obtained, but there were no far-field dispersion measurements. In addition to hexane, several water and decene releases were also undertaken. Decene has similar properties to hexane but without the risk of a large explosion or fire, so that measurement equipment could be placed closer to the cascade to observe the liquid fragmentation process more closely.

The programme of CFD modelling work was undertaken to complement and aid understanding of the experimental test series.

6.5.4 Avocet

Avocet was a series of 5 m³ LNG spill tests undertaken by Lawrence Livermore National Laboratory (LLNL) that preceded the Burro trials. Details of these trials can be found in the report by Koopman et al. (1979). The objective of the tests was to provide information about the measurement systems used in the larger Burro tests. The data includes dispersion measurements. The Avocet trials were also reproduced in the wind tunnel modelling study of Meroney and Neff (1982).

6.5.5 BA Hamburg wind tunnel

The BA Hamburg wind tunnel experiments were undertaken in an open circuit wind tunnel at the Meteorological Institute at the University of Hamburg, Germany as part of the CEC Major Technical Hazards Research Programme Project BA: Research on Continuous and Instantaneous Heavy Gas Clouds (Davies, 1992). Details of BA Hamburg can be found in the work of Schatzmann et al. (1991), Konig-Langlo and Schatzmann (1991) and Marotzke (1993).

Sulfur Hexafluoride (SF₆) gas was released at room temperature through a perforated circular plate about 0.07 m in diameter mounted flush with the tunnel floor.

The University of Hamburg wind tunnel was 16 m long with an inlet nozzle and flow straighteners, a 7.5 m long establishment section and a centrifugal fan. The test section was 4 m long, 1.5 m wide and 1 m high. In the establishment section, 0.02 m high lego blocks acted as roughness elements to establish a turbulent boundary layer profile. In the test section, the floor of the tunnel was smooth, which meant a new boundary layer profile developed in the test section. This was well described by a power law profile.

Gas concentration measurements were made at floor level. All of the dense gas releases were continuous and of long enough duration to obtain stable statistics.

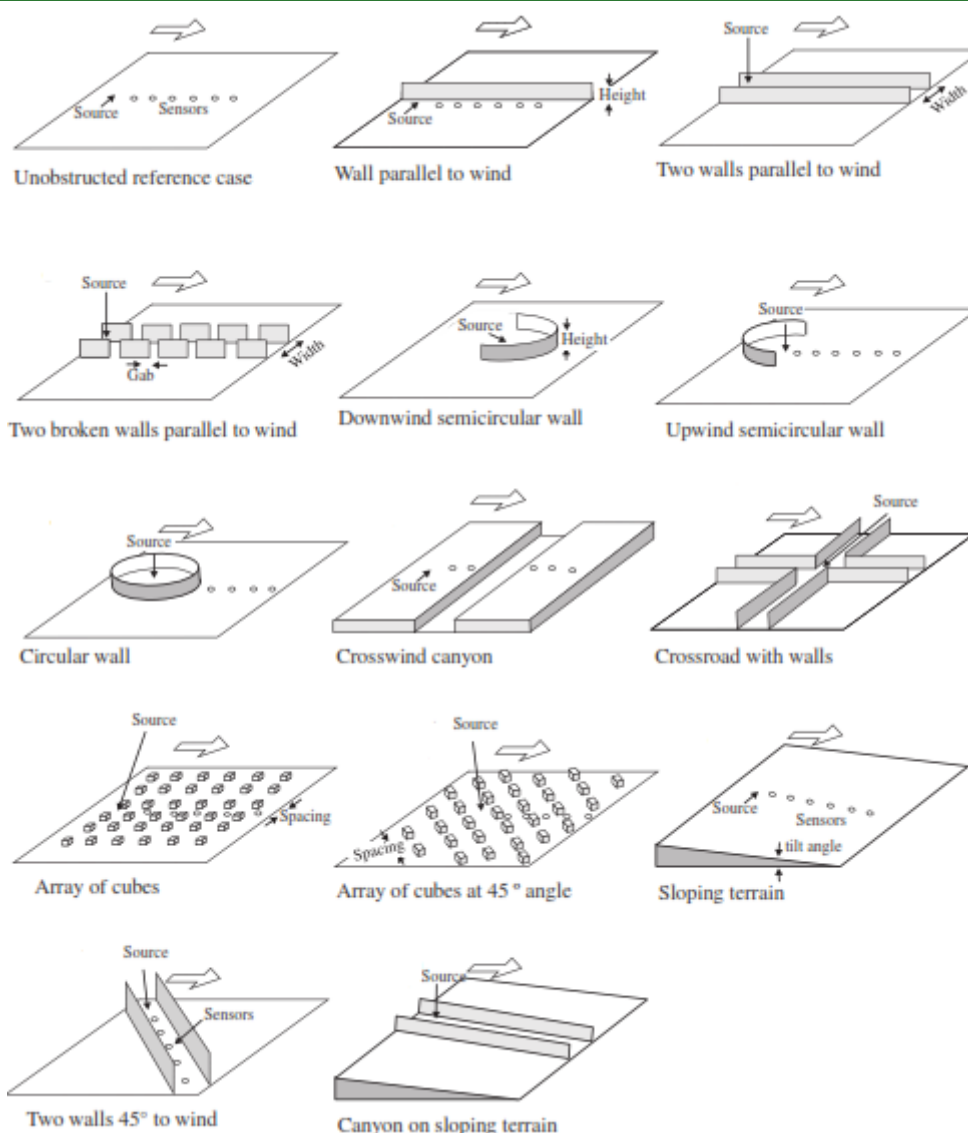


Figure 41 Different test configurations in the BA Hamburg wind tunnel trials (from Nielsen and Ott, 1996a, © Risø copyright 1996)

An illustration of the various configurations tested is shown in Figure 41. The trials included several tests under nil wind conditions, and some with slope gradients of 4 – 11%. There were several fence arrangements tested, including some with circular or semi-circular shape centred around the release point. The semi-circular fences were either upwind or downwind of the source and symmetrical across the along-wind axis passing through the source centreline. The fence height was 0.0301 m and the radius was either 0.1915 m or 0.3064 m from the source centre (Stewart et al., 2016 note that Nielsen and Ott, 1996a, incorrectly list the fence radius as the fence diameter but the correct configuration is described in Schatzmann et al., 1991, and Marotzke, 1993). The experiments were at a scale of 1:164, which equated to an equivalent field-scale fence height of 5 m.

The wind tunnel model was validated with comparisons to the TNO tunnel and the WSL wind tunnel. Discussion of variability between the tunnels in this exercise can be found in Hall et al. (1990).

The dataset was reviewed and included in the REDIPHEN database, SMEDIS and the LNG model validation database. Stewart et al. (2016) note there is small uncertainty related to the temperatures and gas density due to conflicting values given in different data sources.

However, these are relatively minor and should be easily assessed with model sensitivity analysis. There is another slight uncertainty in the transition from rough to smooth floor between the establishment and test sections. This is discussed by Hall et al. (1990) and with some models this could also be assessed with a sensitivity analysis. Overall, it is considered a good quality dataset for model validation purposes.

6.5.6 BA Propane

See Lathen.

6.5.7 BA TNO wind tunnel

The BA TNO wind tunnel experiments were undertaken in the TNO 'Pollution Industrial Aerodynamics' wind tunnel facility and formed part of the CEC Major Technical Hazards Research Programme Project BA: Research on Continuous and Instantaneous Heavy Gas Clouds (Davies, 1992). Details of BA TNO can be found in the works of Van Oort and Builtjes (1991) and Nielsen and Ott (1996a).

The tunnel created initial velocity and turbulence profiles equivalent to atmospheric profiles at scales 1:100 to 1:500. There was a 10 m establishment section to stabilise the boundary layer, within which the floor was covered with a 'smooth carpet' to achieve the required roughness length. The following test section was 6.8 m long, 2.65 m wide and 1.2 m high and was also covered by the carpet so that the boundary layer flow did not change and remained in equilibrium. This simulated a surface layer with a logarithmic velocity profile over a height of about 0.6 m to 0.8 m. The floor of the wind tunnel was horizontal.

Some of the tests were designed to represent a 1:78 scale model of the EEC57 field-scale experiment (part of Lathen) that was undertaken to investigate the influence of a straight fence perpendicular to the wind direction. The fence was located 1000 mm downwind of the source (48 m at field-scale). It had length of 640 mm (50 m long at field-scale) and the height was varied. There were identical cases with no fence present.

Sulfur Hexafluoride (SF₆) gas was released at room temperature through a source of diameter 140 mm. Gas concentrations were measured at floor level and the velocity profile was measured and is provided with the dataset. In one test, a three dimensional concentration field was produced to provide a reference for digital image processing of video of the light scatter from a laser sheet highlighting sections of the plume. This latter test was not included in the REDIPHEM database.

The wind tunnel model was validated with comparisons to the University of Hamburg tunnel and the WSL wind tunnel. Discussion of variability between the tunnels in this exercise can be found in Hall et al. (1990).

The dataset was reviewed and included in the REDIPHEM database, SMEDIS and the LNG model validation database. Overall, it is considered a good quality dataset for model validation purposes.

6.5.8 BMT

In the 1990's, a set of wind tunnel trials were undertaken by BMT Edon Liddard Vince LTD for DNV to contribute towards the SMEDIS project and the REDIPHEM database. Details can be found in the paper by Davies (1999). The objective of the study was to provide near-field gas dispersion measurements of a release affected by flow around obstructions, relevant to dense gas releases in an offshore module. The work was motivated by the Piper Alpha incident in the North Sea in July 1988 and included a replica scale model of the platform and modules. BMT undertook two studies, the first provided data to the Piper Alpha inquiry and involved a replica of the C-module at 1:33 scale. The second study produced additional data using the same set up.

Six releases were processed for entry into the REDIPHEM database, five with dense gas and one neutrally buoyant release for three release geometry variations. The releases were designed to be representative of leaks from pipelines in the form of a circumferential or fan release; a jet or circular hole and; a part circumferential release. The dense gas was a mixture of argon and Freon released at a rate of 50-200 kg/min (full scale). The duration of release was about 50 s. The ventilation rate was $7.4 \times 10^{-3} \text{ m}^3/\text{s}$.

Concentration measurements were made at between 24-65 points within the module, depending on the test. Repeat releases were performed for reliability checks and to ensure adequate sensor coverage. Measurements of velocity and turbulence intensity were made upwind of the release point to provide input data for computational models.

Several tests were detailed enough to provide concentration information suitable for model comparison exercises. For example, FLACS has been compared with the dataset. Data files contain coordinate information of the sensor locations and time histories of concentration.

6.5.9 Bureau of Mines

In the early 1970's, the US Bureau of Mines undertook a set of six field trials of LNG spilled onto water (Burgess et al., 1972). Up to 0.6 m^3 of LNG was spilled onto water in a test pond of 70 m diameter and 8 m deep in confined and unconfined tests. The main objective of the trials was to provide source term information, in particular vaporisation rates. Variables associated with gas dispersion were not measured.

There was also a previous set of smaller trials of spills into an aquarium of dimensions 2 ft x 1 ft x 1 ft (Burgess et al., 1970). In those trials, ice formed on the water surface after approximately 20 seconds. No ice formed in the larger scale trials.

6.5.10 Burro

The Burro field trials involved LNG spills of between 24 m^3 and 39 m^3 spilled onto water. The work was undertaken by Lawrence Livermore National Laboratory (LLNL) at the Naval Weapons Centre (NWC), China Lake, California. Details can be found in the works of Koopman et al. (1982a,b) and Ermak et al. (1989). An image from the Burro 8 trial after 80 s can be seen in Figure 42.

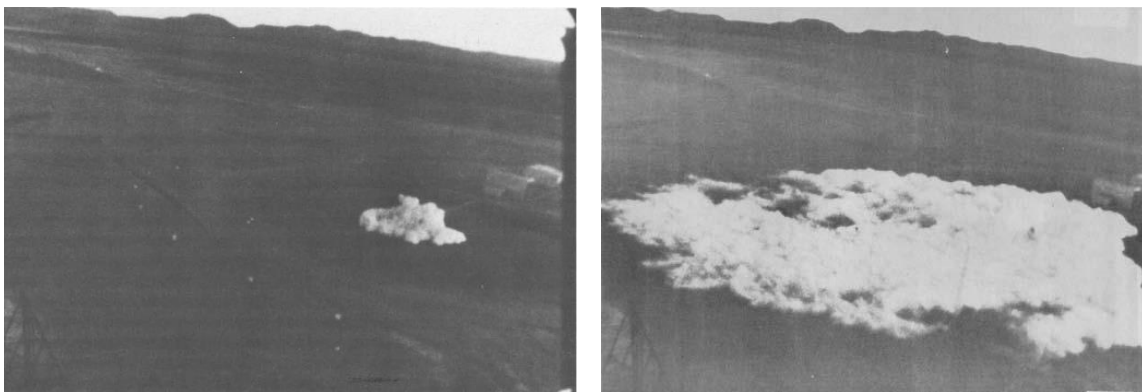


Figure 42 Aerial photograph of the pume from the Burro 8 trial (a) 2 s and (b) 30 s after release (Ermak et al. 1982)

Quasi-continuous spills of LNG were released from 0.25 m diameter downward orientated release pipe 1 m above the surface of a water basin. There was a splash plate just underneath the water surface below the release point to spread the released liquid horizontally. The spill tank was pressurised with nitrogen gas.

The water test basin had an average diameter of 58 m and the water depth was approximately 1 m. The water surface was approximately 1.5 m below the surrounding

ground level. Downwind of the release basin, the terrain sloped upwards at about 7 degrees for 80 m before levelling out to about 1 degree.

Measurement stations were fitted with gas and temperature sensors arranged in arcs from 57 m to 800 m at heights of 1 m, 3 m, and 8 m.

Upwind and downwind meteorological information was recorded. There were five tests in Pasquill Class C conditions with average wind speeds varying from 5.4 to 9.1 m/s, one test in Class D conditions with an average wind speed of 5.7 m/s and one in Class E with an average wind speed of 1.8 m/s.

There is some uncertainty in the source conditions for these tests and Stewart et al. (2016) recommended that modelling studies include sensitivity tests. FERC (2010) suggested that a common source of uncertainty in all Burro (and Coyote) tests is the surface roughness and the potential influence of terrain. In Burro 8, the composition of the LNG and the consequent effect on the molecular weight was noted as another source of uncertainty. Burro 8 is one of the few experimental trials that was carried out in low wind speeds and with potential terrain effects.

The Burro trials have been extensively used in model validation studies. They are included in the MDA, REDIPHEN and the LNG model validation database. The Hanna et al. (1993a) review noted that eight Burro trials are suitable for dispersion model validation.

6.5.11 CHRC wind tunnel

In the mid-2000's, the Chemical Hazards Research Center (CHRC) at the University of Arkansas, USA, undertook a series of wind tunnel experiments on the dispersion of carbon dioxide (CO₂), with and without obstacles. Details can be found in the papers of Havens and Spicer (2005, 2006) and Havens et al. (2007).

The tests were designed to study obstructed and unobstructed dense gas dispersion and to provide validation data for the FEM3A dispersion model. The obstructions included a tank and dike.

The working area of the wind tunnel was 2.1 m high, 6.1 m wide and 24.4 m long. The floor was covered in smooth rubber matting mounted with roughness elements. The scale of the tank and dike was 150:1. The dike was square with an inner dimension of 0.63 m and height 0.037 m. The tank had diameter 0.31 m with a hemispherical dome top and an overall height of 0.283 m. The tank was positioned in the centre of the dike on top of a mesh covering through which the gas was released. In all three tests, the area through which the gas was released was 0.3341 m² (the tank footprint was blocked off in all releases, even when the tank was absent). CO₂ was released at ambient temperature and at 33.4 l/min with 0.5 l/min of propane as a tracer.

Gas concentration measurements were made at a height of 0.005 m, which was as close to the floor as practicable, at intervals of 0.1 m across the cloud. Measurements of the mean velocity profile within the wind tunnel are available.

The results were not perfectly symmetrical about the centreline of the wind tunnel which was suggested by Havens and Spicer (2006) to result from a slight slope on the wind tunnel floor. The floor was level to within 1/100 inch. The results were also affected by the roughness elements. Stewart et al. (2016) discuss a number of modelling issues for these trials. The three CHRC trials were included in the LNG model validation database.

6.5.12 China Lake wind tunnel

The China Lake wind tunnel experiments were undertaken by the Gas Research Institute and Department of Energy. Details can be found in the paper by Neff and Meroney (1981). The objective was to reproduce Burro field scale trials undertaken at the China Lake test site

in the wind tunnel, in order to determine the reliability of wind tunnel modelling of large scale spills.

In the field trials 40 m³ of LNG was spilled. The wind tunnel model was constructed as a 1:240 or 1:85 scale of the China Lake Naval Weapons Center site. Burro trials 4, 5, 7, 8 and 9 were modelled in the tunnel. The tunnel was set up with vortex generators at the entrance followed by a 10 m smooth section and a 3 m approach ramp to the scaled topography of the China Lake site. The test section was 17.4 m long, 3.7 m wide and about 2.1 m high, with an adjustable ceiling. The measurements included wind profile and turbulence measurements and transient concentration data at downwind positions similar to those in the field tests.

The source was a circular area source in the centre of the scaled 'spill pool'. Argon and Freon-12 were used to simulate the dense gas effects from LNG. Tabulated summaries of both model and field-scale release conditions can be found in Neff and Meroney (1981, Tables 1 and 2) along with graphs and tables of results.

Another series of trials were undertaken in the same wind tunnel to model the Avocet 5 m³ LNG spills. Details can be found in Meroney and Neff (1982). The objective of the study was to supplement the field dataset and extend the value of the limited field-scale measurements. In these trials 1:85 and 1:170 scale models of the China Lake test site topography were used. The source gas was again released through an area source centred on the spill pool. Wind profiles, turbulence and concentration measurements were made.

6.5.13 COOLTRANS

COOLTRANS was a large research programme on CO₂ pipeline transportation led by National Grid over the period 2011-2014 (Barnett and Cooper, 2014). The project included a series of experiments involving releases of CO₂ at the DNVGL Spadeadam test site in Cumbria, UK. Details can be found in the papers of Allason et al. (2012) and Cleaver et al. (2016).

Pipeline releases

The objectives of the tests were to investigate the behaviour of releases of CO₂ and CO₂-mixtures in the gaseous and liquid phases from below-ground pipelines that are ruptured or punctured, and from venting operations. The measurement data was intended to provide a high quality dataset for model development and validation.

Burst tests on buried pressurised pipeline sections were carried out. Measurements were taken of the resulting craters and concentrations in the dispersing clouds. Shock tube experiments were also carried out to understand the decompression behaviour of carbon dioxide (Cosham et al., 2012). These tests used a 144 m long, 150 mm diameter pipe, approximately 600 mm above ground level, that was opened at one end to initiate an short-duration, full bore release of CO₂. The pressure and temperature along the pipe were monitored during depressurisation. Further instrumentation was positioned downstream of the exit orifice to collect dispersion data.

The Spadeadam test site was mostly flat with some obstructions and slopes. In some tests, an elongated mound was specially constructed in front of and perpendicular to the outflow to investigate the effects of an obstruction on the flow. In other tests an area of sloping terrain was constructed to one side of the plume centreline.

A full-scale instrumented pipeline-fracture propagation test was undertaken that included gas dispersion measurements. The uncertain source and transient nature of this release make it difficult for model validation.

A series of idealised venting experiments were undertaken. A flow delivery system was designed specifically to provide approximately steady release conditions from a vent

connected by a short length of pipe to a vessel that directed the release vertically upwards. Dispersion measurements were made around the release and downwind at ground level.

Another series of tests involved releasing gas from an isolated section of pipeline through a horizontal vent in order to measure the conditions within the isolated section as the system slowly depressurised.

Seven puncture experiments were carried out for a section of pipeline buried approximately 1.2 m below the ground to simulate a typical transportation pipeline. The test section was a pipe of 914 mm outside diameter supplied with CO₂ under approximately steady conditions. The pipe was backfilled so that the released gas produced its own crater. In one test, a pre-formed crater was used, to allow dispersion measurements to be taken in the near-field. In these puncture experiments, the outflow of gas was continued for long enough so that an approximately steady dispersing plume formed. The plume was videoed and concentration measurements were made at ground level around the release location and downwind of the release.

In all cases, there was no rainout of solid CO₂ from airborne clouds. The presence of solid CO₂ was noted only in small quantities and appears to arise from impinging releases.

In tests with low wind speed conditions, a blanket of cloud was observed to form over the source, which influenced the extent of the upwind and crosswind spread.

Experimental measurements have been compared with “more pragmatic” CFD models according to Cleaver et al. (2016). The work also resulted in a model evaluation protocol for dense phase carbon dioxide (Gant, 2012) but the final report is not currently publicly available.

Gas ingress into enclosures

As part of the COOLTRANS project, there was a set of tests on CO₂ ingress into buildings (Cleaver et al., 2016). There were some initial tests with enclosures during one of the above experiments of a CO₂ pipeline rupture and during the fracture propagation testing. In the former, the enclosure had two deliberate openings, one in the front and one in the back face. The effective ventilation rate of the enclosure was more than would be expected for a conventional domestic building at about 20 ACH with a wind speed of 5 m/s. The size of the deliberate openings relative to the volume of the enclosure were not typical of all domestic buildings.

The measurements made during the fracture propagation testing were for an enclosure with an air change rate of 250 ACH in 5 m/s wind speeds, i.e. much higher than would be expected for a typical domestic property. The temporary enclosure was placed in the path of the gas cloud. The measurements showed similar trends to the case with 20 ACH.

After these initial tests, additional tests were undertaken to specifically investigate gas accumulation in enclosures. The CO₂ was released from a horizontal pipe 0.5 m above ground level with the final section of pipe at the orifice angled downwards 45°. The release diameter was varied between 5 mm and 40 mm, resulting in flow rates from 0.5 kg/s to 29 kg/s with different release durations.

To simulate part of a two storey building, two bulk containers, one on top of the other, were located 15.3 m from the release point. This position was chosen in order to achieve external concentrations between 2% and 20% CO₂, to cover concentrations outside the enclosure that were potentially debilitating or lethal. Each container had two deliberate openings, one on the largest face, perpendicular to the release and one on the smaller face on the side, as shown in Figure 43.

There were three opening widths used: 25 mm, 50 mm and 150 mm, to generate different ventilation rates similar to a domestic property under typical conditions. These were

designed to give a volume flow rate similar to that which would be experienced throughout the whole of a property. Despite this, the air change rates per unit time were still larger than expected for a typical domestic property because the size of the enclosures was small.

The dataset resulting from the experiments was shown to be self-consistent and suitable for model evaluation. At least one test (number 9) was undertaken in low wind speed conditions.



Figure 43 Containers used as a model two-storey enclosure in Cleaver et al. (2016). Openings can be observed on the front and sides of both floors (© IChemE copyright 2016)

6.5.14 Coyote

The Coyote field experiments involved quasi-continuous spills of LNG and liquid methane (LCH_4) onto water undertaken by LLNL at the Naval Weapons Centre (NWC), China Lake, California. Details can be found in the works of Goldwire et al. (1983a), Morgan et al. (1984) and Ermak et al. (1989).

The test series comprised five vapour dispersion and burning experiments and five experiments on Rapid Phase Transition (RPT), which were features observed in the Burro tests. The spill volumes were between 3.3 and 28 m³.

The experimental test setup was similar to the Burro tests, but with more sensors concentrated within 400 m of the source.

As for Burro, there is some uncertainty in the source conditions and Stewart et al. (2016) recommended modelling studies to include sensitivity tests. As mentioned previously, FERC (2010) suggested that a common source of uncertainty in all Burro and Coyote tests is the surface roughness. The composition of the LNG and the consequent effect on the molecular weight also represent another source of uncertainty in the Coyote trials.

The Coyote trials are frequently used in model validation studies for LNG modelling applications. They are included in the MDA, REDIPHEN, SMEDIS and the LNG model validation database. Hanna et al. (1993a) identified 4 Coyote trials as being suitable for dispersion model validation.

6.5.15 Desert Tortoise

Desert Tortoise involved a series of four ammonia dispersion tests conducted at Frenchman Flat, Nevada in the summer of 1983 by LLNL. A detailed description can be found in the report by Goldwire et al. (1983b). The objective of the tests was to study the dispersion of ammonia gas resulting from releases of pressure-liquefied ammonia.

Frenchman Flat is a very flat, (normally) dry lake bed, or playa, with little vegetation.

Between 10,000 kg and 41,000 kg of pressure-liquefied ammonia was released quasi-continuously from a pipe pointing downwind at a height above the ground of 0.79 m. The first test was performed with a 81 mm diameter discharge pipe and the three others were made with a 94.5 mm diameter pipe. This resulted in release rates of about 81 kg/s – 133 kg/s.

As the liquid jet exited the pipe, it flashed and its pressure decreased so that approximately 18% of the liquid changed phase to become a gas. The other 82% remained as a jet of liquid ammonia which was aerosolised by the turbulence in the jet. Little or no liquid was observed to form a pool on the ground. The dispersion of the resulting gas-aerosol cloud near to the release point was dominated by the dynamics of the turbulent jet. Downwind of the jet region, the dynamics of dense gas dispersion dominated and the cloud slumped and spread horizontally.

Concentration measurements were taken at heights of 1 m, 2.5 m and 6 m at seven points along an arc located 100 m downwind of the source. Hanna et al. (1993a) pointed out that in most cases the plume was below the 6 m measurement height and remained within the lateral measurement array. Further measurements were made at heights of 1 m, 3.5 m and 8.5 m at five locations 800 m from the source. There were also two arcs of up to eight portable ground level stations which were located at distances of 1400 m, 2800 m and 5500 m downwind. The wind field was measured within the test area at a height of 2 m and meteorological information and ground heat fluxes were measured upwind and downwind.

For the first two Desert Tortoise tests, the terrain was saturated with water due to heavy rain.

Havens (1992) noted that there is uncertainty in these tests due to specification of the properties of the aerosol and the density/concentration relation used to define the cloud.

The Desert Tortoise trials are frequently used in model validation studies for gas dispersion applications. They are included in the MDA, REDIPHEN and SMEDIS databases.

6.5.16 Eagle

The Eagle experiments involved six large-scale releases of nitrogen tetroxide (N_2O_4) at the Frenchman Flat, Nevada Test Site in September and October 1983. The work was undertaken by LLNL and details can be found in the work of Koopman et al., (1984), McRae (1985), McRae et al. (1987) and Ermak et al. (1989). The objective of the tests was to determine the source strength characteristics and dense gas dispersion behaviour of N_2O_4 spills. There were also two spills (nos 4 and 5) carried out to evaluate a Portable Foam Vapor Suppression System (PFVSS).

The release rates were approximately 2 – 3 kg/s and they resulted in pools covering an area of 3-5 m². The liquid was spilled directly onto the surface of the dry lake bed at the test site. There were two different release configurations: a single-exit confined spill was used to study evaporation rates as a function of liquid pool depth and wind speed; a multi-exit unconfined spill configuration was designed to distribute the N_2O_4 over a large area so that it would evaporate as quickly as it was spilled and provide a large well-defined source of vapour for dispersion studies.

Measurements included temperature at the spill pipe exit, heat transfer from the soil and temperatures of the soil, liquid and vapour. The meteorology was recorded across the site at

a height of 2 m. Vapour cloud concentrations were also recorded. The evaporation rate was measured using concentration, cloud temperature and velocity via a mass flux array situated 25 m downwind of the spill area and consisting of 7 gas stations and 2 wind speed stations.

N_2O_4 dissociates rapidly to NO_2 so both species must be involved in vapour flux measurements. The dispersion array consisted of five 10 m high towers located 785 m downwind of the spill area. This was used to record NO_2 concentration and the extent of the vertical cross section of the N_2O_4 vapours during each spill. Each tower had three NO_2 gas sensors and three thermocouples at 1 m, 3.5 m, and 8.5 m above the ground. The sensors were separated in the crosswind direction by a distance of 100 m.

There was uncertainty associated with the single exit tests because the liquid did not evaporate at the same rate as it was spilled and therefore the source is difficult to characterise for dispersion modelling. Havens (1992) pointed out that there was uncertainty resulting from reaction effects and absorption of nitrogen tetroxide by the ground.

The Eagle tests were reviewed by Hanna et al. (1993a) for inclusion in the MDA but were omitted due to the presence of a barrier to the flow presenting an obstruction and because of instrumentation problems. Ermak et al. (1989) concluded that two of the trials (3 and 6) were suitable for model validation. The trials were included in the REDIPHEN database.

6.5.17 Ecole des Mines d'Ales

Several small scale ammonia dispersion tests carried out in 1996 by the Ecole des Mines d'Ales in Champclauson, France. Details can be found in the paper by Bara and Dussere (1997). The objective of these tests was to study the effectiveness of peacock tail water sprays used by firefighters.

The tests were carried out using one or two 44 kg ammonia bottles turned upside down with a sluice release mechanism that was designed to discharge liquid phase ammonia at a height of about 0.17 m. The average duration of each release was approximately 2 minutes. The test area was an airfield, characterised as a large flat rectangular area of dirt and gravel. The peacock tails were located about 8 m downstream from the source bottle.

Ten instruments for measuring the ammonia gas concentrations were placed on the ground at 13 m, 25 m and 50 m downwind of the source and out to a width of 8 m either side of the centreline. Meteorological data was measured at 4 m. The humidity was fairly low in these tests at about 30% RH. There was significant uncertainty with wind direction during the tests.

Downstream of the peacock tails, a reduction in ammonia concentrations by a factor greater than 10 was found on the axis of the discharge at 13 m from the bottles and by a factor of at least 3 at 20 m from the bottles. No significant reduction was observed beyond 50 m.

6.5.18 Egami et al.

A series of four dense-gas release experiments were funded by the EPA and undertaken by the Desert Research Institute and the Western Research Institute at the Hazardous Spill Test Facility at the Nevada Test Site, Frenchman Flat, Nevada in 1993. Details can be found in the papers by Egami et al. (1995) and Briggs (1995). The objective was to undertake highly controlled experiments to develop a dataset for use in characterising source terms for dispersion models. In particular, source terms for a release in flat terrain under stable conditions.

The dense gas consisted mainly of CO_2 with traces of SF_6 . Two experiments were undertaken in near neutral atmospheric conditions and two during slightly stable conditions.

The test facility was a dry lake with an aerodynamic roughness length of about 0.2 mm. The site around it extended about 1 km to the north and west, 2 km south and 3 km east of the

test facility. The terrain sloped gradually downwards towards the dry lake. There were mountains at 8 – 20 km from the facility ranging in height from about 500 m to 1000 m.

The CO₂ and SF₆ mixture was released into a baffled discharge chamber which was connected to a 1 m³ box that was buried with its top flush with the ground. This enabled the gas to be released at ground level from the top of the 1 m³ box with very low momentum. Between 82 kg and 172 kg of carbon dioxide were released at rates between 0.46 kg/s and 1.61 kg/s. The duration of the releases was 70 – 265 s.

Gas concentrations were measured along an arc perpendicular to the prevailing wind direction at 40 m downwind of the source. Measurements were made at heights from 0.1 m to 1.4 m above the ground. Over 80 measurement devices were in place. Meteorological measurements were also recorded.

The dataset is good quality for model validation purposes. The study had specific quality assurance procedures and standards. The usefulness of the dataset was demonstrated as part of the study through comparisons with SLAB and DEGADIS models.

In 1995, follow-on experiments were undertaken also with carbon dioxide. Details can be found in the paper by Coulombe et al. (1999).

6.5.19 EMU-EnFlo

As part of the Evaluation of Modelling Uncertainty (EMU) project, two dense gas experiments were undertaken in the EnFlo wind tunnel at the University of Surrey. Details of the tests and the EMU project can be found in the report by Hall (1997b) and they were summarised in Hall (1997c) and Robins et al. (2000).

The EMU project was a collaboration between WS Atkins Consultants Ltd, EnFlo Research Centre, ARIA Technologies and NCSR Demokritos. It involved 3 stages A, B and C. These comprised three, seven and two test cases, respectively. There were five wind tunnel experiments, of which two tests involved releases of dense gas (B3 and C1). Test B3 was a continuous jet release from an open door in the courtyard area of an L-shaped building with other buildings present. Test C1 was a continuous jet release on a model industrial site featuring several buildings and complex topography.

The EnFlo wind tunnel has a working section of height 1.5 m, width, 3.5 m and length 20 m. The model scales for this study were 1/133 and 1/250. Mean concentrations were measured using a 16 point system.

The dataset was used for evaluating modelling uncertainty in the EMU project (e.g. Robins et al. 2000) and was included in SMEDIS in which it is labelled as EMU-EnFlo. It was also used by Hanna et al. (2004) for model validation.

6.5.20 EnFlo 2000

The EnFlo 2000 dense gas dispersion experiments were sponsored by HSE and undertaken by Chris Mare and Alan Robins in the EnFlo wind tunnel at the University of Surrey in August 1999. Details can be found in Appendix C of Lines et al. (2000). The objective of the tests was to release dense gas plumes into the wind tunnel and make measurements to provide a dataset for validation of numerical models.

There were four different cases studied, which resulted in 100 experiments including repeats in order to obtain 49 profiles. Repeatability was stated to be within 20%. The majority of the tests were conducted with CO₂ and one case was conducted with krypton. Krypton was used because the higher molecular weight enabled lower full scale wind speeds to be used.

The EnFlo wind tunnel was the same as described in the previous section, with a working section height of 1.5 m, width 3.5 m and length 20 m. The ratio from wind tunnel to full scale was 1:50. The gas was emitted from a vertical area source. Two different size sources were

tested: 50 mm x 50 mm and 25 mm x 100 mm and two flow speeds: 0.8 m/s and 1.0 m/s. The emission velocities were designed to be the same as the approach flow. The approach flow was a 1 m deep neutral boundary layer. The roughness array was made up of elements 20 mm high, 80 mm wide and 240 mm apart, which resulted in an aerodynamic surface roughness of 1 mm.

Mean gas concentrations were measured through 16 gas samplers mounted on traverse equipment in a horizontal line perpendicular to the flow direction. They were moved to measure at locations 0.96 m, 1.44 m, 1.92 m and 3.85 m downwind of the source and heights 0 mm, 25 mm and 50 mm.

These ENFLO tests were specifically designed for validation of numerical models. The two cases that represent low wind speed conditions were used in a model validation exercise by Lines et al. (2000).

6.5.21 EnFlo 2001

A set of wind tunnel trials were carried out at the EnFlo wind tunnel at University of Surrey as part of Dispersion Modelling Project 93-16, sponsored by the Petroleum Environmental Research Forum (PERF). Information can be found in Robins et al. (1999a, b; 2001a, b) and Hanna and Steinberg (2001).

The PERF 93-16 project involved experiments in three different wind tunnels, the Kit Fox field tests and theoretical analysis and model development. In addition to the EnFlo tests, the other wind tunnel experiments were undertaken at the US EPA's fluid modelling facility and the CHRC at the University of Arkansas. The objective of the project was to improve knowledge of the rate of vertical entrainment into dense gas clouds, the along-wind dispersion coefficient σ_x , the cloud advection speeds, the effects of surface roughness, the effects of atmospheric stability and the effects of obstacles. The priority in all of the tests was to accurately determine the atmospheric boundary layer friction velocity, which is a key modelling parameter.

The objectives of the EnFlo study were to explore methods of simulating moderately stable atmospheric boundary layers in a wind tunnel and to measure vertical entrainment rates into dense gas plumes from point and line sources in neutral and stable conditions in order to evaluate current analytical and numerical modelling procedures.

As described above, the EnFlo wind tunnel had a working section with a height of 1.5 m, width 3.5 m and length 20 m. The experiments were designed to be two-dimensional in order to study top entrainment without complications from three-dimensional processes and frontal entrainment. The gas was a nominal 3% by volume propane in carbon dioxide and was released from a line source with a width that could be varied from 1 m to 2.5 m and length of 0.1 m. It was subdivided into seven separate sub-sources. Internal side walls of 0.6 m height were used to limit the width of the line source and plume to the sub-sources in use.

The concentrations downwind were measured at 16 sample points and detailed flow measurements were taken. Two-dimensional dense gas plumes were successfully established in the wind tunnel for a range of plume¹⁶¹ Richardson numbers, $0 < Ri_p < 55$.

6.5.22 Falcon

The Falcon test series consisted of five large-scale field experiments involving quasi-continuous releases of LNG that were carried out on the Frenchman Flat test site in Nevada by LLNL. Details of the tests can be found in Brown et al. (1990). The purpose of the

¹⁶¹ The plume Richardson number is based on the local properties of the plume $Ri_p = \frac{g(\rho_p - \rho_a)H}{\rho_a u_*^2}$ where ρ_p is the local plume density.

experiments was twofold: firstly, to evaluate the effectiveness of vapour fences as a mitigation technique for accidental releases of LNG; secondly, to provide a dataset for model validation purposes.

The spills were between 20 m³ and 63 m³ into a purpose-built water-filled basin equipped with a water circulation system. The spill rates were 8.7 – 30.3 m³/min. This system was designed to ensure that the water in the basin remained thermodynamically well-mixed in order to ensure a high LNG vaporisation rate so that the source vapour rate could be approximated by the spill rate.

The releases were pressure driven with nitrogen gas. The release point was a spider of four 6" (0.15 m) diameter pipes at 90 degrees to each other in order to provide a uniform distribution of LNG over the water surface. The outlet of each arm was orientated downwards. A splash plate was positioned flush with the water surface beneath each outlet to direct the liquid horizontally. The height of the outlets above the splash plates was not provided, but it was approximated by Stewart et al. (2016) as being between 12" (0.30 m) and 36" (0.91 m).

The water basin was 40 m wide, 60 m long with a water depth of approximately 0.76 m. Tests were undertaken with and without the vapour fence. The vapour fence was 8.7 m high, 44 m wide and 88 m long, and it surrounded the water basin. The water basin was located at the downwind end of the fence. The fence was made of a proprietary fiberglass cloth impregnated with a mixture of silicon, Teflon and graphite. Upwind of the water basin was a billboard-type structure made of the same material, which was 13.3 m high and 17.1 m wide. This setup was designed to generate the turbulence characteristic of a storage tank within a vapour fence.

Measurement stations were arranged in straight arrays between 50 m, 150 m and 250 m, with concentration and temperature sensors at 1 m, 5 m, 11 m and 17 m. Meteorological data was recorded.

The source configuration and the presence of the vapour fences cause several challenges for modelling studies. In particular, they give rise to uncertainties in the vaporisation rate, turbulence conditions and vapour temperature. RPTs and the presence of aerosol droplets may also be factors. It was recommended by Stewart et al. (2016) that model sensitivity tests be undertaken to assess the uncertainties.

Wind tunnel modelling of the Falcon spill series was undertaken after the trials by Shin et al. (1991) with the objective of extending the value of the tests.

The Falcon trials were reviewed for inclusion in the MDA but omitted due to the influence of obstacles on the dispersion. The dataset was also omitted from REDIPHEM and SMEDIS, presumably for the same reasons. However, Falcon was included in the LNG model validation.

6.5.23 FLADIS

The European testing program on "Research on the dispersion of two-phase flashing releases", FLADIS, involved three measurement campaigns carried out in April and August 1993 and in August 1994, which included 27 releases of pressure-liquefied ammonia. Details can be found in the work of Duijm (1994), Nielsen et al. (1994), Nielsen (1998) and Nielsen and Ott (1996b). The objectives of FLADIS were to study aerosol sprays, heavy gas dispersion and the transition to passive dispersion.

The ammonia discharge rates varied from 0.25 kg/s to 0.55 kg/s through 4.0 mm and 6.3 mm diameter orifices. The longest test lasted 40 minutes. An example of a 0.25 kg/s release is shown in Figure 44.



Figure 44 Example of a flashing release of ammonia from the FLADIS programme. Discharge rate is approximately 0.25 kg/s. Image from Nielsen et al. (1994, © K. Nyren copyright, FOI).

Sensors were arranged in arcs at distances of 20 m, 70 m and 240 m centred on the release point. Measurements of the composition of the aerosol within the two-phase jet were made during tests. From these measurements, it was observed that the aerosol consisted almost entirely of ammonia near the discharge point, but within a few metres was made up of almost entirely of water.

The FLADIS trials were reviewed and found suitable for inclusion in the REDIPHEN and SMEDIS databases.

6.5.24 FLIE

The Flashing Liquids in Industrial Environments (FLIE) project involved a set of LPG release experiments undertaken by INERIS and the von Karman Institute for Fluid Dynamics. A summary can be found in Lacome et al. (2020).

The objective was to study the initial stages of flashing two-phase releases in order to provide measurement data and numerical tools to assist in risk assessment. Conditions were chosen to simulate LPG under a range of typical industrial conditions.

The tests included nearly 100 experiments involving both horizontal free jets of LPG (butane and propane) and horizontal jets impinging on an obstacle at a distance of 2 m. The tests were undertaken with the pressure-liquefied gas initially at ambient temperature and pressures ranging from the minimum saturation pressure up to a pressure of about 15 bar. Two orifice shapes were used, circular or rectangular, with equivalent diameters from 10 mm to 25 mm.

During the tests, pressures and temperatures were measured inside the release tank, at the release point and inside the jet. The quantity rained out of the jet was recorded.

Temperatures on the surface of the obstacle in the impinged cases were also measured. Ambient conditions were recorded but no concentration measurements were taken.

6.5.25 Gadila

Shell undertook a series of six trials in which 27-193 m³ of LNG was jettisoned off the back of a ship ('Gadila') onto water west of St Nazaire, France. The tests appear to be the largest releases of LNG onto water to date. Details can be found in Kneebone and Prew (1974). The main objective of the experiments was to determine the feasibility of emergency jettison of fuel at a high discharge rate from a stationary ship and a low discharge rate for a moving ship (Luketa-Hanlin, 2006).

Four of the tests were carried out while the ship was moving and two when it was stationary, with the highest volume release occurring when stationary. In the moving tests, the ship was moving at about 5.4 m/s.

LNG was jettisoned through nozzles with diameters of 51 mm and 102 mm, orientated horizontally and located 18 m above the water surface. The spill rates ranged from 2.7 m³/min to 19.3 m³/min and were continuous over a period of 10 minutes. Wind speeds ranged from 1.9 m/s to 5.1 m/s at 30 m.

No concentration measurements were taken but the extent of the visible cloud was recorded using overhead cameras. Infrared cameras were also used and showed that that no coherent LNG pool formed on the sea surface. For the largest volume release, in a wind speed of 3.9 m/s, the visible plume was about 10-12 m high, with a maximum width of 550 m and a length of 2250 m.

The tests showed that LNG could be jettisoned from a ship without the LNG coming into contact with the ship or the resulting vapour cloud engulfing the ship.

6.5.26 Goldfish

The Goldfish test series involved six large-scale, quasi-continuous releases of hydrogen fluoride (HF). Three of the tests were unobstructed and three involved water sprays. According to Hanna et al. (1993a) there was no formal report document for these tests. Most of their documentation came from personal communication with one of the sponsors of Goldfish (D. Blewitt) and from Blewitt et al. (1987). The objective of the trials was to study the effectiveness of water sprays at mitigating dispersion of HF.

The trials were similar in setup to the Desert Tortoise ammonia trials. When the HF was released, some of it flashed into vapour and the turbulent jet aerosolised the remaining liquid. There was no liquid pool observed in the trials.

The release mechanism and some of the measurement instruments were similar to Desert Tortoise. The diameter of the source orifice was not given in any of the references. For inclusion in the MDA, this information was obtained from D. Blewitt through personal communication. The flow rate was 10 kg/s to 30 kg/s. The measurement stations were positioned in lines perpendicular to the wind direction at 300 m, 1000 m and 3000 m from the release point. Along the 300 m line, there were 11 locations with the five closest to the centre taking measurements at 1 m, 3 m and 8 m and the outer six locations taking measurements at 1 m. Along the 1000 m line, there were 13 locations with the nine closest to the centre taking measurements at 1 m, 3 m and 8 m and the outer four locations taking measurements at 1 m. Along the 3000 m line, there were 11 locations with similar variation in measurement heights. In most trials, at 300 m the observed height of the cloud of hydrogen fluoride was less than the highest measurement level of 8 m but it appeared to grow higher than this at the further distances.

When the water curtain spray systems were active, they achieved approximately a 36% to 49% reduction in downwind concentrations of hydrogen fluoride when the water flow rate was supplied with the ratio of water flow rate to acid flow rate of 20:1.

The measured maximum ground level concentrations and cloud width from the tests without water sprays were deemed to be sufficiently accurate for inclusion in the MDA. Havens (1992) noted that it was difficult to use the data for model validation because of uncertainty in the properties of the aerosol and the behaviour of HF.

6.5.27 GRADE

The GRADE experiments involved an approximately instantaneous release of 101 kg of LPG from a 5 x 5 array of small containers with no initial vertical momentum. Very little information is available on these tests (see Lines et al., 2000).

6.5.28 Guldemond

Guldemond (1986) described a set of wind tunnel experiments modelling involving argon releases in the TNO wind tunnel that were designed to simulate ammonia releases in an industrial setting with obstacles. The model was designed to reproduce a 15 ton release of pressure-liquefied ammonia on a 1 km x 1 km area of the DSM site¹⁶² at a scale of 1:500. Most features with scales of 2 m or more were resolved in the model. A model with flat terrain was also produced for comparison, along with tests with a neutrally buoyant cloud.

The first part of the study involved releasing an oil mist to visualise the cloud dispersion. The second part involved concentration measurements. The source was not modelled, instead the assumption was made that the ammonia behaved as a dense gas. There were more than 20 different configurations investigated with the oil mist and eight of these were then chosen for concentration measurements. Concentrations were measured at 26 points within 500 m of the source and a few points at distances of 50 – 1500 m from the source. They were mostly measured at a full scale height of 2 m but at one point there were measurements up to 14 m (building height). Wind speeds of 2 m/s, 4 m/s and 8 m/s were used. Gas release rates were 52 kg/s, 26 kg/s, 13 kg/s and 6.5 kg/s.

6.5.29 Hall and co-workers

For a period spanning over two decades from about 1975, David Hall and various co-workers, mostly at the Warren Springs Laboratory wind tunnel in Stevenage, UK, conducted experiments to study the behaviour of dense gas releases. The wind tunnel had a working section 4.3 m wide, 1.6 m high and 20 m long. Surface roughness was generated using an array of screw heads 50 mm apart and 20 mm high, with a 9 mm head diameter. The releases comprised continuous plumes and finite duration puffs, typically released through a hole flush with the tunnel floor and volumes of gas instantaneously released by collapsing a containment curtain or bellows. The gases used to obtain a range of densities were mainly bromochlorodifluoromethane (BCF) and argon.

Hall and co-workers investigated the effects of plume density and stability (Hall and Waters, 1989), surface roughness (Roberts and Hall, 1994, Roberts et al., 1994), fences (Hall et al., 1991a), plume variability (Hall et al., 1991b) and obstructions (Hall et al. 1999). The common theme of all of the studies was commentary on the effects of scale, i.e. the ability to translate wind tunnel results to full scale. For discussions on scaling in particular see Hall et al. (1975), Hall (1979a), Hall and Waters (1989) and Hall (1997a).

By using scale replicas and dimensional analysis Hall and co-workers contributed towards analysis of Porton Down (1/25 scale model, Hall, 1979b; Hall, 1982; Hall et al., 1982),

¹⁶² There is no expansion of "DSM" in the paper. The implication is that it is a model of the site of C.P. Guldemond's employer DSM Central Research BV, Netherlands.

Thorney Island (1/90 scale model, Hall et al., 1982), Project BA (Hall et al., 1990), FLADIS (Hall et al., 1996) and the URAHFREP field trials on hydrogen fluoride (Hall and Walker, 1995a; Hall, 1997a, Hall and Walker, 2000, Hall et al., 2001), among other applications. Various datasets from Hall and co-workers are included in the REDIPHEN database as “Warren Springs Laboratory” (WSL).

An example of Hall and co-worker’s work have been included in Figure 40 in Section 6.2.1.

6.5.30 Hoot et al.

Hoot et al. (1973) provided details of a set of wind tunnel trials on negatively buoyant plumes undertaken in the wind tunnels at the Fluid Dynamics and Diffusion Laboratory of Colorado State University. The objective of the trials was to check theories for plume rise of vertically-upwards directed releases of negatively buoyant gas and to obtain reliable data on the nature of the plume as it descends. The density difference was generated using mixtures of Freon 12 and air.

The plumes were released from stacks into either a quiescent space, or into a laminar or turbulent crosswind. The quiescent space was achieved in the Industrial Aerodynamics wind tunnel which had a 6 ft x 6 ft cross section. In this wind tunnel, plumes were also injected into a low speed turbulent crosswind. The other tests were undertaken in a thermal wind tunnel with 24 inch x 24 inch cross section.

For the vertical plumes, the specific gravities ranged from 1.08 to 3 and exit velocity ratios¹⁶³ ranged from about 9 to 75. The stacks had diameters of 1/8 inch and 1/4 inch. For the plumes into a laminar crosswind, the specific gravities ranged from 1.10 to 4.16 and exit velocity ratios ranged from about 2.5 to 25. Froude numbers ranged from about 5.2 to 75. The same stack diameters of 1/8 inch and 1/4 inch were used with crosswind velocities of about 0.75 ft/s and 1.5 ft/s. The stack height was varied between 3 inch and 6 inch.

In the thermal wind tunnel, a fixed structure of dimension 4.5 x 4.5 x 4.5 inch was placed in a turbulent shear flow with the stack at the centre of the structure. The velocity at the top of the structure was set at 6.75 ft/s with Reynolds number of about 13,500. Smoke photographs were taken of this case for specific gravities of 1, 1.5 and 2.5, velocity ratios of 1 and 2 and stack height to building height ratios of 1, 1.5 and 2.

The measurements included the maximum height of plume rise, the horizontal point at which the plume begins to descend and the concentration.

In addition to the stack releases, there were also concentration measurements for dense ground source releases into a turbulent boundary layer. In these tests, measurements were made in both neutral and stable boundary layers.

6.5.31 HSE 1985

In 1985, the UK Health and Safety Executive’s Buxton Laboratory carried out a set of field-scale carbon dioxide releases. Details can be found in Moodie (1985). The objective of the work was to provide measurement data to inform the design and effectiveness of water spray barriers used for mitigating dense gas dispersion. The impact of various spray barrier configurations on carbon dioxide dispersion was investigated under different atmospheric conditions.

The Buxton test site was an approximately flat, circular grassy field with a diameter of about 200 m. The spray barrier was located about 65 m from the control cabin and other test site buildings. There was a fixed 18 m high camera mast to record video footage and

¹⁶³ Note that Hoot et al. (1973) say “exit velocities” and here it has been assumed that this should read “exit velocity ratios”.

photographs were taken during each test. The weather conditions were measured at a fixed 10 m high mast. The wind speed and direction were also measured continuously during each test at 1.25 m. Local topographical features were found to influence the conditions of the site. Tests were obtained for a range of wind speeds from 0.6 m/s to 11 m/s. Most tests were conducted at around sunrise and sunset, when low wind speeds were most frequent. It was noted that low frequency horizontal fluctuations in the wind direction were observed during these times.

Water was supplied to the spray barriers from a fire engine capable of delivering 3000-3500¹⁶⁴ l/min of water at a pressure of 7 barg. The trials tested both upward pointing and downward pointing spray barriers with different nozzle types and spray patterns. The carbon dioxide was stored as a refrigerated liquid under its own vapour pressure in tanks of 1.5 and 5.5 te. The gas was released, initially as a radial jet, at 2 and 4.2 kg/s. On release, a dense white cloud formed, that was composed of cold gas, solid particulates and condensed moisture. Some of the solid precipitated out at the source.

The effectiveness of a water spray barrier was determined by comparing concentrations measurements downstream of the barrier with the barrier switched either on or off. Moodie (1985) discussed the influence of nozzle type, barrier orientation and wind speed on the results.

6.5.32 HSE 2012

HSE conducted a series of field tests on continuous liquid hydrogen spills in 2012 that included analysis of pool formation and gas dispersion. Both unignited and ignited releases were investigated. Details can be found in Royle and Willoughby (2014) and Hall (2014), respectively. Only the unignited releases are summarised here. The objective of the tests was to provide measurement data to assist in determining hazards from a realistic release of liquid hydrogen such as might occur from an accidental release during a hose transfer operation. Significant dense gas effects were not observed in the trials. The four unignited tests are summarised in Table 22. An example of a ground level release can be seen in Figure 45 (a) and elevated release in Figure 45 (b).

Table 22 Test number, release height, orientation and duration for unignited liquid hydrogen releases

Test number	Release height (m)	Release orientation	Test duration (s)
5	0 (ground level)	Horizontal	248
6	0.1	Vertically downwards	561
7	0.86	Horizontal	305
10	0.1	Vertically downwards	215

The liquid hydrogen was released through a 1 inch nominal bore orifice at a flow rate of approximately 60 l/min. Measurements were recorded of liquid pool spread, dispersing gas concentration, thermal gradient in the concrete substrate and temperatures within the pool. Gas concentration sensors were placed around the release point at distances of 0.2 m to 7.5 m, and heights from 0.25 m to 2.75 m. Liquid pool sensors were placed at intervals of 0.1 m from 0.5 m to 2.8 m from the source. For Test 7, where the liquid hydrogen was released from height, no liquid rained out and so no liquid pool was formed. Sensors were embedded in the concrete at depths of 0.01 m, 0.02 m and 0.03 m at a distance of 1.5 m from the release point.

¹⁶⁴ Note that Moodie (1985) quotes 3-3500 l/min of water and here this has been assumed to be a typographical error.

The atmospheric conditions in Tests 5, 6 and 7 were similar with temperatures around 10°C, wind speeds between 2.7 m/s and 4.0 m/s and a relative humidity of about 60%. In Test 10 the temperature was about 4°C with a wind speed of about 1.4 m/s and relative humidity of about 87%.

The data has been used for validating both pool spread models and dispersion models (Gianissi et al., 2011; Ichard et al., 2011; Batt, 2014; Jäkel et al., 2017).

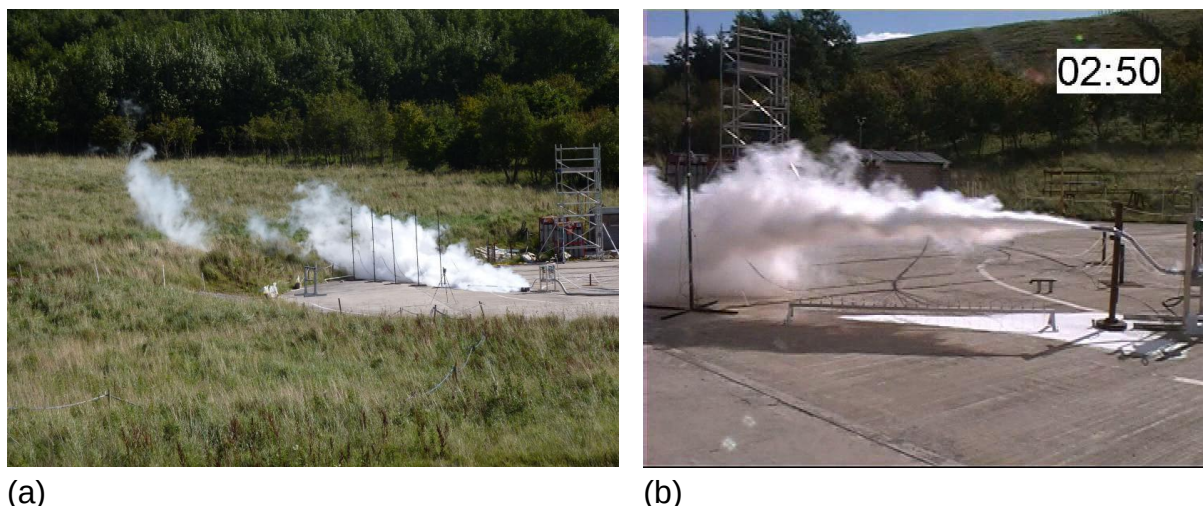


Figure 45 (a) Hydrogen cloud dispersing from a ground level liquid hydrogen release and (b) elevated liquid hydrogen release (Royle and Willoughby, 2014)

6.5.33 ICHMAP (including HAWK)

The Industry Cooperative Hydrogen Fluoride Mitigation and Assessment Program (ICHMAP) was a collaboration of 20 companies formed in 1987 to develop information for improving the design and implementation of mitigation techniques for accidental releases of Hydrogen Fluoride (HF). A summary of the ICHMAP and relevant references for the components making up the program can be found in Diener (1991).

The objective of the ICHMAP tests was to investigate the use of water spray barriers and vapour barriers, and to develop validated computer models for calculating release rates and jet and plume dispersion of accidental releases of HF. The study followed on from the Goldfish trials in which the use of a dike was ineffective.

The water spray barrier work included small-scale laboratory tests and large-scale wind tunnel tests that were undertaken at the Nevada Test Site. In the laboratory, a 6 inch wide, 12 inch high, 40 inch long totally enclosed flow chamber was set up under an exhaust hood. Anhydrous HF was injected at a rate of approximately 150 ml/min for 10 minutes. The substance flashed to produce a vapour and aerosol mixture at the orifice exit. Two spray nozzles were used to spray the resulting cloud with water or augmented water (containing additives). The acidic water run-off was collected and analysed for HF content. Key variables were the relative flow rates of water to HF and the spray droplet size.

The wind tunnel tests, known as the HAWK series, were conducted in 1988. They included 87 tests in which the HF aerosol particle size was measured in a wind tunnel that was 140 ft long, 16 ft high and 8 ft wide. The HF was released from a square-edged orifice at a rate of approximately 5 gallons per minute. The impact on HF removal efficiency of varying several parameters was tested. The tests varied the ratio of water to HF flow rate, the way the water spray was applied (e.g. fog or jet), the HF temperature and pressure, water spray additives, ambient relative humidity, wind speed and the use of steam. They found that HF removal rates of 25% to 90% could be achieved with water to HF flow rate ratios of 6:1 to 40:1.

The vapour barrier study examined HF dispersion and also the impact of a vapour barrier on a flammable gas release (a hazard that may coexist on an industrial site). The first phase of the study included a review of the effectiveness of vapour barriers. In phase two, two vapour barrier configurations were tested by the Christian Michelsen Institute using the CFD model FLACS (no experiments were conducted). The third phase consisted of over 200 tests in a wind tunnel to quantify the impact of vapour barriers and obstacles on dilution and transport times of HF clouds. The work was undertaken by Cermak Peterka Petersen Inc. (CPP). The wind tunnel was 75 ft long by 8.5 ft high by 12 ft wide. Configurations modelled include flat, open ground and a heavily obstructed and moderately obstructed process unit. The wind tunnel model was validated against selected Thorney Island and Goldfish trials.

Concentrations were measured at distances equivalent to full scale of 3000 m for cases with and without barriers and obstacles. Cloud arrival times, departure times and durations were measured. The work demonstrated that the effectiveness of the vapour barrier was dependent on the release configuration, the release site and the design of the barrier. In general, the effect of obstacles and two dimensional vapour barriers was to decrease near-field concentrations but in the far-field the concentrations returned to the unobstructed concentrations. The vapour box that surrounded the release point decreased concentrations in the near-field and the far-field and delayed cloud travel times.

The final part of the ICHMAP program included the development of a modelling system for HF emission, vaporisation and dispersion. HGSYSTEM was used as the basis of the model.

6.5.34 Imperial Chemical Industries (ICI)

Two different series of tests were carried out on instantaneous and continuous releases of ammonia by ICI, UK in 1974. Details can be found in Reed (1974). The objective of the tests was to characterise the effectiveness of retention basins.

The first set of tests simulated catastrophic failure of a containment vessel 0.15 m in diameter and 0.45 m high, containing 3.5 kg of liquid ammonia. The vessel was sealed with a quick-release lid, pressurised to 3.5 bar and then opened. The second set of tests comprised a series of discharges from a tank of ammonia (at 7.5 bar and 16°C) through a 1 mm diameter orifice, located at a height of 1 m above ground level and orientated horizontally, 'slightly' upwards and vertically downwards into a metal tray.

No concentration measurements or quantities were reported. Photos were taken of the instantaneous releases and it was observed that 90% of the liquid was lost from the vessel on release and no liquid reached the ground. In the continuous releases, it was found that when the discharge orifice was horizontal or slightly upwards, an aerosol cloud formed with no liquid observed on the ground. When the orifice was pointed slightly downwards, a small fraction of liquid ammonia was collected.

6.5.35 INERIS

A series of 15 large-scale ammonia field trials were undertaken by INERIS at the Terrain of External Experimentation (TEE) test site of CEA-CESTA (Center for Scientific Studies and Techniques d'Aquitaine) between December 1996 and April 1997. Details can be found in Bouet (1999).

The experiments studied the effects of the type of orifice, the atmospheric stability, the presence of obstacles, the presence of a barrier and the use of "peacock tails" (water sprays) as a mitigation method.

The TEE test site was flat and free of obstacles. It had a radius of about 2 km, with a 10 m by 10 m square concrete slab 0.15 m thick at its centre, which was used as the release pad. Released quantities were typically of the order of 2000 kg – 3000 kg with average flow rates

of 3kg/s – 4 kg/s. In most of the tests the release orifice was 2 inch (50.8 mm) diameter. Each of the 15 trials had a different release configuration, as summarised in Table 23.

Table 23 Summary of 15 ammonia trials carried out by Bouet (1999)

No.	Test description
1	Gas phase horizontal discharge at a height of 1 m. The only test carried out in the gas phase.
2	Liquid phase horizontal discharge at 1 m height through a 20 mm hole.
3	Liquid phase release through a 2 inch flange at a height of 1 m. The distance between the two elements of the flange was 1.6 mm, corresponding to a leakage area of 255 mm ² and an equivalent release diameter of 18 mm.
4p	Liquid phase horizontal discharge at 1 m height through a 30 mm hole.
4	Liquid phase horizontal discharge at 1 m height.
5	Liquid phase horizontal discharge at 1 m height impacting on a wall surface 3 m x 3 m located 3 m from the end of the release device.
6	Liquid phase horizontal discharge at 1 m height impacting on a wall surface 3 m x 3 m located 1 m from the end of the release device.
7	Liquid phase downward vertical discharge impacting on the ground from a height of 3 m.
8	Liquid phase downward vertical discharge impacting the ground from a height of 1 m.
9	Liquid phase downward vertical discharge impacting the ground from a height of 1 m in a retention basin of area 2 m x 2 m and 1 m high (4 m ³).
10	Release identical to release No. 4 with a water curtain located 25 m downstream of the discharge point triggered 5 minutes after the ammonia discharge started.
11	Release identical to rejection No. 4 with a water curtain located 60 m downstream of the discharge point triggered 5 minutes after the ammonia discharge started.
12	Release identical to No. 4 with the temperature of the liquid ammonia inside the tank lowered to -12 ° C before the test.
2b	Release identical to No. 2 with an orifice of diameter 18 mm.
8b	Downward vertical discharge impacting the ground from a height of 1 m in a retention basin of area 10m x 10m and 0.05 m high (5 m ³).



Figure 46 Wall obstructing ammonia release, retention area obstructing ammonia release (test 9) (from Bouet, 1999, © INERIS copyright)

The peacock tails in Trials 10 and 11 spanned 16 m each side of the water release point (i.e. 32 m across in total) and reached a maximum height of 10 m.

Temperature and pressure measurements were recorded within the ammonia tanks during the tests at heights ranging from 50 mm to 1450 mm. The concrete slab and the impacted wall were both instrumented with thermocouples. The site was equipped with more than 150

instrument masts with the possibility of fixing devices at 0.1 m, 1 m, 2 m and 3 m. The masts were arranged on 180° arcs from 20 m to 1700 m. Meteorological conditions were recorded at 1.5 m and 10 m. Test ambient temperatures ranged from 5°C to 24°C and relative humidity from 20% to 90%. Atmospheric stability was estimated to vary from Pasquill classes A – D.

Bouet (1999) noted that none of the tests produced a positively buoyant cloud of ammonia.

Six different measurement techniques were used to measure the ammonia concentrations across the whole range of ppm. This resulted in a high-quality dataset for concentration with distance from the source and for the vertical concentration gradient within the dispersing cloud. Bouet (1999) demonstrated the use of the dataset in a model validation exercise, using the Phast model.

6.5.36 Jack Rabbit I

Jack Rabbit I consisted of a series of ten field trials that each involved releases of between 1 and 2 tons of pressure-liquefied chlorine or ammonia (Fox and Storwold, 2011). The project was sponsored by the US Department of Homeland Security (DHS) and the Chemical Security Analysis Centre (CSAC) and was undertaken at Dugway Proving Ground, Utah in April 2010. Details, including extensive additional resources and reports, can be found on the Utah Valley University website¹⁶⁵. The objective of the project was to improve understanding of rapid large-scale releases of toxic inhalation hazard (TIH) materials (e.g. from railcars) and to help inform first responders. The ten trials consisted of two initial 1 ton pilot tests, four 2 ton releases of chlorine, and four releases of anhydrous ammonia.

The tests were undertaken within a shallow depression 1.16 m deep with a radius of 25 m. The pit had sides with slope 1:7 and it was surrounded by a bank of height 0.84 m and internal slope of 1:7 bringing the total depression depth to 2 m. The outside slope of the bank was 1:9 and the surrounding terrain was flat. The terrain was salt playa (a dried lake bed). Most of the trials were undertaken in low wind but two were carried out in stronger wind conditions.

The tank was positioned in the centre of the depression with the release orifice pointed downwards at a height of 2 m. During the release, some of the liquid chlorine and ammonia rained out onto ground and percolated into the salt playa. Examples of the cloud formation after the 1 ton releases can be seen in Figure 47 (a) and (b) for ammonia and chlorine, respectively. The elevated cloud in the ammonia image is due to the vigorously boiling pool. The wind speed was very low (<1 m/s) and so the clouds persisted in the pit for more than 30 minutes.

Concentration measurements were made on concentric rings of sensors at distances of between 5 m and 2500 m. An extensive meteorological dataset was recorded, including vertical wind profiles up to 32 m. A large amount of video footage was also recorded.

There were some anomalies during the trials, such as apparent Rapid Phase Transitions (RPTs) shortly after the releases stopped. Some of these were attributed to infiltration of ammonia and chlorine into the ground.

The data from the Jack Rabbit I trials were used to inform the subsequent, larger-scale, Jack Rabbit II tests. Recently, Hanna et al. (2016) revisited this data and compared concentration measurements to the Lyme Bay data.

¹⁶⁵ <https://www.uvu.edu/es/jack-rabbit/> Accessed on 24th April 2020

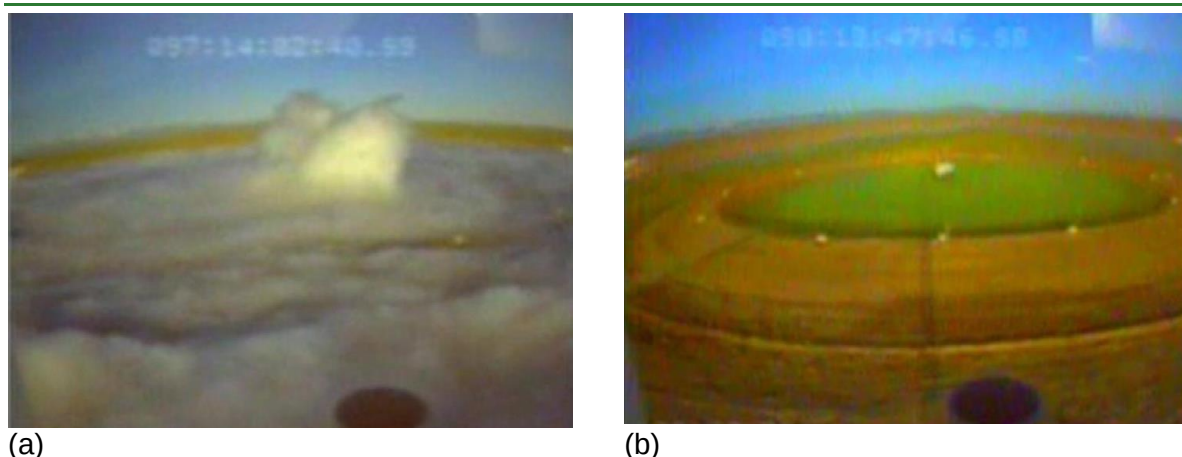


Figure 47 Cloud formation after 3 minutes from 1 ton releases of (a) ammonia and (b) chlorine (from Bauer 2013)

6.5.37 Jack Rabbit II

Jack Rabbit II followed on from Jack Rabbit I and involved a series of 7 to 20 ton releases of pressure-liquefied chlorine at the Dugway Proving Ground in 2015/16 (Fox et al., 2016, 2017). Details, including significant additional resources and references, can be found on the Utah Valley University website (see Jack Rabbit I).

The objective of the study was to provide data for subject matter experts that could be disseminated to emergency planners and responders to facilitate public protection during a catastrophic release of chlorine or another TIH material. The project involved collaboration between emergency response subject matter experts, environmental systems researchers, numerical modellers and atmospheric scientists.

The tests were conducted in two phases. The first phase in 2015 involved 5 to 9 ton chlorine releases directed vertically downwards from a flange on the underside of a 10 ton capacity tank. The release orifice was 6 inches (0.152 m) in diameter at a height of 1 m above the concrete slab and it was activated by removing a rupture disc. The release point was surrounded by an array of over 60 Conex shipping containers that were used to represent a mock urban environment. Vehicles were also present. Some of the containers and vehicles were instrumented to assess ingress rates and gas accumulation.

In the second phase of tests in 2016, nearly all of the containers were removed and the gas dispersed across a flat unobstructed area. The first three tests used the same 10 ton release vessel as the 2015 but varied the release angle and consisted of releases vertically downwards, 45-degree downwards and vertically-upwards. A final test was undertaken with a downward orientated release from a 20 ton chlorine road tanker.

Concentration measurements were taken on several arcs downwind of the release to distance of 11 km. Detailed meteorological measurements were recorded and videos were taken using stationary cameras and a drone.

The measurements of gas concentrations inside vehicles and containers were reported by (Sohn et al., 2016). The largest obstacle consisted of Connex containers three storeys high and two front and back, to produce a block of six container. Some of the containers were mechanically ventilated. Measurements of the air change rates were undertaken separately using SF₆ as a tracer gas.

The Jack Rabbit II dataset is high quality. The experiments were designed and carried out in close collaboration with a dedicated modelling working group. A significant amount of work has gone into recording and assimilating the measurement data to make it suitable for model

validation purposes. An international model inter-comparison exercise was undertaken using the data, which was published in a special issue of the Atmospheric Environment journal¹⁶⁶. The comparison of model predictions to the data were presented in the paper by Mazzola et al. (2020). HSE's initial contribution to the project was documented by Gant et al. (2018). The Jack Rabbit II dataset can be requested by email to Jack.Rabbit@st.dhs.gov.

6.5.38 JGA

The Japan Gas Association (JGA) conducted a study of dispersion of evaporated gas from LNG pools in 1975. According to Webber et al. (2010), the study comprised continuous spills of up to 60 m³/hr into 10 x 10 m square bunds. They measured the vaporisation rates and spreading rates of the liquid pool, although there was some error incurred due to the unevenness of the surface. The original reference JGA (1976) has not been obtained for this review.

6.5.39 Johnson and Diener

Johnson and Diener (1991) described a series of field experiments on chlorine, water, CFC-11, methylamine and cyclohexane that took place in the summer of 1989 at Norman, Oklahoma and at the US DOE Liquefied gaseous fuels spill test facility (Nevada Test Site) at Frenchman Flat, Nevada in August/September 1990. The objective of the work was to understand the behaviour of pressurised liquid releases, including aerosol formation.

Three release tanks were used containing 1.5 m³ of water, 0.3 m³ of CFC-11, and 1.3 m³ of chlorine, methylamine or cyclohexane. CFC, water and cyclohexane have boiling temperatures above ambient but chlorine and methylamine were stored cryogenically. Each tank was insulated. Both test programs used a similar liquid release tank and release piping. The liquid release rates and liquid capture system were also similar. Pressures and temperatures near the release orifice were recorded, together with temperatures at several levels in the tanks. The Nevada experiments also had a downstream temperature measurement array. The results were presented in terms of liquid capture vs liquid superheat. Meteorological information was recorded but concentrations in the dispersing clouds were not measured.

The datasets described by Johnson and Diener (1991) were used in validation of the CCPS liquid release model RELEASE.

6.5.40 Kit Fox

The Kit Fox test series involved 52 field CO₂ release experiments at the Frenchman Flat, Nevada test site. The trials formed part of the Dispersion Modelling Project 93-16, sponsored by the Petroleum Environmental Research Forum, which also included three wind tunnel studies. Detailed of the project can be found in Hanna and Chang (2001) and Hanna and Steinberg (2001). The project's objective was to study dense gas releases in an array of obstructions. The experimental setup was designed to represent an industrial site at a scale of about 1:10 of full scale.

There were two types of flat billboard-shaped obstacle arrays used in separate trials. One was a larger array with height 2.4 m and one was a smaller array with height 0.2 m.

The trials involved both short-duration puff and continuous plume releases, comprising 6 trials with a plume released into the large billboard array, 13 trials with a puff released into the large billboard array, 12 trials with a plume released into the small billboard array and 21 trials with a puff released into the small billboard array. The CO₂ was released through a square opening 1.5 m x 1.5 m at ground level near the middle of the obstacle array. When

¹⁶⁶ <https://www.sciencedirect.com/journal/atmospheric-environment/special-issue/10FRFPWRB27>, Accessed on 6th January 2021.

the large billboards were present, the gas was released at a rate of about 4 kg/s for 2 mins to 5 mins for the continuous plumes and 20 s for a finite duration puff. When the large billboards were removed, the rate was decreased to 1.6 kg/s.

All of the experiments took place in the evening near to sunset. The average wind speed was about 2.5 m/s. Concentrations were measured at four monitoring arcs at 25 m, 50 m, 100 m and 225 m.

Hanna et al. (2004) used the Kit Fox dataset in validation of FLACS and recommended its use to evaluate other numerical models.

6.5.41 Landskrona

A series of 11 field experiments undertaken in Landskrona, Sweden in 1982 by the Swedish National Defence Research Institute. Details can be found in Nyrén and Winter (1983), Nyrén (1984) and they were summarised by Bouet (1999). The objective of the tests was to measure the flow rate of a two-phase ammonia release and to compare the measurements to a theoretical model.

The tests used a commercial container containing 1,400 kg of ammonia at 6 bar and 9 °C. The discharges were made from a pipe with an internal diameter varying from 32 to 40 mm. Six tests were carried out with a 2 m long pipe and five with a 3.5 m pipe. In each case, the pipe was located 2 m above the ground. Each release lasted 60 s to 90 s. For all but four of the tests, the tank pressure varied widely. For the remaining four, the outlet pressure was 2.2 bar and the mass flow rate was 2.2 kg/s. The jet touched the ground at a point between 6 m and 10 m from the point of discharge. No liquid ammonia was observed on the ground.

No concentration measurements were made. The ambient temperature was 8 °C with a relative humidity of 42% and wind speed of 13 m/s.

6.5.42 Lathen / BA Propane

The Lathen trials consisted of an extensive set of field-scale propane release experiments (51 trials are included in REDIPHEM). The trials are often referred to as BA Propane as they formed part of the CEC Major Technical Hazards Research Programme Project BA: Research on Continuous and Instantaneous Heavy Gas Clouds (Davies, 1992). In some references, they are only referred to by particular trial, e.g. EEC57. Details can be found in Nielsen and Jensen (1991), Heinrich and Scherwinski (1990), Nielsen and Ott (1996a) and Nielsen (1998).

There were two phases to the project. In the first phase, TÜV and Riso were involved. In the second phase only TÜV were involved and there was more uncertainty in the source conditions.

In most of the tests, the source comprised a jet of liquefied gas pointing horizontally or vertically upwards at a height of about 0.5 m. There were also some tests with a smaller, mobile jet pointing vertically downwards towards the ground. Other tests involved two-phase release from a cyclone source and a gas-phase release from a container filled with boiling liquid. The various configurations resulted in release rates of between 0.1 and 3 kg/s propane for duration of between 200 and 500 s and puff releases of 20 kg/s in 2 s.

The trials were both unobstructed and obstructed, in some cases releasing the jet between two parallel fences. There were 9 trials with no obstructions.

For the jet releases, the exit pressure was high and so no pool formed on the ground. Different size nozzles could be fitted to the source, but measurements at the source indicated that the actual release rate was higher than the nominal value (Nielsen and Ott, 1996a) and so there is some uncertainty in the sources with higher release rates.

In the cyclone release, the source was emitted in all directions. Nielsen and Ott (1996a) report that about 33% of the liquid material separated inside the cyclone and formed a pool on the ground.

Sensors were located parallel to the centreline at downwind distances ranging from 20 m – 50 m and a height of 0.05 m. In the TÜV-Riso tests, the meteorology was recorded. In the tests operated solely by TÜV, meteorological measurements were not recorded, but instead they relied on the nearest meteorological tower and local observations. Atmospheric stabilities ranged from Pasquill Classes A-G, even for low wind speed cases. According to Lines et al. (2000), a significant number of the tests can be classified as low wind speed, relative to other experiments.

Lathen was used in model validation by Lines et al. (2000) and the data was included in the SMEDIS and REDIPHEN validation datasets.

6.5.43 Lux

Lux (1980) described two series of experiments on UF_6 undertaken by Goodyear Atomic Corporation in an environmental chamber. The first set of tests comprised 30 releases of UF_6 under a variety of atmospheric conditions in order to investigate the effect of these conditions on UO_2F_2 particle size distribution, the release cloud formation and cloud settling rates. The parameters studied were the temperature (0°C – 40°C), relative humidity (20%-90%), and wind speed (2.5 mph – 5.5 mph), for UF_6 sample sizes in the range 1.8 g – 79.3 g.

The second set of tests comprised 37 releases of UF_6 . The objective was to investigate the effectiveness of UF_6 cloud ‘knockdown’, or mitigation. Details can be found in Lux (1982). The releases were from a suspended non-directional release with mitigation measures including coarse water spray, air jet, (electrostatically and non-electrostatically charged) steam spray, CO_2 , Freon-12, fine water mist (uncharged), boric acid mist (charged and uncharged) and an ionised dry air stream. Note that boron simulates nuclear criticality control procedures.

A laser densitometer and a lightbeam cloud penetration device were used to calculate the relative success of each mitigation measure.

The results showed that, despite the density of the UO_2F_2 particulate matter resulting from the release (6.37 g/cc), the resultant cloud immediately rose to the ceiling of the enclosure and did not sink to floor level, as might have been expected.

6.5.44 Lyme Bay

A series four of chlorine field trials were undertaken by the Chemical Defence Establishment at sea in Lyme Bay, off the south coast of England in 1927. A summary can be found in Wheatley et al. (1988). The chlorine was released from cylinders mounted at the rear of a ship at rates ranging from 3.60 kg/s to 11.5 kg/s. In each trial, the rate of release was fairly constant over a duration of approximately 15 minutes and a continuous plume of chlorine formed downwind of the ship.

Concentration measurements were made from submarines positioned at four locations downwind with instrumentation at heights of 3.1 m, 6.2, m and 9.2 m above sea level. The ship and the submarines travelled in line at approximately constant distances apart perpendicular to the wind. Chlorosulphonic smoke was used to make the plume visible. Measurements of concentration were generally made at one minute intervals. Mean concentration, the distance from the point of release and the weather conditions were all recorded.

The concentration measurements show little variation with time suggesting that a steady state was achieved during each trial. Wheatley et al. (1988) calculated a mean concentration at a given station for a given trial from an average over the measurements, along with a one-minute averaged peak at that location.

Meteorological information was provided but there was no record of where it was recorded. Wind speeds ranged from 2.5 m/s – 4.1 m/s at 10 m, air temperature ranged between 10.4 °C and 12.9 °C, relative humidity ranged from 82% to 89% and the sea temperature ranged from 11.1 °C to 12.7 °C. The wind profile was not measured and so the roughness length was estimated from typical values for flow over the sea at 0.001 m.

Wheatley et al. (1988) noted that there was uncertainty in the actual distance of the submarines from the source and their ability to keep at their required station. They also note that there may be uncertainties in the measurements due to coastal and estuary effects.

Wheatley et al. (1988) concluded that the Lyme Bay data from Trials 5 and 6 were suitable for model testing purposes and they used the data in a model validation exercise. They found that the data from Trials 3 and 4 could not be used, due to errors in experimental procedures.

Recently, Hanna et al. (2016) revisited the Lyme Bay data and compared it to measurements from Jack Rabbit I.

6.5.45 Maplin Sands

The Maplin Sands test series involved 34 field experiments in which LNG and LPG were released onto the sea. The trials were conducted by Shell Research Ltd in 1980 on a test site in the Thames Estuary, UK. Details can be found in Puttock et al. (1982), Colenbrander et al. (1984 a,b,c) and Ermak et al. (1989).

The objective of the trials was to study dispersion and combustion of flammable gases. The experiments comprised 11 continuous releases of LPG and 10 continuous releases of LNG. There was one instantaneous release of LPG and two instantaneous releases of LNG. The volume spilled in each trial was approximately 5 m³ - 20 m³ and some of the spills were ignited.

In the continuous releases the liquefied gases were released from a 150 mm diameter pipe orientated vertically downwards above the water surface. The exact distance from the orifice to the surface varied between tests. Release rates typically varied between 19 kg/s and 42 kg/s. In the instantaneous cases, the liquid was released by rapidly sinking a barge loaded with LNG or LPG.

Measurement arcs were arranged at distances of up to 650 m from the release point. Gas sensors were placed on masts at heights from 0.9 m to 2.8 m. According to Hanna et al. (1993a) there were a total of 360 measurement sensors used in these trials, 200 measured gas concentrations, the rest were for measuring the ambient conditions. Meteorological information such as wind direction, friction velocity and relative humidity were also recorded. In one of the LPG releases very low wind speed was recorded and the dense gas cloud was observed to spread upwind a considerable distance.

Perhaps the biggest source of uncertainty in these trials arises from the fact that few sensors recorded data, i.e. the spatial resolution of the data was poor. There were issues with only a limited number of sensors recording gas concentrations due to the instruments not being in the gas cloud. In high winds, the plume was narrow and unfortunately either the wind direction was not coincident with the instrument array axis, or the plume was so narrow that it passed between sensor stations. There is some uncertainty in the vaporisation rate and Stewart et al. (2016) recommended running sensitivity tests on the source conditions when using the data for model validation.

The Maplin Sands data was included in the MDA and the LNG model evaluation databases but it was omitted from REDIPHEN and SMEDIS due to the substrate being water. The uncertainty in the trials means that the MDA only used four of the continuous LNG trials and eight of the continuous LPG trials. Several of the dispersion models tested by Hanna et al. (1993a) showed significant under-predictions of the Maplin Sands concentration data.

6.5.46 McBride et al.

McBride et al. (2001) summarised a set of over 240 trials undertaken in the Boundary Layer Wind Tunnel by Rowan Williams Davies and Irwin Inc. (RWDI). The objective of the study was to model the dispersion of 1 tonne chlorine releases in complex terrain in the wind tunnel and using CFD in order to investigate the impact of neglecting terrain effects in risk assessment. There were 8 sites modelled including relatively flat sites and those with features such as valleys and ridges. All of the sites included a range of on-site buildings. Some also featured off-site buildings, including multi-storey residential structures.

The wind tunnel had a working section 20.8 m long and 5 m wide. The 8 site models were placed on a turntable so that they could be rotated to look at different wind directions (see Figure 48). The model scale was 1:500, representing a site 'diameter' of 5 km at full scale. This allowed chlorine dispersion over a full-scale equivalent distance of 1.2 km.

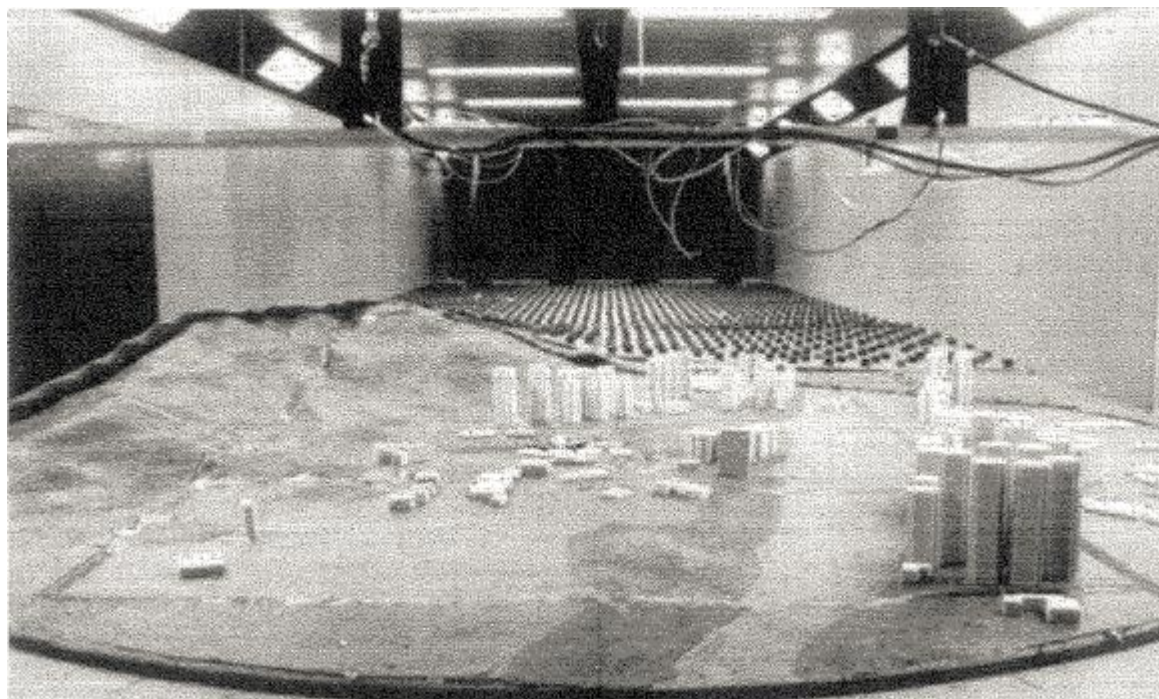


Figure 48 RWDI wind tunnel model of Site 7. Image from McBride et al. (2001, © IChemE copyright)

The chlorine was assumed to be stored in a pressure-liquefied state. In order to simulate this in both the wind tunnel and the CFD the source terms were calculated using source term models in EJECT and DRIFT taking the values at the point at which the aerosol was 99% evaporated.

The wind tunnel modelling was undertaken in two phases. In the first phase, the dense gas was visualised using smoke and in the second phase propane was used as a surrogate tracer gas for chlorine and the gas concentration was measured. The propane was released through a sintered bronze plate with an initial concentration of 100%. Both instantaneous and continuous releases were modelled. Each instantaneous release was repeated five times.

For each site, a range of different wind speeds were investigated. Approximately 30 tests were undertaken at each site comprising combinations of release rate, wind direction and wind speed. Propane concentration was measured at 30 receptor locations at a height corresponding to a full scale height of 1.5 m.

Numerical modelling was undertaken using DRIFT, HGSYSTEM and CFX-4. The results indicated that flat terrain models could overestimate the chlorine hazard range by up to a factor of 5 and the predicted direction of cloud spread could be out by 90°.

6.5.47 Meroney and co-workers

Robert Meroney has been heavily involved in research on dense gases since the 1970s. Many of the studies have focussed on wind tunnel trials and numerical modelling. A summary of much of his work can be found in Meroney (2010) and a list of papers is given on Meroney's website¹⁶⁷.

Examples include wind tunnel models of Burro and Avocet (see Neff and Meroney, 1979; Meroney and Neff, 1982; and Section 6.5.12), work on HSE's water spray curtain studies (Meroney et al., 1984); wind tunnel models of dense gas behaviour in the proximity of fixed structures (Kothari and Meroney, 1979, 1984); wind tunnel releases of negatively buoyant gases from height (Hoot et al., 1973; Hoot and Meroney, 1974; and Section 6.5.30) and wind tunnel studies of vapour barrier studies for HF (Meroney et al., 1989).

Like Hall and co-workers, Meroney (1987a, 1987b) discussed and promoted the use of reduced-scale physical models and reported on several frequently used field datasets, for example, the Thorney Island experiments.

6.5.48 MODITIC

The "Modelling the dispersion of toxic industrial chemicals in urban environments" (MODITIC) project was a European Defence Agency (EDA) project running for three and a half years from September 2012. The project was funded by the Ministries of Defence of Norway, Sweden and France and the French Ministry of Ecology, Sustainability and Energy. The work was undertaken by the Direction Generale de l'Armement (DGA) and INERIS, France, the Norwegian Defence Research Establishment (FFI), the Swedish Defence Research Agency (FOI) and the University of Surrey, UK. An overall summary of the project can be found in Endregard et al. (2016).

The main objective of the MODITIC project was to improve understanding of the physical processes and the associated challenges for modelling dispersion of non-neutral gases in complex urban environments. The aim was to improve dispersion models used in emergency situations by military personnel as well as civil emergency services.

Within the project, atmospheric wind tunnel experiments were undertaken to acquire experimental datasets for a series of dispersion scenarios. These scenarios were then modelled with both CFD and Gaussian models.

The wind tunnel experiments were conducted in the meteorological wind tunnel at the Environmental Flow Research Centre (EnFlo) at the University of Surrey. The tunnel has a working section of 20 m x 3.5 m x 1.5 m with an overall length of 27 m. Details can be found in Robins et al. (2016).

The scenarios were designed with increasing complexity from a simple hill to an urban area comprising a part of Paris in order to investigate how dense and neutrally buoyant gases interact with an increasingly more complex wind field. The scenarios were as follows:

¹⁶⁷ <https://www.engr.colostate.edu/~meroney/Gaspap.htm>, Accessed on 6th January 2021.

- A two dimensional hill with sources upwind and downwind of the crest and a release rate of $0.1 \text{ m}^3/\text{min}$
- A backward facing step with the source in the recirculation region downwind of the step and a release rate of $0.1 \text{ m}^3/\text{min}$
- A backward facing step with cubes downwind of the step and the source located in the recirculation region downwind of step. Release rate of $0.1 \text{ m}^3/\text{min}$
- A simple array of cubes perpendicular to the wind direction and rotated 45 degrees. Three source locations upwind of the array and a release rate of $0.05 \text{ m}^3/\text{min}$
- A complex array with five different shapes including tall buildings and trees. Three sources, two located upwind of the array, one located within the array. Release rate of $0.05 \text{ m}^3/\text{min}$
- An area of Paris at 1:350 scale. Three sources located within the buildings. Three different wind directions. Release rate of $0.05 \text{ m}^3/\text{min}$

Carbon Dioxide was used as the dense gas.

The MODITIC project finished in 2015. A follow on project, MODISAFE, has been proposed to seek to improve understanding of source characteristics and loss processes/agent fate, e.g. absorption, deposition. It is intended to use a similar approach to MODITIC by implementing wind tunnel modelling, field trials and numerical modelling but at the time of writing (2021) the project has not yet started.

6.5.49 Muller

Muller (1997) described a series of wind tunnel experiments on releases of SF_6 undertaken at ETH Zurich. The objective of the study was to investigate the effects of nil wind conditions and ground slopes of 5% - 26% on dense gas releases of varying initial density.

Measurements were taken of the passing of the gravity current front edge and of concentration. The dataset is available in the REDIPHEN database but it contains a significant number of negative concentration values. Also, in the description of the tests, it is stated that on some occasions the concentration instrumentation was used in an uncalibrated state simply to record the passing of the density current front. Unfortunately, there are no records of which trials this methodology was implemented and without this information the Muller (1997) dataset is of limited use for validation purposes.

6.5.50 NASA

NASA conducted a series of seven field experiments of liquid hydrogen spills including dispersion measurements at the NASA HSC White Sands Test Facility in New Mexico. Details can be found in Chirivella and Witcofski (1986). In five of the tests, 5.7 m^3 liquid hydrogen was released over durations of 35-85 s.

The liquid hydrogen was released by pressurising it with helium up to a pressure of 0.7 MPa, which caused approximately 35 % of the liquid hydrogen to flash on release. The liquid hydrogen was spilled onto compacted dry sand with a steel plate located under the spill point.

There was uncertainty in the results, in particular due to liquid hydrogen penetrating into the sand. There was also a lack of measurements within the liquid pools that formed during the tests and so the vapour source was not well defined for modelling purposes. The dataset is still frequently used as a test case for hydrogen modelling validation purposes (e.g. Venetsanos et al., 2010) due to the scarcity of other liquid hydrogen datasets.

6.5.51 Petersen and Ratcliff

Petersen and Ratcliff (1989) and Petersen and Diener (1990) documented a set of wind tunnel trials that studied the effect of large surface roughness on dense gas dispersion,

which were commissioned by the API. The objective was to obtain a dataset to improve understanding of the effects of surface roughness on dense gas dispersion, for use in model development and validation. The concentration measurement data was used for comparison with SLAB and DEGADIS.

The experiments used a 1:100 scale model of three homogeneous and three heterogeneous surface roughness configurations. The homogeneous cases were equivalent to full scale z_0 values of 0.03 m, 0.2 m and 0.5 m. The heterogeneous cases were designed to represent a typical tank farm and a process unit. The tank farm included 18 cylindrical tanks with full scale equivalent height of 9.1 m and diameter 35.1 m, positioned 61 m from each other (centre to centre). Each tank was in a bund with a berm height of 2 m. The processing unit comprised a pipe rack structure 21 m high, 168 m long and 31 m wide with several towers and vessels surrounding it. Homogeneous surface roughness with z_0 values of approximately 0.03 m and 0.5 m were used upwind and downwind of the heterogeneous roughness.

Gas mixtures creating relative densities of 1, 1.4 and 4 were used. For each roughness configuration, both point and area sources were used. The point source was a horizontal release at ground level from a 0.24 m pipe. The area source had 5 m diameter and resulted in a vertical release. A large area source was also created using a rectangular array of nine small area releases with effective width of 22 m.

There were two release locations and two wind directions for the tank farm case and four release locations and four wind directions for the process unit case.

Concentration measurements were made at 0.5 m above ground level along three or four horizontal rows downwind. Each row also had a vertical measurement array at six or seven elevations. The results were analysed to provide maximum ground level concentrations, plume height and plume width.

6.5.52 Porton Down

An extensive set of 42 field trials were performed at Porton Down, UK using Freon-12. Further details can be found in Picknett (1978a, b, c; 1981)

The tests comprised instantaneous releases of 40 m³ of dense gas into grass fields. The majority of the tests were over flat terrain but trials 1 – 4, 9 – 11, 14 and 15 had slopes of 1:13 or 1:14 with the wind direction up or downslope. Also, trials 6 – 8 and 10 recorded very low wind speeds.

The dataset with a summary of conditions was documented for each of the 42 trials in two volumes. It generally comprised concentrations and dosages along with information on the movement of the cloud, cloud height, width and plan area. The relative success of each trial was noted. Hall et al. (1982) created wind tunnel models of Porton Down trials 3, 8, 21, 29, 33, 37 at 1/25 scale. The study provided additional insight into the field-scale dataset.

Despite the amount of data available, the Porton Down dataset was omitted from the MDA because it lacked a continuous array of monitors capable of providing continuous concentration measurements. Instead, the main monitors only provided dosage measurements. Dosages can be used to estimate a mean concentration during the time over which the cloud passed through the monitoring array, but Hanna et al. (1993a) found that those estimates were not useful when trying to quantify model performance. All of the models produced estimates of peak concentration that exceeded the average concentrations estimated from the dosages.

It was also noted at the time by Hall et al. (1982) that these experiments would have benefitted from being undertaken at a larger scale, which was one of the factors which led to the subsequent Thorney Island trials.

6.5.53 Rauchegger et al.

A set of five field tests of continuous releases of tetrafluoroethane at ground level and at height were reported by Rauchegger et al. (2015). There was no information provided about the test site, except for a roughness length for each test and locations of measurement apparatus.

The aim of the study was to find models to extend the VDI guideline 3783 Part 2 (see Section 5.7.48). With this aim in mind the objective of the experiments was to provide additional measurements for model validation. In particular, to determine the length, width and height of the dense gas clouds and the influence of source height. The focus here was dense gas release and dispersion on a small scale such as might occur from standard gas cylinders.

The first to third tests were for dense gas releases to measure the length, width and height of the dense gas cloud. In the first test there were three trials with release rates 12-36 g/s released in wind speeds of 1-1.5 m/s. They found that the distance to the 1% concentration increased with increasing flow rate. In the second test, three trials were undertaken with mass flow rates of 9-35 g/s released in wind speeds of 0.8-1.1 m/s. They found that the width of the dense gas cloud (to the 1% concentration level) increased with increasing mass flow rate. In the third test, four trials were undertaken with a mass flow rate of 10-50 g/s in wind speeds of 0.8-1.3 m/s. The height of the centreline boundary to 1% concentration was taken to be the height of the gas cloud. They found that the cloud height increases with increasing mass flow rate

The fourth set of tests was for releases at height and the fifth set of tests considered the length of the neutral gas field, once the gas had been diluted with air to below 3000 ppm and heavy gas effects no longer occur. In the fourth test, four trials were undertaken with release rates of 14-39 g/s released in wind speeds of 0.9-1.4 m/s. They found that the length of the dense gas field, to the 1% concentration level, decreased with increasing source height. For example, a 24 g/s release decreased in length from about 7 m for a ground level release to about 1 m for a 1 m high release. They also established that there is a critical source height beyond which a dense gas cloud at ground level will not exist. The fifth test comprised three trials with a flow rate of 48 g/s released in wind speeds of 1-1.6 m/s. The passive dispersion model AUSTAL2000 was compared with these results and showed good agreement.

All of the datasets comprised nearfield and farfield measurements of concentration and downwind distances, cloud widths and heights. Meteorological data was recorded.

6.5.54 Resplandy

Two experimental test series of pressure-liquefied ammonia releases undertaken in 1967 at Boisse la Bertrand military camp and 1968 at Mourmelon military camp, France. Further details can be found in Resplandy (1969) and Bouet (1999).

The main objective of the study was to determine under what conditions ammonia diffuses into the atmosphere from a liquid phase discharge in order to determine the radius of the isolation zones to prescribe around pressure storage. Additionally they sought to test the effectiveness of intervention methods available to emergency responders in the event of an accidental leak of ammonia and also to examine the potential for repackaging the liquid ammonia subsequent to release.

In all of the trials the ammonia was initially stored at a pressure of 7 bar. The quantity of ammonia released on average during the tests was around 300 to 500 kg with a maximum of 1,000 kg over durations between 1 and 6 minutes.

In the Boisse la Bertrand tests, they performed nine unobstructed releases of approximately one minute duration from a 2 inch duct pointing vertically upwards, which resulted in a

release quantity of approximately 330 kg of liquid ammonia. In addition, they carried out two tests of approximately one minute duration using a 1 inch duct pointed vertically upwards and vertically downwards with a screen present. The wind speeds were between 0 m/s and 3 m/s.

In the Mourmelon tests, they studied diffusion of a liquid ammonia release resulting from emission through a vertical orifice into a stably stratified atmosphere, with various orientations and they observed the contamination of the atmosphere inside a caravan that was submerged in the ammonia cloud. They also studied gas phase leaks of various initial directions and for a vertical orientation with a screen present. Finally, they looked at containment and mitigation measures in the forms of earth and cement retention basins and water interactions with ammonia. As for the previous tests, the wind speeds were between 0 m/s and 3 m/s.

Bouet (1999) commented that the Resplandy experiments were amongst the first carried out on ammonia and unfortunately they provided mostly qualitative observations on the behaviour of ammonia releases, rather than quantitative measurement data that could be used for model validation.

6.5.55 Riccardi et al.

A set of sulphur hexafluoride jet releases inside a ventilated room in the IRSN/Saclay site, France. Information can be found in Ricciardi et al. (2008).

The objective of the trials was to study the behaviour of heavy gas released into a ventilated room, in order to improve understanding of the consequences of a uranium hexafluoride release into a ventilated room. A secondary aim was to provide experimental data to validate CFX for modelling dense gas dispersion that was used subsequently to model uranium hexafluoride releases.

There were two rooms with different sizes used in the study, a small room with a volume of 36 m³ and a larger one with a volume of 1500 m³. A range of jet emission rates were applied in each room, from 6 m/s to 42 m/s and durations of 2 minutes, 5 minutes or 15 minutes. In the small room, the emission tube diameter was 3 mm, 5 mm or 12 mm and in the large room 12 mm was used. In both rooms, the gas was injected in the middle of the room at a height of 0.15 m, orientated pointing vertically upwards.

Ventilation rates in the small room were set at 1 ach, 3 ach and a series of tests with discontinuous, changing rates. In the large room, the constant ventilation rates applied ranged from 0.2 ach to 3 ach, and two trials were conducted with discontinuous, changing rates.

Each room had measuring apparatus installed on three horizontal planes, totalling between 11 and 14 sampling points. The concentration of sulphur hexafluoride in the room was monitored continuously at each of the points. Care was taken to undertake repeats and ensure good reproducibility of each test.

The data is stated to be of good quality and was compared to predictions from a model developed in CFX.

6.5.56 Schatzmann et al.

Schatzmann et al. (1995) described a set of wind tunnel trials undertaken at the EPA Meteorological Wind Tunnel. Their objective was to determine the effect of an isolated building on the dispersion characteristics of a high-momentum dense gas jet, such as might be released from the valve of a pressurised storage tank.

The working test section of the wind tunnel was 2.1 m high, 3.7 m wide and 18.3 m long, and the model at 1:30 of full scale.

The source conditions were maintained constant throughout the tests. The jet was released vertically upwards from full scale equivalent source diameter of 0.047 m and height 1.5 m. The gas released was a mixture of SF₆ and CO₂ with ethane as a tracer. Two different buildings were used. One was rectangular in shape with a flat roof and the other had a 45° sloping roof which increased the building height.

Concentrations were measured at 18 locations on the surface of the modelled building and again at the same locations without the building present to comparison. Various wind speeds, wind directions, source/building distances and building shapes were modelled. Velocity measurements were made to characterise the boundary layer.

6.5.57 Texas A&M

A series of 5 medium-sized LNG field tests were performed at Texas A&M University's Brayton Fire Training Field (BFTF) over the period from October 2005 to March 2008. Details can be found in Cormier (2008). The objectives of the tests were to look at the effectiveness of LNG mitigation measures for fire personnel and to assess the source term (mass evaporation rate) and vapour dispersion behaviour with obstacles for CFD modelling.

Most of the LNG spills were into concrete bunds, either onto the ground or onto water, in order to generate pools of LNG. Release areas were 43.6 m² and 67.5 m², resulting mostly in unconfined pools. The dispersive phase was frequently obstructed by the bund walls. The mitigation measures tested were an upward vertical jet water curtain and high expansion foam. These were assessed for their effectiveness at dissipating the cloud and controlling the emission rate of LNG vapour.

The largest volume of LNG released was 41 m³. Release rates were 91.2 kg/min over durations of 12 – 86 minutes. The release pipe was a 2 inch aluminium pipe pointed 45° downwards from horizontal.

There was an array of instrumentation both at the release area and at different distances and elevations downwind. Gas concentrations and temperatures measurements were recorded. Meteorological information was also recorded and wind speeds were in the range from 0.5 m/s to 7 m/s.

The tests were used as part of Cormier's doctoral thesis for validation of CFD modelling. Webber et al. (2010) suggested that at least some of the tests were not suitable for source term model validation.

6.5.58 Thorney Island

Over the period from 1982 to 1984, a series of dense gas field trials organised by HSE were carried out at an abandoned Royal Air Force airfield on Thorney Island, West Sussex, UK. Details can be found in McQuaid and Roebuck (1985), McQuaid (1987) and Ermak et al. (1989). Hall and Waters (1984) presented comparisons between Thorney Island Trials 7, 11, 13, 15 and 18 and a wind tunnel model at 1/90 scale. Their discussion provides some additional insight into the trials. The data is available on the ADMLC website¹⁶⁸.

The experiments were split into three phases: Phase 1 consisted of 16 instantaneous releases of 2000 m³ of dense gas; Phase 2 consisted of 10 instantaneous releases of 2000 m³ of dense gas with obstacles; Phase 3 consisted of continuous releases with a fenced enclosure surrounding the gas container. Between Phases 2 and 3, there were also an extra three trials of continuous releases of 2000 m³ of dense gas over empty terrain and an additional single release similar to those in Phase 1. The instantaneous release trials were

¹⁶⁸ <https://admlc.com/thorney-island/> Accessed on 24th April 2020

similar in design to those undertaken previously at Porton Down, but about 50 times larger (Hanna et al., 1993a).

The original objective of the trials was to study the dispersion of fixed volumes of heavy gas but the program was subsequently extended to include continuous releases.

The test area was 2 km long and 500 m wide, and made up of areas of concrete runway and grass. It was flat to within a maximum slope of 1 in 100. The dense gas released was a mixture of Freon-12 and nitrogen, and was ducted below ground to a vertical outlet at ground level. In the continuous tests, this outlet had a 2 m diameter cap over the outlet at 0.5 m above the ground that was designed to release the gas with near-zero vertical momentum.

There were 38 fixed measurement stations, each with 5 gas sensors. The gas was measured at four heights, with the lowest at 0.4 m and the highest depending on the proximity to the source: 4 m near the source, 10 m at most measurements stations and 14.5 m in the far field. There were also four mobile masts each with four gas sensors and sonic anemometers to measure velocity. In the far field, the measurement stations were arranged in straight lines every 100 m from 100 m to 500 m. More sensors were concentrated in the near field, at distances less than 200 m, in arrays of curved arcs.

The recorded wind speeds were quite low in several of the releases. For example, for the instantaneous releases used in the MDA, the wind speeds range from 1.7 m/s to 7.4 m/s (stability classes D to F). In the two continuous tests used the wind speed was only 2.1 m/s and 1.5 m/s (stability classes E/F and F).

There is much less uncertainty in the source term in the Thorney Island tests compared with other datasets involving releases of LNG, such as Maplin Sands, Burro, Coyote and Falcon. This is primarily because the source in Thorney Island was a well-controlled release of dense gas, not a vaporising liquid spill. Uncertainties that remain are mainly down to the roughness length and the atmospheric stability. It should also be noted that while the variation in the height of the terrain was only about ± 0.5 m across the site and may appear minimal, this is comparable in magnitude to the cloud height in some cases and it may have influenced the results.

The Thorney Island dataset was included in the MDA, REDIPHEN, SMEIS and LNG model validation databases. Nine out of the 16 instantaneous release trials and two of the three continuous ones were included in the MDA. The other trials were dropped because of wind shifts during the trial, the cloud being elevated, the release mechanism malfunctioning and stratification in the density of the initial cloud.

The Thorney Island experiments provide a good quality dataset but they are challenging to model, particularly using CFD, due to the shallow cloud, the surface roughness conditions and the presence of stably-stratified atmospheric boundary layers (Batt et al., 2018).

6.5.59 University van Kunstmest Fabrieken bv

Two experimental test series were undertaken by the University van Kunstmest Fabrieken, Holland in 1972 and 1980. Details can be found in Blanken (1980) and Bouet (1999). The tests in 1972 involved two releases of 38.4 kg of pressure-liquefied ammonia. The objective was to measure the amount of ammonia collected on the ground during release.

A container of ammonia at 3.5 bar and 0°C was setup to release ammonia through an 8 mm diameter nozzle resulting in a mass flow rate of 0.64 kg/s. The first test was set up with the discharge point horizontal, perpendicular to the wind, located at 1.8 m from the ground. The second test was set up to discharge vertically downwards at 2 m from the ground.

The first test reported 5.5 kg of liquid ammonia collected representing 14.3% of the ammonia released. The second test reported 27.3 kg of liquid ammonia collected, representing 71.1% of the ammonia released.

There was no record of the ammonia collection method and the ammonia concentration was not measured.

For the tests in 1980, ammonia stored at 13.4 bar and 38 °C was discharged through a pipe 100 mm long and 2 mm in diameter into moist air. The objective of the tests was to study the size of the droplets in the jet. According to the summary of Bouet (1999), they found that in an ammonia atmosphere, the jet was transparent and the liquid separated from the jet and puddled on the ground. In humid air, the spray was opaque and the liquid ammonia did not collect. It was assumed that the ammonia aerosol initially formed during release vaporized quickly when it diluted with air. And it was concluded that the cloudiness was caused by the condensation of water, which forms an aerosol of aqueous ammonia.

Only qualitative results were obtained, no concentration measurements were made.

6.5.60 Unno et al.

Unno et al. (2015) documented a series of small-scale field trials involving liquefied hydrogen and LNG spills, undertaken by Iwatani Corporation, Kawasaki Kisen Kaisha, Ltd. and Nippon Kaiji Kyokai, Japan.

The objective of the study was to compare the dispersion behaviour of liquefied hydrogen compared with LNG and to investigate the flammability limits of hydrogen in low ambient temperatures.

In the tests, 6 litres of liquid were spilled from a stainless steel open dewar vessel onto two different surfaces, which consisted of an austenite stainless steel plate and a concrete plate of dimension 1.2 m x 1.2 m and 8 mm thick. The distance between the dewar and the surface was approximately 0.9 m and the spill took approximately 15 s.

No measurements were taken, only visual data was obtained. Basic weather conditions were recorded. The results are unlikely to be suitable for model validation.

6.5.61 URAHFREP

The URAHFREP (Understanding the dispersion of industrial Releases of Anhydrous Hydrogen Fluoride and the associated Risks to the Environment and People) project was undertaken as part of the EC's Fourth Framework Programme. It started in 1998 and ran for three years. HSE led the project and its aims were to investigate the dispersion behaviour of flashing accidental releases of Anhydrous Hydrogen Fluoride (AHF). The experimental trials comprised both field and wind tunnel tests. A summary of the project can be found in Porter and Nussey (2001). Further details can be found in Hall and Walker (2000), Hall et al. (2000, 2001) and Ott (2001).

A key objective was to determine whether a release of AHF would likely result in a buoyant gas or a dense gas in the various stages of its dispersion. Prior to these experiments, only the Goldfish experiments provided insight. Goldfish indicated that AHF would act as a dense gas, but in those tests the possibility of a transition to a buoyant cloud was very low because the humidity of the desert air was too low for the exothermic reaction with atmospheric water vapour.

The URAHFREP field tests were conducted by the Defence and Evaluation Research Agency (DERA) (under contract to CEA) and their partners in August 2000 at Porton Down, UK. The experiments were designed to be reduced-scale replicas of the order of a tenth of the size of a full-scale release. There were twelve semi-continuous releases with release rates of 0.06 – 0.15 kg/s and approximately 15 – 20 kg of AHF in each test. Two of the tests released a 50/50 mix of AHF and isobutane at about 0.1 kg/s. The wind speeds were mostly between 1.3 and 7 m/s with relative humidities in the range 46% to 92%. One release constituted low wind speed and high humidity conditions.

The release mechanism resulted in a steady horizontal pressurised jet at temperatures below the boiling point. This meant that the resulting spray was not generated by flashing. The release pressure and nozzle diameter were selected in order to minimise rainout, which was successful in all but one trial (Trial 3). Where liquid AHF did rainout, there was significant ‘scorching’ to the vegetation. The AHF releases were followed by a passive smoke release to characterise the ambient turbulence.

Concentration was measured on a 60° sector from 20 m to 1000 m downwind. Different concentration devices were used, enabling some measurements to be verified. Temperature measurements were taken, mostly at 5 m and 20 m downwind of the release. Video footage was also captured. Meteorological measurements were recorded.

The wind tunnel trials comprised 120 releases of zero-momentum buoyant plumes and a set of buoyant puffs from ground level sources (Hall et al., 2000, 2001). These were positively buoyant and details are not included here.

The URAHFREP project found that the usual worst-case conditions (low wind, stable and humid conditions) may provide significant cloud buoyancy leading to significantly reduced ground level concentrations.

The project was designed to assist in improving models and to provide datasets suitable for model validation. It is a good quality dataset and has been used in the validation of various models (e.g. DRIFT).

6.5.62 Van Ulden

Van Ulden (1974) documented a set of field experiments involving 1 tonne of Freon-12 spilled on water at Maasvlakte, Netherlands. The objective of the tests was to acquire a better understanding of the behaviour and control of large accidental chlorine spills, without the hazards of releasing a large quantity of chlorine.

The experimental setup comprised a vessel with 1000 kg of liquid Freon at ambient temperature placed over an open tank filled with hot water. The liquid was released quasi-instantaneously from the bottom of the vessel using a rupture disc, which broke once the pressure in the vessel reached about 7 bar (the vapour pressure of chlorine at ambient temperature). On contact with the water, sufficient heat was provided for the Freon to completely evaporate in about 5 s. Water vapour condensed in the release and made the cloud visible.

After about 35 s the diameter of the cloud was about 100 m with a depth of about 0.5 m. After about 70 s it was clear that the cloud was starting to behave as a neutrally buoyant gas.

There do not appear to have been any measurements made except to record the diameter of the visual cloud with time. Van Ulden used the dataset qualitatively to propose mathematical models to characterise the flow (e.g. Van Ulden, 1988).

6.5.63 Verfondern and Dienhart

Verfondern and Dienhart (1997, 2007) documented a series of four liquid hydrogen releases onto water and an aluminium sheet. Two tests were undertaken onto a circular pool of water that was 3.5 m in diameter and filled to a depth of about 1 m. Two further tests were onto a square aluminium sheet 2 m x 2 m and 0.02 m thick. A complicated release mechanism was used in an effort to minimise the initial momentum. The liquid hydrogen passed through a diffuser to widen the cross-section from the inlet pipe by a factor of about 10. The diffuser was approximately 0.02 m above a 0.4 m diameter pan. The pan was placed on the substrate surface so that the liquid discharged into it and then eventually overflowed onto the surrounding surface. A round aluminium sheet was also fixed above the pan to prevent the

boiling liquid escaping in an uncontrolled fashion. It was estimated that 30% of the liquid hydrogen flashed at the start of the tests. The release rates were about 0.005 m³/s over 62 s. Instruments at 20 different positions measured the spread of the liquid pool. The atmospheric conditions were recorded throughout the experiments.

No measurements were recorded in the dispersing gas cloud. The observations indicated that it achieved positive buoyancy very quickly.

6.5.64 Wannberg et al.

Wannberg et al. (2010) documented a set of 32 low wind speed (<2 m/s) experiments in which positive, negative and neutrally buoyant gases were released at the Nevada Test Site in February 2007. The objective of the study was to generate a dataset of gaseous plume measurements in low wind speed conditions for the evaluation of numerical models.

The buoyant gas used was ammonia, the neutrally buoyant gas was ethylene and the dense gas was propylene. Release rates ranged from 1 to 20 kg/h. Five tests of five minute duration were undertaken to represent puff releases of ammonia and ethylene and five tests of 20 minute duration were used to represent plume releases. For propylene there were five tests of five minute duration puffs, six tests with 20 minute duration plumes and one 30 minute duration plume. Of the 32 releases undertaken, 30 provided useful data.

The release point was situated at 2 m above ground level and had an internal diameter of ¾ inch. The dataset included measurements of release rates, concentrations up to 100 m from the release point and local meteorological conditions. Measurement stations were laid out radially from 10 to 100 m around the release point and at a height of 2 m.

The measurement data was used for model comparison exercises with ALOHA, EPIcode and SCIPUFF. Tabulated input information was provided by Wannberg et al. (2010). All of the models were compared to all of the datasets. In general, they all had difficulty replicating the experimental measurements. The work highlighted that the models should be used with care in low wind speed conditions. In particular, ALOHA under-predicted observed concentrations.

6.5.65 Other

A significant amount of experimental work has been undertaken on density currents or gravity currents in addition to the work documented above. Most of these experiments have been undertaken in laboratory water flumes using saline and fresh water to generate the density difference. They provide a large body of information for investigating specific density driven flow characteristics and have been used for validating fundamental theory behind density currents. An overview can be found in Simpson (1997). An example of their use in modelling dense gases can be found in Rottman et al. (1985), where fluid interaction with obstructions similar to Thorney Island was investigated. These types of experiments have not been included in this review.

There are various trials measuring infiltration and air change rates in buildings without a contaminant present. There are three examples with details in the work of Liddament and Allen (1983). These comprise the Mark XI energy research project, Ontario, Canada; the Maugwil Test Building, Duebendorf Switzerland; and the Runcorn Development Corporation House, Runcorn, UK.

6.6 Summary

This Chapter has provided a brief description of experimental studies which include dispersion of dense gases. A tabular 'quick reference' summary of all of the experiments can

be found in Annex I¹⁶⁹. The discussion below identifies the main features of the experiments and identifies where further work might be useful.

6.6.1 Features of the experiments included in this study

Type of experiment

This review has briefly examined 42 field trials and 21 wind tunnel studies that involved dense gas releases. It is not exhaustive and many more wind tunnel studies have been undertaken by experts such as David Hall and Robert Meroney. The following section discusses some of the main features of the experimental studies and identifies where further work may be useful.

Substances

The different substances (or mixtures) released in the experiments are summarised in Figure 49. The substance with the largest number of tests is LNG. This focus on LNG has presumably been due to its importance as a fuel and therefore the requirement to investigate the safety aspects of transporting and storing it in large quantities. Carbon dioxide, Freon, argon, krypton, SF₆ (and combinations thereof) are not flammable or reactive, which makes them ideally suited to experimental work, particularly wind tunnel studies.

In many of the experiments, the dense gas was generated by a release of a liquid that was either temperature- or pressure-liquefied (or, in some cases, a refrigerated pressure-liquefied gas). In the tables that follow, studies where the dense gas originated from a gas-phase release are marked with an asterisk to differentiate them from liquid or two-phase releases.

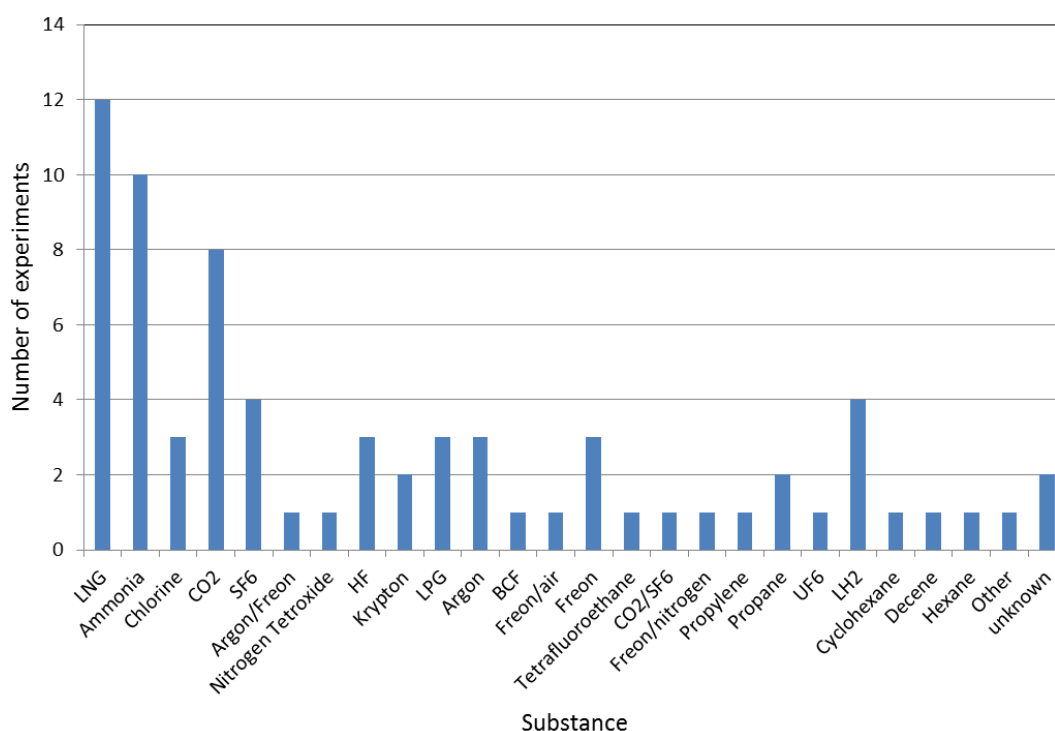


Figure 49 Number of experiments for each substance or mixture of substances. Experiments that included multiple substances are counted for each substance

¹⁶⁹ "ANNEX_I_Summary_tables_incidents_experiments.xlsx"

Surface

There were 11 field experiments that investigated dense gas dispersion over water, or involved releases onto water. These are listed in Table 24. In all of these experiments, the dense gas was generated from a liquid or two-phase release. Nearly all of them involved LNG. Gadila and Lyme Bay were both releases from a ship.

Table 24 Experiments in which the dense gas disperses over water

Experiment	Substance
API/Esso	LNG
Bureau of Mines	LNG
Burro	LNG
Coyote	LNG
Falcon	LNG
Gadila	LNG
Lyme Bay	Chlorine
Maplin Sands	LNG, LPG
Texas A&M	LNG
Van Ulden	Freon-12
Verfonderen and Dienhart	Liquid hydrogen

The remainder of the field experiments were on land, and all the wind tunnel experiments also were also characterised as releases on land.

Of the land-based field trials, there were five in which the porosity of the substrate could have affected the source conditions or led to other complications, such as the rapid phase transitions observed in Jack Rabbit I. These five tests are listed in Table 27. Again, all of these were initiated from liquid or two-phase releases.

Table 25 Experiments in which porosity of the substrate could affect the source of the dense gas

Experiment	Substance
AGA	LNG
Eagle	Nitrogen Tetroxide
Ecole des Mines d'Ales	Ammonia
Jack Rabbit I	Chlorine, ammonia
NASA	Liquid hydrogen

Obstructions and topography

There were 28 tests which included obstructions, and 11 tests in which topography may have influenced the gas dispersion behaviour. The tests with obstructions are identified in Table 26. Those involving topography are listed in Table 27.

Table 26 Experiments in which obstructions may be a factor affecting dense gas dispersion

Experiment	Substance	Field	Wind tunnel	Obstruction
AGA	LNG	x		Bund
BA Hamburg*	SF ₆		x	Various cubes and fence configurations
BA TNO*	SF ₆		x	Fence
BMT*	Argon/Freon		x	Off-shore module
Bureau of Mines	LNG	x		Bund
CHRC*	CO ₂		x	Tank and dike
COOLTRANS*	CO ₂	x		Elongated mound
Eagle	Nitrogen	x		Barrier
	Tetroxide			
EMU-ENFLO*	Krypton		x	Buildings, model industrial site
Falcon	LNG	x		Vapour fence
FLIE	LPG	x		Large obstacle (wall)
Guldemond*	Argon		x	Model industrial site
Hall et al.*	BCF, argon		x	Buildings and fences
Hoot et al.*	Freon/air mix		x	Cube
ICHMAP	HF	x	x	Vapour barrier, heavily and moderately obstructed process units
ICI	Ammonia	x		Retention basin
INERIS	Ammonia	x		Wall, retention basin
Jack Rabbit II	Chlorine	x		Shipping containers and vehicles
JGA	LNG	x		Bund
Kit Fox*	CO ₂	x		Billboard arrays
Lathen / BA	Propane	x		Various fence configurations
Propane				
McBride et al.*	Propane		x	8 different model sites including industrial and residential buildings
MODITIC*	CO ₂		x	Step, single cube, arrays of cubes, scale replica of Paris
Petersen and Ratcliff*	?		x	Tank farm
Resplandy	Ammonia	x		Screen, retention basins
Schatzmann et al.	SF ₆ /CO ₂ mixture		x	Isolated building
Texas A&M	LNG	x		Bunds
Thorney Island*	Freon-12/N ₂	x		Fenced enclosure

*Denotes gas phase releases

Table 27 Experiments in which topography may be a factor affecting dense gas dispersion

Experiment	Substance	Field trial	Wind tunnel	Topography
BA Hamburg*	SF ₆		x	Slopes
Burro	LNG	x		Test site terrain
China Lake*	Argon, Freon-12		x	Scaled replicas of Burro
COOLTRANS*	Carbon dioxide	x		Sloping terrain, crater
EMU-Enflo*	Krypton		x	Model site with complex topography
Guldemonnd*	Argon		x	Model site with complex topography
Jack Rabbit I	Chlorine, Ammonia	x		Crater
McBride et al.*	Propane		x	8 different model sites with complex topography
MODITIC*	CO ₂		x	2D hill
Muller*	Sulfur hexafluoride		x	Slopes
Porton Down*	Freon-12	x		Slopes

*Denotes gas phase releases

Source height

There were 28 experiments involving elevated sources¹⁷⁰, which are listed in Tables 28 and 29. The experiments where the release orientation was given are listed in Table 28, and those without an indication of the orientation in Table 29. Table 28 shows that the majority of elevated releases were orientated vertically downwards or horizontally. There are only three trials which include vertically upwards orientated releases.

¹⁷⁰ There are 29 including Ricciardi et al. (2008), which has not been included because it was an indoor release

Table 28 Experiments in which the release was from an elevated position and orientated horizontally

Experiment	Substance	Vertically upwards	Vertically downwards	Horizontal	Other
API/Esso	LNG				30° upwards from horizontal Tank overfilling
Atkinson and Coldrick	Hexane, water, decene				
Burro	LNG		x		
COOLTRANS*	Carbon Dioxide			x	
Coyote	LNG		x		
Desert Tortoise	Ammonia			x	
Ecole des Mines d'Ales	Ammonia		x		
FLIE	LPG			x	
FLADIS	Ammonia	x		x	
Goldfish	Hydrogen fluoride			x	
Hoot et al.*	Freon/air	x			
HSE 2012	LH2		x	x	
Imperial Chemical Industries	Ammonia		x	x	Some were 'slightly' upwards from horizontal
INERIS	Ammonia		x	x	
Jack Rabbit I	Chlorine, ammonia		x		
Jack Rabbit II	Chlorine	x	x		45° downwards from horizontal
Landskrona*	Ammonia			x	
Texas A&M	LNG				45° downwards from horizontal
University van Kunstmest bv	Ammonia		x		
Unno et al.	Liquid hydrogen, LNG		x		
Verfondern and Dienhart	Liquid hydrogen		x		

*Denotes gas phase releases

Table 29 Experiments in which the release was from an elevated position but the orientation has not been established

Experiment	Substance
Falcon	LNG
Gadila	LNG
Lyme Bay	Chlorine
Maplin Sands	LNG, LPG
Rauchegger et al.*	Tetrafluoroethane
Schatzmann et al.*	Sulfur hexafluoride/Carbon dioxide mixture
Van Ulden	Freon-12
Wannberg et al.*	Propylene

*Denotes gas phase releases

Low or nil wind

There were at least 19 tests under low or nil wind conditions, which are listed in Table 30. Water flume experiments are useful for investigating gravity currents in nil wind conditions, but these have not been reviewed here.

Table 30 Experiments undertaken in nil or low wind conditions

Experiment	Substance
Burro	LNG
Gadila	LNG
Maplin Sands	LNG
COOLTRANS*	Carbon dioxide
Egami et al.*	Carbon dioxide
HSE 1985*	Carbon dioxide
Kit Fox*	Carbon dioxide
ENFLO 2000*	Carbon dioxide, krypton
Jack Rabbit I	Chlorine, ammonia
Resplandy*	Ammonia
URAHFREP	Hydrogen fluoride, hydrogen fluoride /isobutane mix
Wannberg et al.*	Propylene
Lathen / BA Propane	Propane
Muller*	Sulfur hexafluoride
Lux*	Uranium hexafluoride
Hall and co-workers*	BCF, argon
Hoot et al.*	Freon/air mix
Porton Down*	Freon-12
Thorney Island*	Freon-12/nitrogen mixture

*Denotes gas phase releases

Ingress

There were three tests where ingress of dense gas into a structure was monitored, which are listed in Table 31. The work of Ricciardi et al. (2008) was not included here because it did not study ingress of the gas, but they did provide measurements of the behaviour of dense gas once inside a ventilated building.

Table 31 Experiments in which dense gas ingress into a fixed structure was monitored

Experiment	Substance	Structure
COOLTRANS*	Carbon dioxide	Two storey structure
Jack Rabbit II	Chlorine	Vehicles and containers
Resplandy	Ammonia	Caravan

*Denotes gas phase releases

There have been various experimental trials studying air flow into and out of buildings, without dense gases, some examples are mentioned in Section 6.5.65.

Mitigation measures

There were 16 tests which included consideration of mitigation measures. These are listed in Table 32 along with a brief description of the measures implemented. Mitigation measures are discussed further in Chapter 7.

Table 32 Experiments in which mitigation measures for dense gas dispersion were considered and type of measures

Experiment	Substance	Mitigation measure
AGA	LNG	Bund
Falcon	LNG	Vapour fence
Texas A&M	LNG	Upward vertical jet water curtain, high expansion foam, walled bund
Resplandy	Ammonia	Obstruction/screen, earth and cement retention basins and water interactions
Ecole des Mines d'Ales	Ammonia	Peacock tail water sprays
INERIS	Ammonia	Peacock tail water sprays
BA Hamburg*	Sulfur hexafluoride	Various walls
BA TNO*	Sulfur hexafluoride	Various walls
HSE 1985*	Carbon dioxide	Water spray barriers
CHRC*	Carbon dioxide	Dike
Eagle	Nitrogen Tetroxide	Portable Foam Vapor Suppression System (PFVSS)
Goldfish	Hydrogen fluoride	Water sprays, dike
ICHMAP	Hydrogen fluoride	Water spray/fog barriers (including augmented water), vapour barrier/box
Lux	Uranium hexafluoride	Coarse water spray, air jet, (electrostatically and non-electrostatically charged) steam spray, Carbon Dioxide, Freon-12, fine water mist (uncharged), boric acid mist (charged and uncharged) and an ionised dry air stream
Thorney Island*	Freon-12/nitrogen mixture	Fenced enclosure
Meroney*	Various	Vapour barrier for HF, water spray curtain

*Denotes gas phase releases

6.6.2 Potential gaps in available experimental data

A summary is given below of potential gaps in the available experimental datasets or areas where further study might be useful to supplement existing work.

Experimental trials in ideal conditions and in a range of atmospheric conditions, including transition from dense to passive dispersion behaviour

Experiments are undertaken for different purposes, ranging from idealised tests that are designed to investigate perhaps just one aspect of the physical behaviour (such as an entrainment rate into a plume) to complex releases that are designed to mimic as closely as possible a realistic scenario, such as the chlorine road tanker release in Jack Rabbit II Trial 9. Wind tunnel tests can provide detailed measurements and, since tests can be repeated under nominally identical conditions, they are useful for assessing the variability in short-duration or puff releases. However, they have limitations in scaling effects, problems with laminarisation and they do not account fully for atmospheric effects, such as wind meandering. Ideally, one would have a combination of both idealised and realistic scenarios to fully investigate a given problem, combined with wind tunnel studies and model comparisons.

Havens (1992) identified a number of uncertainties that arise in field-scale experiments that can complicate their subsequent use for model validation. In many experiments, the source is complex or not accurately measured. Havens recommended that a set of experimental trials be designed to provide dispersion data in ideal conditions, with no complications due to the presence of aerosols and accurately determined source conditions. They should be conducted on flat terrain with no obstacles and low surface roughness and should include a range of release rates and wind speeds in order to span a range of Richardson numbers (based on release conditions described in Section 3.2.2; see also Spicer and Havens, 1989, and Havens and Spicer, 1990). The experiments of Egami et al. (1995) go some way towards meeting Havens requirements of well-controlled experiments in ideal conditions, and they attempted to look at the effects of atmospheric stability, although changes in the weather during the test schedule meant that they did not manage to achieve the full range of desired conditions involving low wind speeds and stably-stratified atmospheres.

Havens highlighted that the ultimate limit of understanding dense gas dispersion lies within understanding passive dispersion and consequently the effects of the atmospheric boundary layer. He argued that it is crucial for observations and measurements to be continued until the cloud becomes passive.

Experimental trials involving changing meteorological conditions

Modellers are often interested in having experimental datasets in which meteorological conditions are static, to avoid complications or uncertainties arising from wind speeds or atmospheric stabilities changing over time. However, this can be difficult to achieve in practice. In reality, incidents can occur over several hours, during which time the meteorological conditions can change significantly. Therefore, there are benefits in looking at both static and changing meteorological conditions.

Wind tunnel and full scale dense gas dispersion over topography

Table 23 shows that there are five studies identified in this review which consider realistic topography, rather than just slopes and hills in isolation. Only one of these is at field scale. It would be informative to look at both passive tracer and dense gas releases in varied topography, with a range of atmospheric conditions and at varying scales. These trials would expand on previous work, such as that of McBride et al. (2001). For example, they would assist in understanding when it is important to account for topography in modelling and when topographical effects can reasonably be neglected in favour of assuming the terrain is flat. Wind tunnel modelling would enable the size of the gas cloud to be scaled while other

conditions remain unchanged. Field trials might be required to study more complex atmospheric boundary layer effects.

Full scale dense gas dispersion in the industrial/urban environment

There are several studies, particularly in wind tunnels, which have explored the effects of surface roughness on dense gas dispersion, where the gas cloud is deeper than the surface roughness height. Alongside these, there are several which have looked at dense gas plume interaction with isolated obstacles and a limited number of studies looking at plume interaction with homogeneous arrays of obstacles (see Table 26). However, there are relatively few studies of dense gas releases in urban environments, for example, where the cloud is channelled along street canyons (Endregard et al., 2016, Section 6.5.48; Petersen and Ratcliff, 1989, Section 6.5.51).

There are several full scale urban dispersion experiments for passive releases where the environment is significantly higher than the initial cloud depths, e.g. Urban 2000 (Allwine et al., 2002); Joint Urban 2003 (Allwine and Flaherty, 2006a); Madison Square Garden 2005 (Allwine and Flaherty, 2006b); Midtown Manhattan 2005 (Allwine and Flaherty, 2007); DAPPLE (Arnold et al., 2004). There are few studies where the scales of the obstructions are large compared with the dense gas cloud (e.g. Thorney Island, Jack Rabbit II), but the obstructions in these cases are limited in extent.

Studying the combined effects of obstacles and terrain could be useful for application to cities, such as Hong Kong, Montreal and Rio de Janeiro, where there are densely-populated urban environments with significant variation in underlying topography. Even relatively flat capital cities, such as London and Paris, have some areas with sloping terrain.

The hazard associated with dense gases means that these full-scale dense gas release experiments in urban environments are unlikely to take place, on safety grounds. To address this knowledge gap, efforts may need to rely on wind tunnel studies and modelling.

Vertically upwards orientated releases from height

There are very few dense gas experiments where the gas release is orientated vertically upwards and from varying heights (see Table 28). These cases may have lower downwind concentrations and transition to passive dispersion over relatively short distances but they can show the effects of dense gas dispersion in the nearfield. Examples in this study include Runcorn, UK (Section 4.4.4), Bhopal, India (Section 4.5.25), Richmond, California (Section 4.5.40) and Antwerp, Belgium (Section 4.5.47).

The effects of atmospheric stability in conjunction with releases from height has been shown previously (Hoot et al., 1973). Under neutral atmospheric conditions, the dense gas plume might not touch down and cause a significant hazard but stably stratified, low wind conditions may augment the density effects preventing effective dispersion and increasing the hazard. Releases in urban and industrial environments, as found in the incidents mentioned above, where the gas cloud touch down is blocked or disturbed by the presence of obstructions both lower and higher than the release point may be of interest particularly in relation to the impact this has on the period of transition to passive dispersion.

Infiltration and ingress

There is little experimental work on infiltration of dense gases into structures, particularly real structures such as homes and offices or designated shelters. Those known to this study are summarised in Table 31. It is important to test whether the 'well-mixed' assumption in models is valid or whether there are any conditions under which it is not.

In particular, there are no studies investigating infiltration into subterranean spaces such as sewers, subways, basements, underground car parks and bunkers, despite incident information indicating that this occurs (see Table 16 in Chapter 4).

The Jack Rabbit II trials (Section 6.5.37) are perhaps the only work on infiltration of dense gases into vehicles. Combinations of stationary, moving, running and not running vehicles are of interest as reported information indicates that both civilian and emergency services vehicles drive through gas clouds during incidents, both intentionally and unintentionally (see Table 16 in Chapter 4).

Indoor to outdoor dense gas dispersion

There are several incidents which have resulted from leaks indoors escaping the structure and dispersing outdoors (see Table 15 in Chapter 4). An indoor source provides a complex secondary source for atmospheric dispersion modelling, likely to result from gas exiting the structure via adventitious openings and ventilation systems. This study has not found any examples of experiments where the source arises from dense gas escaping from within a structure.

Sources

This experimental review has not covered source terms in detail, and has instead focused on dispersion. However, source conditions for dense gas releases usually have a strong effect on the subsequent dispersion behaviour. For model validation studies, it is beneficial to have accurate knowledge of the source conditions. For scenarios involving two-phase jets and/or evaporating pools, this can be a challenge.

The review of incidents indicated that on many occasions, the source of dense gas arises from a pressurised leak from a crack in a pipe or valve, at a variety of elevations and angles. There are no studies looking at these irregular, but commonly occurring, source conditions (an observation also made by Britter, 1998). This may reflect the fact that source conditions for irregular cracks are hard to characterise for use in model validation studies. It is nevertheless a knowledge gap.

There is little work on catastrophic releases, i.e. instantaneous or near-instantaneous releases. Thorney Island represents a medium scale instantaneous gas release but this does not consider a release of a liquefied gas such as occurred in the Houston (Section 4.5.17) or Potchefstroom (Section 4.5.12) incidents.

Congestion

Gas dispersion through hedgerows or through complex pipe networks are known contributors to the hazard in incidents involving flammable gases (if the flammable gas in a congested area is ignited, the flame will accelerate as it passes through the array of obstacles, leading to high over-pressures and/or deflagration-to-detonation transition). However, there is little experimental work investigating their impact on dispersion of dense gases in congested areas.

Congested environments are also locations where increased deposition can occur (see below).

Dry deposition

There is very little experimental work on the impact of dry deposition on dense gas cloud dispersion. It has been demonstrated using models that dry deposition can have significant impact on reducing hazard ranges (Hanna and Chang, 2008; Dillon, 2009; McKenna et al. 2017a). Many models do not include dry deposition because there is insufficient experimental information available to characterise it. Dillon (2009) and SAIC (2010) discuss future work that should be undertaken to improve understanding and modelling of deposition. Work is currently underway at Arkansas University (Spicer et al., 2019) to address this knowledge gap, for chlorine at least.

7 MEASURES FOR MITIGATING DENSE GAS RELEASES

7.1 Introduction

This section discusses measures for mitigating different stages of a dense gas release, including measures focused on the source, the dispersion stage and exposure. Further useful information on mitigation measures can be found in the book: Lees' Loss Prevention in the Process Industries (Mannan, 2012, Section 15.53). In particular, Mannan (2012) discusses the use and merits of bunds, foam barriers, solid barriers and various fluid barriers and provides a body of references. Examples of the use in practice of many of the mitigation measures discussed here can be seen in several of the incidents in Chapter 4.

7.2 Guidance

For most substances, there are specific guidance documents available on mitigation measures, either through relevant regulatory or government bodies, or through consortiums of industry stakeholders. For many of the mitigation measures discussed below, particularly those at the source and for dispersion, knowledge of the substance released is a key factor in their success.

7.2.1 HSE

Regulations such as COMAH (HSE, 2015a) provide a source of generic information on prevention, control and mitigation measures for industrial sites, as shown in Figure 50.

458 Examples of the types of prevention, control and mitigation measures which are likely to be particularly important in safety reports are:

- (a) structural integrity of containment;
- (b) process control systems, including back-ups;
- (c) systems for protecting and ensuring the continuity of electrical supplies;
- (d) fire and explosion protection systems;
- (e) devices for limiting the scale or consequences of accidental releases, eg scrubbing systems, water-spray vapour screens, emergency catch pots or collection vessels, emergency shutoff valves, remotely-operated shutoff valves (ROSOVs), secondary containment systems;
- (f) alarm systems including fire and gas detection;
- (g) automatic shutdown systems;
- (h) inerting and suppression systems;
- (i) safety instrumented systems;
- (j) emergency venting through valves or explosion panels;
- (k) rapid shutdown and other emergency procedures;
- (l) special precautions against unauthorised actions.

Figure 50 Excerpt from COMAH regulations (HSE, 2015a)

Specific information is not contained in the regulations because they cover such a wide range of substances. However, HSE provide a series of additional supporting documents pertaining to good practices for a variety of hazardous substances under different circumstances, e.g. bulk storage, smaller containers, transport. Most of these guidance documents include information on control and mitigation measures, although they often refer

the reader to substance suppliers and other sources for specific information. The following documents are available from the HSE website¹⁷¹:

- HSG191 – Emergency planning for major accidents: Control of Major Accident Hazards Regulations 1999 (COMAH) - Good practice guidance reflecting the COMAH regulations. HSG191 does not contain specific mitigation measures, it is designed to assist in emergency planning and preparedness. It is included here as a form of mitigation through prevention.
- HS(G)28 and HSG40 – Includes some information on mitigation such as leakage control measures, PPE and first aid for chlorine. Also includes guidance for releases that occur inside buildings. There is significantly more detailed information on mitigation in the Chemical Industries (CIA) guidance summarised below.
- HSG51, HSG140 and HSG 176 – This series of health and safety guidance documents highlight the hazards of handling flammable liquids (and their vapours) (HSG140), storage in tanks (HSG176) and storage in containers (HSG51). Each document includes information on control measures, mitigation measures and other safety measures.
- HSG186 The bulk transfer of dangerous liquids and gases between ship and shore. Includes measures for prevention and control of spillage relevant to an industrial dock-side environment and precautions against fire or toxic gas release.
- HSG244 – Provides guidance on Remotely Operated Shut-Off Valves (ROSOVS) including considerations involved in deciding whether they are required for a site.
- HSG173 – Provides guidance to employers for monitoring exposure of employees to substances hazardous to health by inhalation.

HSE also publish substance-specific documentation for some industry areas. For example, there is an Offshore COSHH essentials document for hydrogen sulphide, which includes information on planning, controls and emergency mitigation (HSE, 2011).

7.2.2 National Fire Chiefs Council's Central Programme Office

The National Fire Chiefs Council's Central Programme Office (NFCC's CPO) manages a series of programmes under the NFCC's portfolio of work. They are responsible for the maintenance of NOG, which were established in 2018 and are available on the website¹⁷². This guidance includes a significant amount of information on mitigating actions. There is a regular review system to ensure that the guidance is up to date and able to expand to include new areas of operational interest.

The guidance includes training material that is recommended to enable fire and rescue service personnel to develop competence in operations involving hazardous materials. This comprises the following resources, which are available from the NFCC CPO website¹⁷³:

- Foundation for hazardous materials – Published in 2018 as part of the NOG. A 453 page document covering science, general hazards, physical hazards and health hazards
- The environmental protection handbook for the fire and rescue service, Environment Agency, 2013
- Initial operational response to a CBRN incident, Home Office, 2013
- Responding to a CBRN(e) event: Joint operating principles for the emergency services, First Edition, 2016

¹⁷¹ <https://www.hse.gov.uk/pubns/books/index-hsg-ref.htm> Accessed on 18th June 2020

¹⁷² <https://www.ukfrs.com/index.php/guidance> Accessed on 17th August 2020

¹⁷³ <https://www.ukfrs.com/guidance/search/foundation-material> Accessed on 17th August 2020

- Dangerous Goods Emergency Action Code (EAC) list (see Section 7.2.3, also known as HAZCHEM), NCEC, 2017
- The Emergency Response Guidebook (ERG, 2020, see Section 7.2.4), US DOT, 2020

In addition to the NOG, the CPO also manage an online system to collect learning from individual fire and rescue services and to assess whether the information should be cascaded upwards to a national level via National Operational Learning (NOL). Learning resulting from this process is published on the CPO website¹⁷⁴.

7.2.3 Dangerous Goods Emergency Action Code list

The Dangerous Goods Emergency Action Code (EAC) list (also known as HAZCHEM) is produced by the National Chemical Emergency Centre (NCEC¹⁷⁵). It is associated with the Carriage of Dangerous Goods. Used alongside Emergency Action Code Cards they comprise a set of actions that can be taken if necessary, without the use of reference materials or expert advice. The codes relate to firefighting extinguishing media, PPE, explosivity and whether there is a public safety hazard outside of the immediate area of the incident.

The list and cards are available to purchase from various sources such as the HSE website¹⁷⁶.

7.2.4 ERG

The US Emergency Response Guidebook (ERG, 2020) provides practical first response guidance for dealing with incidents involving hazardous materials based on a 'look up' reference system. It provides initial isolation distances around the release and protective action distances in a downwind zone. The distances are designed to represent potentially affected areas in the first 30 minutes after release.

Further details of the ERG can be found in Section 5.7.18.

7.2.5 Chemical Industries Association (CIA)

The Chemical Industries Association (CIA) administers the Chemsafe scheme for providing expert advice to the emergency services during chemical emergencies. The advice can comprise of provision of information remotely (Level 1) or at the scene (Level 2) and practical assistance at the scene (Level 3). Chemsafe provides free scientific advice at any time, access to chemical information and experts, amongst other resources. A summary can be found on the NFCC's CPO website¹⁷⁷. The NCEC delivers the Level 1 remote assistance via a dedicated telephone number.

The CIA Chlorine Network has recently drafted a set of detailed guidance notes for dealing with chlorine emergencies (CIA, 2020). The document summarises properties of chlorine, different types of spill and details of PPE. It provides detailed guidance on mitigation measures for liquefied chlorine spillages and use of water sprays for gas dispersion.

7.2.6 Liquid Gas UK Ltd

Liquid Gas UK Ltd (previously UKLPG) provides a series of 27 codes of practice (COP) for LPG, including transportation, storage, installation, operations and utilisation. They have

¹⁷⁴ <https://www.ukfrs.com/action-notes> Accessed on 17th August 2020

¹⁷⁵ <https://the-ncec.com/en> Accessed on 17th August 2020

¹⁷⁶ <https://books.hse.gov.uk/bookstore.asp?FO=1347084&DI=650111> Accessed on 17th August 2020

¹⁷⁷ <https://www.ukfrs.com/foundation-knowledge/foundation-hazardous-materials?bundle=section&id=21854&parent=20376> Accessed on 17th August 2020

been developed by industry experts in consultation with government authorities and are available from the Liquid Gas UK Ltd website¹⁷⁸.

7.2.7 Other guidance

Substance datasheets and other substance databases, such as the PHE Chemical Hazards Compendium or WISER (see Section 3.7), not only contain substance properties but also provide information on mitigation measures appropriate to the particular substance, such as type of foam, and substance-specific PPE.

For some substances there are product-specific mutual aid schemes for provision of assistance during incidents involving those substances. For example,

- ChlorAid – for UK emergencies involving exposure, leaks or spills of chlorine. Information can be found on the NFCC's CPO website¹⁷⁹
- BromAid – a consortium of European bromine companies that provides mutual aid in an emergency and seeks to maximize bromine safety in transport and use. It is designed to complement national and international chemical industry emergency response. Further information can be found on the website¹⁸⁰ including guidance for procedures at the scene of an incident involving bromine.

7.3 Measures that affect the vapour source

Different mitigation measures are appropriate for different substances. Examples include: high expansion foam, thermally insulating concrete, and impounding basins for evaporating liquid spills. Emergency shut down, emergency vents and valves are other effective measures.

7.3.1 Emergency shut down, emergency vents and valves

Industrial sites are fitted with various emergency systems as part of their safety procedures. These include emergency vents and valves and emergency shut down systems. These sorts of measures require regular maintenance and checks to ensure that they operate when required, particularly if they are not used under normal operating procedures. They also require appropriate positioning of functioning sensors to detect operating abnormalities.

While valves and vents are in place to ensure safety, they are often also the point of release. There are several incidents where the gas has been released from a vent (e.g. Seveso, Section 4.5.18) and many where gas was released due to a failed shut off valve (e.g. Jaipur, Section 4.5.49).

Emergency shut down is likely to be a last resort as it is usually prohibitively expensive to stop and restart large industrial facilities. This may be the cause of delays to shut down in some incidents (e.g. Mexico City, Section 4.5.24).

Guidance on remotely operated shut-off valves (ROSOVs) can be found in HSE (2004a).

7.3.2 Containment bunds and impounding/retention basins

The guidance cited in the preceding section gives details of appropriate bunds and impounding/retention basins for use around sites handling hazardous substances.

The effects of bunds and basins on ammonia releases were studied by Bouet (1999). He found that when an ammonia jet was released into a retention basin, 50%-65% of the

¹⁷⁸ <https://www.liquidgasuk.org/resources/codes-of-practice> Accessed on 18th June 2020

¹⁷⁹ <https://www.ukfrs.com/guidance/search/chloraid> Accessed on 17th August 2020

¹⁸⁰ <https://www.bromaid.org/> Accessed on 17th August 2020

ammonia released accumulated as liquid in the basin. Therefore, retention can be an effective way to reduce the level of concentration in the environment following a release. The work highlighted the importance of ensuring the protective measures are appropriate for the substance or storage type. In this case, the retention basin must be properly placed and sized so that the jet impacts on it (directly or indirectly after the impact on an obstacle). Bouet (1999) also showed that measures, such as retention basins must be properly maintained and for substances such as ammonia, they should be kept clear of water to avoid energetic reactions on release.

The use of containment bunds for mitigating the source is particularly useful for refrigerated liquid spills. The bund should be as small as possible to limit the surface area of the liquid pool, while still containing the released liquid. A suitable material should be used as the substrate and walls of containment bund in order to reduce the rate of heat transfer to the liquid, for example thermally insulating concrete. Mannan (2012) reported work that found that the distance to the concentration IDLH could be reduced from 2.6 km to 320 m with modifications to bund designs.

Ad hoc emergency containment bunds can be used to contain spills or slow spread. Sand, sand bags and inflatable booms (for spills on water) can be used for this purpose (HSE, 1999b)

Containment bunds also improve the effectiveness of foam and other substances, to reduce the surface area for evaporation of the spill and reduce contamination of the rest of the site.

Substances that are incompatible should not share the same retention basin. HSE (2009, Table 2) sets out a matrix of recommendations for segregation of dangerous substances based on their hazard classification. Note that the table is unable to show that some substances which are compatible in terms of hazard classification may be chemically incompatible and react with each other. Examples of this, which produce dense gases are

- Acids and hypochlorites – generate chlorine gas
- Acids and sulphides – generate hydrogen sulphide

As an example incident, in Savannah, Georgia (Section 4.5.32) 340,000 gallons of 45% sodium hydrosulfide solution was stored in the same enclosed area as 250,000 gallons of acidic cleaning solution. When the tanks leaked, the chemicals reacted and generated hydrogen sulphide, which spread off-site to the surrounding area.

7.3.3 Fine water fog

A very fine water fog can be applied to spills of liquefied gases which are water miscible, such as ammonia. Water fog can also create an ice crust over the surface of certain spilt liquids, reducing the evaporation rate HSE (1999b). The use of water sprays to mitigate vapour dispersion is discussed further below.

7.3.4 Foam and other additives

Foam is used to reduce the rate of evaporation and usually applied when certain substances are spilled in liquid form. According to Mannan (2012), foam should be applied gently and may require continuous application and frequent re-application. The specific type of foam, or other additives, must be suitable for the substance. For example, HSE (1999c) highlights that for chlorine, foam can cause renewed production of vapour because of the heat supplied. Therefore, it should only be applied after discussion with the chlorine supplier and the local fire authority. The CIA (2020) also provide guidance for the application of foam to chlorine spills, including the observation that most foams used by the fire brigade are not recommended for use on liquid chlorine spillages. HSE (2015b) highlighted that when dealing with flammable liquids and their vapours, foam should be applied with a foam pourer,

not a jet, in order to avoid build up of static charges and possible ignition sources. Specialist equipment and high capacity pumps, foam generators and pourers are required for this.

The effect of foam can vary. Some types are designed to insulate the surface of the spill and prevent vaporisation, while others are designed to absorb the vapour and 'scrub out' the aerosols. High-expansion foam can be used with vinyl chloride. A foam called Hazmat 2 was found to suppress vapour production as follows: >95% for bromine, 67-82% for chlorine, 70-85% for hydrogen fluoride and >61% for sulphur dioxide (Mannan, 2012).

Other additives are neutralising substances such as lime. An incident in Chicago, Illinois (see Section 4.5.1) is an example of where lime was used (in combination with fuel oil) to suppress evaporation after use of foam failed. This case also highlights one of the issues of this approach, namely reduction in bund capacity due to the volume of additives.

In the Mill Woods, Canada incident (see Section 4.5.15) a combination of water flushing, ventilation and nitrogen gas blanketing was successful at suppressing propane release from a vaporising pool.

7.3.5 Plastic sheeting

For a liquid spill of chlorine, HSE (1999d) and the CIA (2020) suggest that once the liquid spread has been restricted by a bund or by using sand, it can be covered in polythene plastic sheeting to reduce the vapourisation rate.

7.4 Measures that directly mitigate the dispersion of gas

Examples of mitigation measures for gas dispersion include containment bunds/walls, vapour fences, water sprays and forced air mixing. As for source mitigation measures, the appropriate approach usually depends on the substance.

7.4.1 Containment bunds and walls

Containment bunds provide a relatively simple means of mitigating dispersion by preventing the gas from leaving the containment area, at least up to the height of the containment wall. Bund walls are primarily designed to contain liquid spills and often of the order of 1 – 2 m, which is likely to be low compared to the cloud depth. However, once the gas cloud exceeds the wall height, they can act as a vapour barrier, providing a mechanism to dilute the cloud.

Containment walls can also have undesirable effects. In the Amuay incident (Section 4.5.50), bund walls likely contributed to 'unhelpful' channelling of the vapour current.

Walls around the site can reduce the impact on neighbouring areas but increase the risk of severe hazards on the site itself. In the Jaipur incident (Section 4.5.49), there was a 2.5 m wall around the site which was very effective as a mitigation measure against spread of the vapour cloud into the neighbourhood around the site but also meant that the cloud depth built up within the contained area and as a result, some personnel were unable to escape and were trapped in buildings. Ignition of the cloud within the site led to a severe vapour cloud explosion.

Vapour barriers and walls have increasingly been used in the USA at LNG facilities, in response to the regulatory requirements for flammable vapour from design spills not to travel off-site¹⁸¹.

¹⁸¹ See US Code of Federal Regulations 49 CFR 19.2059, https://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title49/49cfr193_main_02.tpl. Accessed on 14th January 2020.

7.4.2 Water spray barriers

A significant amount of work has been undertaken on the effectiveness of water sprays on gas dispersion and it is an area of active research (e.g. Mukherjee et al. 2018), which is deserving of its own independent review. A brief review can be found in Mannan (2012). Schoten et al. (1999) provided an overview of research and the design and use of water curtains and steam curtains in Europe up to 1999 and their work remains a good summary document. Schoten et al. (1999) concluded that improvements are needed in guidance, design codes, models for effectiveness, testing and verification of the effectiveness.

Water sprays can be used for both flammable gases and toxics. There are various types of water spray barriers. Industrial sites tend to have fixed installations, which usually comprise a set of nozzles several metres above the ground pointed downwards. These can be indoors or outdoors. Mobile spray systems tend to be a set of nozzles oriented at an angle of about 45° to horizontal. The effects of a vertical water curtain include the following:

- Mechanical effects: acting as a barrier to the gas dispersion, increasing mixing and dilution
- Thermal effects: warming a cold gas
- Physico-chemical effects: absorbing gas, with or without chemical reactions

The parameters governing the efficiency of a water curtain can be grouped as follows:

- Fluid curtain configuration, e.g. distance from source, elevation etc.
- Spray and nozzle parameters, e.g. flow rate, pressure etc.
- Release conditions, e.g. density of the released substance, pressure, etc.
- Meteorological conditions, e.g. wind speed, atmospheric stability etc.

A summary of the effects of these parameters can be found in Schoten et al. (1999).

For an example of the impact of water curtains, Bara and Dusserre (1996) investigated the use of water curtains to protect firemen during incidents involving dense gas dispersion. The objective was to provide information to help firefighters determine at what distances they should place the water curtain and what concentrations they might expect to achieve beyond it. They found for an ammonia release that the water curtain could reduce downwind concentration by a factor of ten at a distance of about 13 m and a factor of three at approximately 20 m. Some experimental studies on the use of water curtains for mitigation of various substances are summarised in Table 33.

Table 33 Experimental studies in this report that investigate mitigation of dense gas dispersion with water curtains

Experiment	Substance	Comment
Texas A&M	LNG	Upward vertical jet water curtain
Ecole des Mines d'Ales	Ammonia	Peacock tail water sprays
INERIS	Ammonia	Peacock tail water sprays
HSE 1985	Carbon dioxide	Water spray barriers
Goldfish	Hydrogen fluoride	Water sprays
ICHMAP	Hydrogen fluoride	Water spray/fog barriers (including augmented water)
Lux	Uranium hexafluoride	Coarse water spray, steam spray, fine water mist (uncharged), boric acid mist (charged and uncharged)
Meroney	Various	Water spray curtains

Schoten et al. (1999) and others highlighted some of the issues with water curtains:

- Speed of activation for them to be effective in the case of a flammable cloud reaching ignition sources
- Lack of guidance on design and operation
- Absence of design codes
- Difficulties estimating effectiveness
- Maintaining systems during the system's lifetime
- Blockage of nozzles

When water spray barriers are used, consideration should be given to environmental implications of contaminated water run-off. While they are called water curtains, they can contain various additives. Industrial sites normally have facilities to collect contaminated surface water but this will not be the case elsewhere.

The impact of water spray barriers on dense gases has been modelled in various studies. For example, bespoke spray barrier models HGSPRAY (Fthenakis, 1993) and DVS (Dandrieux et al., 2003) have been developed. Water sprays have also been modelled in CFD codes, notably FDS (see also Gant, 2006).

7.4.3 Steam curtains

Steam curtains are typically permanent installations used for dispersion and containment of flammable dense gases (Mannan, 2012). They are often installed as a horizontal pipe with a row of small holes fixed to the top of a wall surrounding a facility. The wall forms an initial barrier which prevents the cloud from spreading further. It also forces the cloud along the wall. These actions delay the cloud dispersion and provide time for the detection system to operate and alarm so that operators can activate the steam curtain.

The steam pipe is split into sections so that it can be activated at the sections nearest the leak. It is supplied from the mains by remote controlled valves. It should be designed in conjunction with the wall dimensions, spacing to potential sources of escape and detector locations.

The steam curtain is unlikely to contain small, diluted leaks that are more likely to be carried over the wall by atmospheric dispersion, it is specifically designed to contain and dilute flammable dense gas clouds. The system could also be applied to toxic dense gas clouds but it would need modification because toxics typically require dilution to much lower concentrations before the hazard is mitigated.

It should be noted that both steam jets and water curtains can cause an ignition hazard due to static electricity and care should be taken to earth metalwork in the vicinity of the jets.

7.4.4 Forced air mixing

Forced air mixing is designed to increase dilution and therefore reduce clouds to below hazardous levels. It is particularly useful when gas has accumulated in confined or congested spaces. Forced air mixing is typically an indoor measure. There is little information available about forced air mixing outdoors, although there is evidence of its use. For example, in the Mönchengladbach incident (see Section 4.5.26). Helicopters were used to dilute the carbon dioxide that had accumulated in the streets alongside large fans, which were used to dilute carbon dioxide that had accumulated in basements.

7.5 Measures that mitigate exposure

Mitigation measures for exposure may be very varied, depending on the scenario and the type of population exposed. They include personal protective equipment (PPE), sheltering in place and evacuation. A brief discussion of detection is also included here.

7.5.1 PPE

Advice and guidance on PPE can be found on the HSE website¹⁸² and many of the substance databases, such as the PHE Chemical Hazards Compendium (see Section 3.7), have information about substance-specific equipment.

Industrial sites and response personnel should have access to appropriate PPE, although it is evident from incidents that this is not always the case or the equipment is simply not used. For example, in the ammonia incident in Dakar, Senegal (see Section 4.5.32) the emergency intervention team were hindered because they did not have the appropriate PPE. In Dalton, Georgia the release continued for more than eight hours because neither the fire department nor the site personnel had the PPE to safely enter the area to stop the release.

Off-site, it is unlikely that the general public will have access to appropriate PPE and it is not practical to supply it on such large scales. Therefore, other means of mitigating exposure need to be considered such as exclusion zones, sheltering in place or evacuation.

7.5.2 Detectors / monitors / sensors

Gas detectors, monitors or sensors do not mitigate exposure to hazardous substances in their own right but they can be key to identifying the appropriate mitigation measures to follow. They can include fixed sensors positioned on sites handling hazardous substances; sensors on hazardous substance transport vehicles; mobile devices, hand-held devices and personal devices worn by employees or emergency response personnel. For example, gas sensors were used in the Mönchengladbach incident to determine when the carbon dioxide gas concentration had reduced to an acceptable level for evacuated people to return to their homes.

There are several British Standards and HSE publications concerning detectors. For example, BSI (2016) concerns workplace atmospheres and measurement of toxic gases and vapours. HSE (2004b) provides guidance for flammable gas detectors for on shore sites and Walsh and Kelsey (2017) provides guidance for off shore sites. HSE (2006) contains guidance for monitoring employee exposure to hazardous substances by inhalation.

7.5.3 Exclusion zones / hot zones / cordons

Exclusion zones provide a means to manage exposure. In a preventative capacity, Land Use Planning and REPPIR regulations require the calculation of three zones in order to advise on developments within communities with consideration of population sensitivity and proximity to hazardous sites (see Section 2.2 or the HSE website¹⁸³ for details). This means that for a major hazard site or pipeline, even before an incident occurs, consideration has been given to the distribution of the community surrounding it in order to mitigate the impact.

If an incident does occur, reactive zones may be set up by the site management itself, as part of a safety procedure, or by the emergency response personnel. These zones are sometimes based on modelling predictions, often undertaken in real-time, for example a CHEMET¹⁸⁴ from the Met Office.

¹⁸² <https://www.hse.gov.uk/toolbox/ppe.htm> Accessed on 24th April 2020

¹⁸³ <https://www.hse.gov.uk/landuseplanning/methodology.htm> Accessed on 24th April 2020

¹⁸⁴ <https://www.metoffice.gov.uk/services/government/environmental-hazard-resilience/chemical-meteorology-chemet> Accessed on 24th April 2020

Another method for setting exclusion zones is a generic pre-defined isolation zone, for example, Table 34, as included in the NOG.

Table 34 Generic cordon distance guidance reproduced from the NOG¹⁸⁵

Generic initial cordon distance guidance Note: continuous risk assessment should be carried out to ensure that the cordon remains appropriate and proportionate to the risks identified by the incident commander	
Incident type	Initial cordon distance (metres radius)
Explosives –CBRN(E), terrorist (*Consider no fire and rescue service attendance or treat as 'exclusion' distances for fire and rescue service personnel, take guidance from police and explosive ordnance disposal (EOD))	100 m for an activated device Unexploded devices: * 100 m for a suitcase-sized device 200 m for a car-sized device 400 m for a lorry (or when size of device is not known)
Chemicals being transported	25 m for solids 50 m for liquids 100 m for gases, vapours, particulates
Radiation	Outside buildings: 50 m – unshielded or damaged potentially dangerous source 100 m – major spill from a potentially dangerous source 300 m – fire, explosion or fumes involving a potentially dangerous source 400 m or more to protect against an explosion – suspected bomb (exploded or unexploded) Inside buildings: Affected and adjacent areas (including the floor above and below) – damage, loss of shielding or spill of a potentially dangerous source Entire building and outside distances detailed above – fire or other event that can spread a potentially dangerous source materials throughout the building (for example through the ventilation system)

More sophisticated look-up guides have been produced for different substances. For example, the US ERG (ERG, 2020, see Section 5.7.18). Note that the ERG was derived for North/South American meteorological conditions and North/South American transported quantities and its validity for use elsewhere should be confirmed.

Monitoring of the substance using sensors is important for real-time adjustment of zones and for information on when they can be relaxed. Research such as Atkinson et al. (2017) discusses timescales for clearance of unignited vapour clouds.

7.5.4 Sirens and loud speakers

Sirens and loud speakers are two methods used to inform site personnel and the general public of incidents or to take action such as shelter in place or evacuation to mitigate exposure.

They are an effective means of alerting people but there are several issues with their use. There are incidents where sirens and loud speakers were ineffective because the public do not know what they mean, ignore them, or where they are not present. For example in

¹⁸⁵ <https://www.ukfrs.com/scenarios/health-hazards> Accessed on 15th September 2020

Richmond, Virginia in 2001 (Section 4.5.40), members of the public said that they did not know what the sirens meant and others ignored police instructions to stay indoors. In Dalton, Georgia (Section 4.5.43), there were no emergency sirens or community-wide emergency alert systems, so the police had to enter the vapour cloud to alert residents of the evacuation.

7.5.5 Water fogs or sprays

Water curtains etc can be used for mitigating dispersion (see Section 7.4.2), depending on the substance, but they can also be used for mitigating exposure. In particular, exposure of emergency response personnel.

7.5.6 Shelter in place

Guidance for sheltering in the UK can be found in the HM Government document “Evacuation and shelter guidance” (Cabinet Office, 2014) and covers details on the practicalities and logistics of sheltering. It states the following:

Shelter in place should be considered for no-notice events when:

- there is no time to undertake an evacuation before the hazard arrives;
- going outside would expose people to greater harm or dangerous conditions; or
- the immediate risk is unclear

The degree of protection being inside provides is dependent on the duration of the emission, the passage time of the cloud, the ventilation rate, the absorption of gases by surfaces in the structure and the deposition of any particles. It is also dependent on other variables such as the vulnerability of the population.

A significant amount of research has been undertaken into the effectiveness of shelter in place as a measure of mitigating exposure to gas releases. Examples of reviews are the Green book (1992) and Sorensen et al. (2004). While there is information on shelter in place for toxics, there is less information which specifically accounts for the density implications.

The principle of shelter in place is to remove exposure to the peak concentration. Indoor exposures could take place over a longer duration because the lower ventilation rate means that once the outdoor cloud has passed the shelter, concentrations may still persist inside the shelter. However, peak concentrations inside the shelter will usually be lower. Often, it is exposure to short-duration high concentrations that causes serious health effects. As an example, in the chlorine incident at La Barre, Louisiana (Section 4.5.7), an infant died when its concerned father carried it outside, where the gas concentration was higher. A 2-month old infant that remained in the house survived.

The following is some of the advice recommended in the literature:

- Close windows and doors and stop ventilation systems such as HVAC to minimise ventilation.
- Take refuge in parts of structures/rooms that have the lowest ventilation rates. Typically this means the most poorly ventilated room in the structure, preferably without windows. Some studies suggest the largest unventilated room (Davies and Purdy, 1986), while others suggest a smaller space such as a wardrobe in a house because the fabrics provide surfaces for sorption of substances.
- Rooms such as bathrooms and kitchens where ventilation rates are generally higher should be avoided.
- Both Jack Rabbit II (Byrnes and Matthew, 2016) and Cleaver et al. (2016) suggest that sheltering upstairs is better than downstairs. The Green Book (1992) also suggests selecting rooms in the lee of the wind.
- Keep out of low areas, for example basements, cellars, bunkers.

- For vehicles, the Jack Rabbit II project found that there was a greater than 10 to 1 ratio from exterior concentrations to interior concentrations. Byrnes et al. (2017) recommended that occupants shut off HVAC and close all vents. They also advised driving lateral to the wind or if not possible, stop the car, close all vents, windows and doors and ring for help.
- In general, vehicles are not as effective as buildings for sheltering in place (ERG, 2020)

Some strategies advise trying to seal doors and windows with tape. This was rejected by experts during the Jack Rabbit II project (Byrnes and Matthew, 2016) because the time taken to collect the required materials together and undertake the procedure causes a delay in seeking a safe place. The benefits were not deemed significant enough to justify this delay.

Eventually, the outside concentrations will be lower than the inside concentration. People should stay inside until this time and then exit the building because high concentrations (relative to outdoor concentrations) can persist for longer indoors. Afterwards, the structure should be ventilated as much as possible. As discussed in Section 3.5, many factors affect the ingress of gases and also their subsequent ventilation. The wind and the proximity of the structure to other structures (i.e. wind-shielding effects) will be important. In particular, enclosed spaces such as basements, cellars or tanks should be well ventilated before entering. However, it should be noted that it is far more dangerous to leave a structure early than it is to stay inside too long.

Note that shelter in place is not an effective mitigation measure against flammable dense gases, unless the shelter has been specifically designed for this purpose. This is discussed in the next section. Also, it may not be the best option if the gas will take a long time to clear the area or if buildings cannot be closed tightly.

7.5.7 Designated shelters

Purpose designed temporary refuges are another type of designated shelter, most commonly found on off-shore facilities, for which they are a requirement under the Offshore Installations (Safety Case) Regulations (guidance in HSE, 2006b). They are built to withstand exposure to both toxic and flammable gases at an installation until it is safe for the occupants to exit the refuge or be evacuated. Their functions include automatic shut-down of HVAC and provision of facilities within the refuge for monitoring and control of the incident and for organising evacuation. Perhaps the main criterion for temporary refuge design is to provide an environment in which the occupants can survive, but also allow rational decisions to be made in terms of managing an incident and evacuation (Tam et al., 1996; HSE, 2010). To this end they are constructed to a leakage standard of 0.25 ACH (HSE, 2006c) and calculated impairment times dependent on the installation (Coldrick, 2013).

The main issues with designated shelters, in particular those with high design tolerances such as temporary refuges, is inappropriate use and poor maintenance. For example, there have been records of incidents where doors were wedged open (Spouge, 1999).

7.5.8 Evacuation

Discussion of evacuation compared with shelter in place can be found in Sorensen et al. (2004). Guidance for evacuation in the UK can be found in the HM Government document “Evacuation and shelter guidance” (Cabinet Office, 2014). As for sheltering, this document covers details on the practicalities and logistics of executing an evacuation.

Evacuation is clearly an effective means of mitigating exposure, but it incurs a high risk associated with timing. The decision to evacuate, rather than shelter in place, needs to be made relatively early on in an incident, otherwise there is a risk of increased exposure as

people leave buildings. Therefore, perhaps the most difficult aspect of this measure is deciding when it is required. Then, it is necessary to decide who to evacuate and what areas and logistics such as how to communicate the evacuation orders effectively, where to evacuate to and transport means etc. Evacuees should be sent to a definite place by a specific route far enough away so that they will not have to be moved again if the wind shifts (ERG, 2020).

After evacuation, a decision needs to be made on when people can return. The longer the evacuation order remains in place, the greater the costs. For example, in the Jaipur incident about half a million people were evacuated and in the Mississauga, Ontario incident 215,000 people were evacuated and some did not return home for six days.

7.6 Summary

There is a wide range of guidance on controls and mitigation measures available from UK government and regulatory bodies as well as from consortiums of industry stakeholders and research institutes. A key component in the effectiveness of mitigation measures is whether the substance is known or not. If the substance is known, substance-specific measures can be applied. When the incident originates from a fixed site and the site operator can be involved relatively quickly, they may have the information required to assist emergency personnel in mitigating the incident. When the substance is unknown, there is generic guidance available which can be used in the initial stages of the incident until sufficient information is acquired to request input from experts if necessary.

8 SCENARIOS

8.1 Introduction

This chapter explores scenarios which could result in dense gas dispersion. A scenario is designed to pull together methods or concepts discussed in greater detail. It might be a worked example using exemplar quantitative inputs to calculate specific outputs, or it might be a more descriptive example. There are several existing collections of scenarios relevant to dense gas dispersion, both quantitative and descriptive, presented below.

After the existing scenarios the rest of this chapter contains a collection of six new scenarios compiled as part of the present study. These scenarios draw on the content covered in this review to outline six different contexts where a dense gas dispersion event may arise. These six contexts are loosely defined by regulatory area, as follows:

- Scenario 1 – Static site (COMAH regulated)
- Scenario 2 – Static site (non-COMAH)
- Scenario 3 – Pipelines
- Scenario 4 – Transport (road/rail)
- Scenario 5 – Transport (maritime)
- Scenario 6 – Non-regulated, unknown source

8.2 Existing scenarios

The existing scenarios presented in this section serve different purposes. Hanna et al. (1996; 2008), COST ES1006, US EPA, the NUREG Handbook and the French Working Group (FWG) Good Practice Guide all provide sufficient information to allow for worked examples and model comparison exercises. PRACTICE and NOG are more descriptive and relevant to emergency response exercises.

8.2.1 Hanna et al. (1996)

In their guidelines for the use of vapour cloud dispersion models Hanna et al. (1996) provided a set of seven worked scenarios for model testing and comparison, including tables of input conditions for each case. These scenarios are illustrated in Figure 51 and summarised briefly in Table 35. Six out of the seven scenarios result in the release of a dense gas; Scenario 5 is positively buoyant. However, using their source Richardson number criteria (see Section 3.2.2), only four out of the seven continue to evolve as dense gases. In Scenario 3, the release is only likely to remain dense very close to the source so the dispersion can be treated as effectively passive. In Scenario 6, density effects force the plume to touch down but the dispersion does not continue to be dominated by density effects. This is converse to Scenario 4, where the density effects persist beyond touchdown.

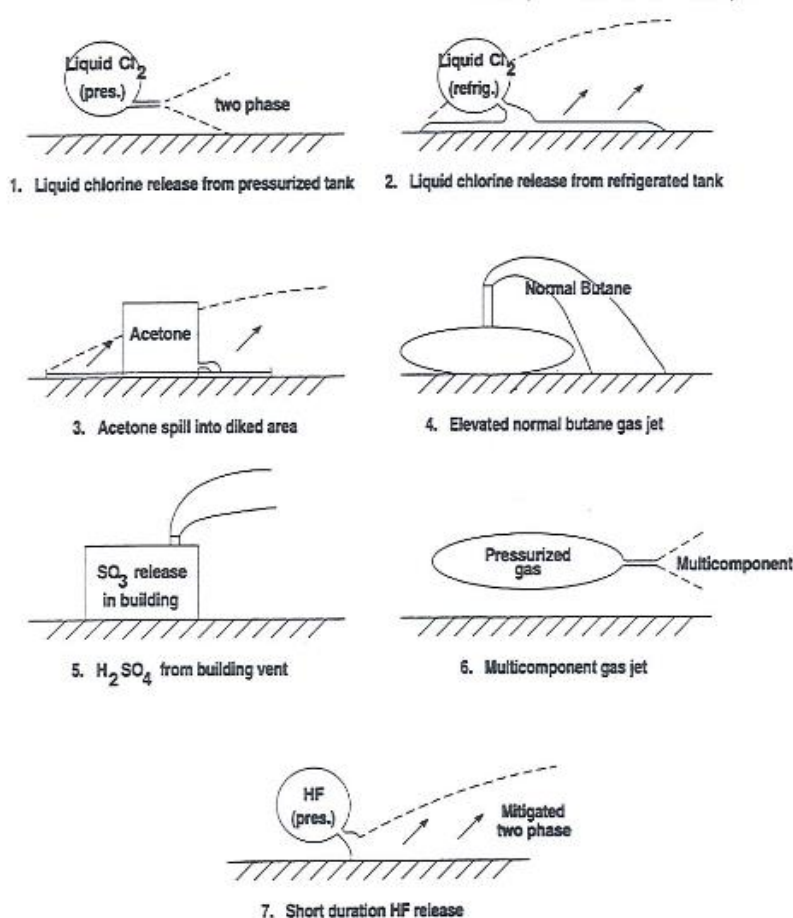


Figure 51 Illustration of seven release scenarios for worked examples in Hanna et al. (1996).
All of the scenarios except scenario 5 exhibit dense gas effects at some point during their release (© AIChE copyright 1996)

Table 35 Brief summary of seven scenarios used as worked examples in Hanna et al. (1996)

Scenario	Brief description	Source Richardson number
H1	Continuous pressurised horizontal release of liquid chlorine. Two-phase pressurised jet.	1,360,000
H2	Evaporation from refrigerated liquid spill of chlorine. Cryogenic pool.	782
H3	Liquid spill of large tank of acetone forming an evaporating pool.	3.61
H4	Continuous vertical dense normal butane gas jet	28,100
H5	Slowly time-varying venting of warm sulfuric acid plume from building	n/a
H6	Pressurised gaseous release of multi-component mixture	106
H7	Transient (mitigated) area source release of hydrogen fluoride	957

There is a significant amount of detail provided with the scenarios in the form of a 'Scenario Data Archive' and Appendices for each case with additional calculations, information and modelling results. The archive comprises all of the input data required to run the models tested: ALOHA, DEGADIS, HGSYSTEM, SLAB, INPUFF (passive dispersion) and ISC (passive dispersion).

8.2.2 Hanna et al. (2008)

Hanna et al. (2008) used three sets of input data from analysis of three chlorine railcar incidents (Festus, Macdona and Graniteville) to compare the performance of various models, including calculation of SPMs. This work provides ready-made scenarios generated from real incidents and an existing model comparison exercise which can be used if a model comparison exercise is desired. Some additional details of the study can be found in Section 5.4.3 and the incidents are summarised in Section 4.5.

8.2.3 COST ES1006

The COST ES1006 project used three scenarios: Michelstadt, CUTE and AGREE. Each scenario provided a different set of information:

- Michelstadt was a wind tunnel simulation of a tracer released in a scaled model of a city, designed to be representative of a typical European city
- CUTE was a full scale experiment in a city where tracer was released and measured
- AGREE was an incident in which a gas was released

Each of these scenarios was developed to provide as much information as possible for modellers in a blind and non-blind exercise to test the models. These scenarios were created primarily for testing neutrally buoyant dispersion models. Of the three AGREE is of interest because the chemical released was the pressure-liquefied gas vinyl chloride monomer, which would include some density effects on release.

In the AGREE exercise the scenario comprised the following information:

- Description of the accident and its consequences
- Characteristics of the site and surroundings
- Meteorological data
- Emission estimation
- Concentration measurements
- The design of the exercise – a summary of what was available and what was required

The modellers were able to use the information as they saw fit, as they might in an emergency response situation. For example, the estimated amount released varied from about 190 – 7200 kg depending on the source used and it was up to the modeller to decide what they used in their model input. Topographical information and fixed structures were provided.

The details provided were as follows:

- The substance
- The storage conditions of the substance and the release conditions
- Estimations of the amount released
- The location of the substance on the site and any information describing the site

- Any mitigation attempted
- Approximate time frames
- Meteorological data collected the from local meteorological network in the vicinity of the site at the time
- Recordings from 52 gas sampler probes located around the site, part of the facility environment monitoring system
- Location of an array of additional monitor points added as part of the study for model comparison

8.2.4 PRACTICE

The PRACTICE initiative¹⁸⁶ provided scenarios for exercises in response to chemical, biological, radiological and nuclear incidents. For example, derailment of a chlorine railcar. They provided the following information in a tabular format:

- Title
- Scenario justification
- Scenario outline
- Cause
- Threat compounds and their properties, i.e. substances and endpoints etc
- Dissemination, i.e. amount and release mechanism etc
- Location
- Indication or alert, i.e. raising of alarm etc
- Possible consequences and development, i.e. release time and timeframes
- Challenges, i.e. affected persons, responder actions
- References

8.2.5 NOG

The National Fire Chiefs Council's NOG includes a set of scenarios¹⁸⁷ to assist in identifying the knowledge, control measures and actions needed to combat the hazards of that particular scenario. The actions are split into generic 'All Incident Actions' and specific actions based on incident type. At present there are 26 incident types, as follows:

Commercial or residential building fire	Rescue from depth
Industrial or agricultural building fire	Rescue from height
Domestic dwelling fire	Rescue of trapped person
Fires in tall buildings	Rescue from collapsed structure
Building under construction or demolition	Rescue involving animals
Fire in a waste site	Road traffic collision

¹⁸⁶ Preparedness and Resilience Against CBRN Terrorism using Integrated Concepts and Equipment
<https://cordis.europa.eu/project/id/261728> Accessed on 24th April 2020

¹⁸⁷ <https://www.ukfrs.com/scenarios/health-hazards> Accessed on 24th April 2020

Wildfire	Aircraft rescue
Fire in electrical installation	Railway or tram rescue
Aircraft Fire	Explosives and cylinders
Fire on board a vessel	Flammables
Railway or tram fire	Health hazards
Road vehicle fire	Environmental protection
Rescue from water	

A top level view of the type of information included is shown in Figure 52 for the 'Health Hazards' scenario.



Figure 52 Example of top level content for NOG 'Health Hazards' scenario. 'Control' tab is open to illustrate content

8.2.6 US EPA

The US EPA (1993a) guidance on application of dispersion models for hazardous or toxic atmospheric releases contains detailed information on source terms for dispersion modelling and a table (Table 2-2 in US EPA, 1993a) of storage release scenarios and post-release characteristics for ammonia (anhydrous and aqueous), chlorine, hydrogen fluoride (anhydrous and aqueous), hydrogen chloride (anhydrous and aqueous), ethylene oxide and sulphur dioxide. It also contains eight descriptive scenarios for modelling, to illustrate the main different types of release, shown in Figure 53. For each of these eight scenarios, input information is provided, including methods for calculating the information in a clear step-by-step approach using flow charts to assist in decision making. The scenarios are used as worked examples for the models ADAM (US), ALOHA, DEGADIS, HGSYSTEM and SLAB.

In this study, a release is considered dense under the following conditions:

Continuous:
$$U_{ref} \left[\left(\frac{g(\rho_0 - \rho_a)}{\rho_a} \right) \frac{q_0}{D} \right]^{-\frac{1}{3}} \leq 6$$

Instantaneous:
$$\left[\left(\frac{g(\rho_0 - \rho_a)}{\rho_a} \right) \frac{V^{\frac{1}{3}}}{U_{ref}^2} \right]^{\frac{1}{2}} > 0.2$$

These expressions essentially amount to source Richardson numbers similar to those of Britter and McQuaid (1988, see Section 3.2.2). Following these criteria, it can be seen in Table 36 that all of the scenarios result in dense gas dispersion, except for Scenario 4.

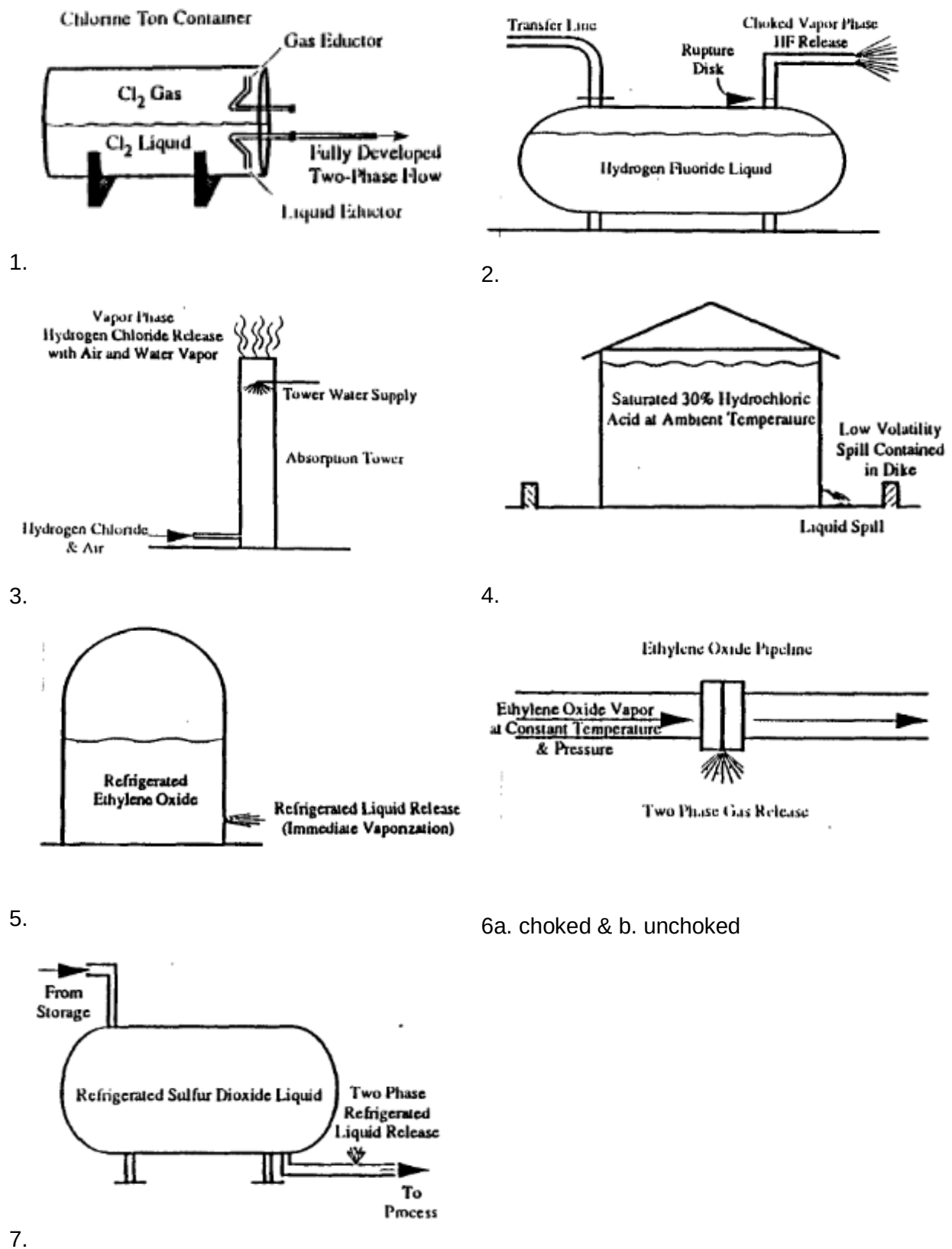


Figure 53 Illustration of eight release scenarios for worked examples in US EPA (1993a)

Table 36 Summary of release scenarios used as worked examples in US EPA (1993)

Scenario no.	Description	Richardson number
E1	Tubing from bottom of pressurised, ambient temperature vessel storing 1 ton (0.91 tonnes) liquefied chlorine is broken off. This produces an initial two-phase pressurised liquid release	1.311 (continuous)
E2	Rupture disk breaks and relieves material from vapour space of pressurised, ambient temperature tank storing liquid hydrogen fluoride. This produces an initial single-phase gas release (choked). Release could be treated as instantaneous or finite duration.	0.332 (if assumed instantaneous) 2.638 (if assumed finite duration - continuous)
E3	Water flow is lost to tower absorbing hydrogen chloride from vent stream. This results in single-phase gas release (unchoked)	1.048 (continuous)
E4	Hole develops in side of atmospheric storage pressure tank storing 30% weight hydrochloric acid in liquid phase. This results in a single-phase, low volatility liquid release.	136.7 (continuous)
E5	Hole develops in refrigerated vessel storing liquid ethylene oxide at atmospheric pressure. Since hole is below the liquid level, the initial release is single-phase, high volatility liquid release.	1.403 (continuous)
E6a & b	Hole develops in saturated vapour phase ethylene oxide pipeline. This leak results in two-phase gas release. This scenario represents two release classes: The release flow rate may be choked (a) or unchoked (b).	(a) 2.435, (b) 1.226 (continuous)
E7	A hole develops in a pipe from the bottom of a vessel storing liquid sulphur dioxide. Initial release is a two-phase refrigerated liquid release.	0.5068 (continuous)

8.2.7 NUREG Handbook

The NUREG handbook (SAIC, 1998) contains eight detailed example scenarios relevant to nuclear fuel cycle facilities. Only Scenario 5 and 6 result in dense gas dispersion and these are summarised in Table 37.

Table 37 Summary of release scenarios used as worked examples in the NUREG Handbook (SAIC, 1998).

Scenario no.	Description
N5	Spillage of hydrogen fluoride from a railway tank car Hydrogen fluoride is being unloaded from a tank car. The process uses nitrogen to apply pressure and force the hydrogen fluoride out of the tank car and into an acid storage vessel. The tank car and the storage vessel are connected by “HF-service” flexible hoses during the transfer. There are two potential scenarios identified from this process: a) A break in the nitrogen padding gas hose releases hydrogen fluoride vapour. This is similar to scenario 6bii, described below. b) A break in the hydrogen fluoride liquid transfer hose releases liquid hydrogen fluoride. It is assumed to be a cold day and the ground temperature is below the boiling point of hydrogen fluoride. The released liquid is assumed to be cool, at 10 K or more less than its boiling point and it forms an evaporating pool on the ground. In this case, it is known from experiments that there is no evidence of density effects in the dispersion of the oligomerised hydrogen fluoride and no aerosol is formed from an evaporating pool to increase the density. Therefore, the dispersing cloud does not need to be treated as a dense gas. There are two other alternative scenarios discussed for a release of liquid hydrogen fluoride from the hose: i. The hydrogen fluoride is very warm, at 10 K or more above its boiling point so that release from the vessel results in a flashing liquid jet with vapour and aerosol formation. This is similar to Scenario 6bi, described below. ii. The hydrogen fluoride is within +/- 10 K of its atmospheric boiling point. In this case it is difficult to predict the proportion of the hydrogen fluoride that will remain airborne as fine liquid droplets or form a pool. In this case, care needs to be taken with correctly identifying sources and sinks of heat that could affect the state of the release. They point out that yet another scenario would be if there is a large difference between the hydrogen fluoride pool temperature and the ground temperature, such as for a cryogenic pool.
N6	Uranium hexafluoride liquid (>70°C) cylinder rupture Two potential scenarios were identified, which could result from a uranium hexafluoride liquid cylinder rupture: a) The uranium hexafluoride cylinder has been overfilled and is subsequently being heated. Thermal expansion of the liquid causes the cylinder to rupture resulting in an instantaneous release of uranium hexafluoride. The cylinder is assumed to rupture above the triple point of uranium hexafluoride. On release, some of the liquid flashes to vapour and some solidifies to form particles, which are assumed to remain airborne (a source of uncertainty). Flashing results in the

almost instantaneous mixing with ten times by mass of air at ambient conditions. The uranium hexafluoride reacts with the humidity in the air and the result is an instantaneously released dense gas cloud.

- b) The uranium hexafluoride cylinder is accidentally dropped and a small hole develops in the cylinder wall. There are two cases depending on the location of the hole with respect to the contents of the cylinder:
 - i. The hole is below the liquid level and releases a downward jet of uranium hexafluoride liquid. The flow through the orifice is single phase but it flashes on release. It is assumed that the aerosolised material forms fine solid particles which remain airborne with the vapour, despite the jet impinging on the ground.
 - ii. The hole is above the liquid level and releases a vertical jet of uranium hexafluoride vapour. The discharging vapour is continually replaced by evaporation of liquid uranium hexafluoride inside the vessel until the process cools the contents to the extent that it decreases to the sublimation point and the source ceases. The anticipated dispersion is a vertical dense gas plume followed by touchdown and a dispersing dense gas cloud.

The format of the scenarios is similar to Hanna et al. (1996) where the context is described, information, assumptions and calculations are presented and dispersion simulations are carried out, if relevant. The models used in the examples are ALOHA, NRCCRUNCH, NRCDENZ and NRCPLUME. The model predictions are discussed and uncertainty and sensitivity studies are undertaken, if required.

8.2.8 FWG Good Practice Guide

The French Working Group (FWG) Good Practice Guide compiled by INERIS (Lacome and Truchot, 2016) contains three case studies, summarised in Table 38, used by the working group to present examples and demonstrate good practices. They were aimed at scenario reconstruction for atmospheric dispersion incidents using 3D modelling, ie CFD. In particular, they sought to use the case studies to compare the results of different users; to determine the key points leading to any discrepancies; and to undertake validation of 3D modelling with experiments. The first two scenarios are fictitious while the third uses one of the Kit Fox experiments (see Section 6.5.40).

In Lacome and Truchot (2016) details are provided to set up the examples and some output information of model comparisons is presented.

Table 38 Summary of scenarios used as case studies in the French Working Group Good Practice Guide (Lacome and Truchot, 2016).

Scenario no.	Description
F1	Gas dispersion in an empty field through a pipe 1 m from the ground from a source pressurised at 8 bar with three different types of gas - Negatively buoyant gas (C_3H_8) - Positively buoyant gas (NH_3) - Neutrally buoyant gas (CO) Each has its own release conditions and they are released in two classes of atmospheric conditions F3 and D5
F2	Dispersion of propane with obstacles and a wall present
F3	Validation using experimental case study from Kit Fox. Dispersion of CO_2 in an obstacle array

8.3 New scenarios

A set of six dense-gas release scenarios has been compiled to illustrate key aspects of dense-gas dispersion and mitigation measures that are relevant to industrial regulation and emergency preparedness and response in the UK. Broadly defined by regulatory area, they present the context, the current modelling practice and illustration of existing and potential challenges.

Each scenario contains the following headings:

- Introduction
- Typical features
- Potential dense gas incident sources and contributing factors
- Factors affecting dense gas dispersion
- Mitigation measures and emergency response
- Use of modelling
- Modelling challenges

The potential for indoor and outdoor releases has been highlighted and relevant quantities have been outlined, where possible.

For each scenario, reference is made to relevant previous incidents, which have been summarised previously in Chapter 4 and include further representative quantities. In Table 39 the new scenarios are cross-referenced to existing scenarios discussed in Section 8.2, which include quantitative information specifically designed for model comparison exercises. Note that several of the existing scenarios are relevant to more than one new scenario but they have been split up here to highlight their relevance to particular scenarios.

Table 39 New scenarios and corresponding existing scenarios from Section 8.2

New scenario	Relevant existing scenario numbers from Section 8.2
1 – Static site (COMAH regulated)	H1, H2, H3, E4, E5
2 – Static site (non-COMAH regulated)	H4, H6, H7, E1, E2, E3, E7, N6a*, N6bi*, N6bii*, AGREE, F1, F2, F3
3 – Pipeline	E6a, E6b,
4 – Transport (road/rail)	H6, N5a, N5bi, N5bii, Hanna et al. (2008)
5 – Transport (maritime)	H4
6 – Non-regulated, unknown source	Any - unknown

* Note that the N6 scenarios all relate to uranium hexafluoride, which may or may not be on a COMAH-regulated site but would be regulated by ONR under REPIR 2019

8.3.1 Scenario 1 – Static site (COMAH regulated)

Introduction

A COMAH regulated static site is defined here as a facility subject to regulation under the Control of Major Accident Hazards (COMAH) Regulations 2015. Examples of such facilities include fuel storage sites and chemical processing plants.

There are two types (tiers) of establishment which are subject to COMAH, known as 'Upper Tier' and 'Lower Tier' depending on the quantity of dangerous substances they hold. Upper Tier establishments will hold greater quantities of dangerous substances meaning that additional requirements are placed on them by the regulations. Examples of the lower and upper tier quantities of some named substances under the COMAH 2015 regulations¹⁸⁸ can be seen in Table 40. The competent authority for COMAH sites is HSE and the relevant environment agency from the devolved governments.

Table 40 Examples of the lower and upper tier quantities (in tonnes) of some named substances under the COMAH 2015 regulations

Substance	Lower tier (tonnes)	Upper tier (tonnes)
Anhydrous ammonia	50	200
Bromine	20	100
Chlorine	10	25
Hydrogen Sulphide	5	20
Liquefied flammable gases (eg LPG, LNG)	50	200
Methylisocyanate	-	0.15
Petroleum products (eg gasoline)	2500	25000
SulphurTrioxide	15	75
TCDD	-	0.001

Most major accident hazard incidents, for which there is a large body of information available, are from large static sites, which would fall under Control of Major Accident Hazards (COMAH) Regulations 2015 in Great Britain. There are many examples in Chapter 4. From Great Britain, examples of incidents at sites subject to COMAH regulations include Flixborough (Section 4.4.1) and Buncefield (Section 4.4.5).

¹⁸⁸ <https://www.legislation.gov.uk/ukxi/2015/483/schedule/1/made> Accessed 22nd September 2020

Worldwide, the following incidents (with section numbers) from the present review would likely be subject to COMAH regulations:

4.5.3 Manhattan, New York	4.5.29 Texas City, Texas
4.5.4 Cleveland, Ohio	4.5.30 Jonova, Lithuania
4.5.5 Poza Rica, Mexico	4.5.32 Baton Rouge, Louisiana, 1989
4.5.8 Feyzin, France	4.5.33 St Herblain, France
4.5.10 Blair, Nebraska	4.5.35 Brenham, Texas
4.5.14 Chicago, Illinois, 1974	4.5.36 La Mede, France
4.5.16 Baton Rouge, Louisiana, 1976	4.5.38 Savannah, Georgia
4.5.18 Seveso, Italy	4.5.49 Jaipur, India
4.5.24 Mexico City, Mexico	4.5.50 San Juan, Puerto Rico
4.5.25 Bhopal, India	4.5.53 Amuay, Venezuela
4.5.26 Naples, Italy	4.5.55 Philadelphia, Pennsylvania
4.5.28 Gore, Oklahoma	

Typical Features

COMAH sites may have multiple dangerous substances on site and several in sufficient quantities to be regulated under COMAH. Site operators must take all measures necessary to prevent major accidents and should understand the requirements placed on them to operate safely. All establishments are required to prepare and retain a major accident prevention policy (MAPP), which includes describing arrangements for the handling of emergencies. In addition all Upper tier establishments are required to prepare a safety report. Its purpose is to detail the arrangements for the control of major accident hazards and to limit the consequences to people and the environment of any that do occur. Therefore, site operators and personnel should be familiar with potential hazards and associated risks.

While there are many substances which are subject to the COMAH regulations, fuels are perhaps the most common substance group in Great Britain to be handled or stored in quantities regulated under COMAH. There may be multiple substances on a site, which may or may not be subject to the COMAH regulations.

It is common to have several contractors on a site at any given time who are likely to be less familiar with the site layout and procedures.

The COMAH regulations and Land Use Planning (LUP) restrictions mean that sites are less likely to be in close proximity to sensitive populations. However, it is likely that they provide employment for local communities so there are likely to be residential centres nearby. Local authorities will be aware of the site and should have been informed of the hazards as part of emergency preparedness procedures.

Some COMAH sites are likely to be on flat land and are chosen specifically for this attribute. This is perhaps particularly the case for fuel storage sites where flat land is required to accommodate large storage tanks. It is fairly common to find these sites near water bodies, such as the sea or an estuary where land is often flatter. There may be small topographical features on site, such as banks and berms.

Not all COMAH sites are flat. Others may have evolved over the years to encompass varying terrain and more complex site layouts as they seek to expand or repurpose.

Proximity to water bodies provides a means of access to sites by ships and barges. Sites are also likely to be in reasonable proximity to arterial roads and motorways with regular road tanker transport to and from site. They may also have railway sidings on site with railcars transporting hazardous substances. Loading and unloading facilities will be associated with all of these means of transport.

Sites may have major accident hazard pipelines associated with them.

Some sites may not have very many buildings, depending on the industry. There may be a significant amount of open space, including large car parks. Process facilities on site tend to be grouped, for example, multiple adjacent storage tanks in one area. There may be various walls, fences and other fixed structures, such as warehouses, on site.

Some sites may have one or multiple significant heat sources such as refineries.

Sites often have some vegetation, hedgerows and shelterbelts both on site and nearby.

The site is likely to have a drainage system, at least for surface water run-off. It may have its own sewer system.

Few buildings may be occupied and they may only be occupied by minimal personnel. A shift system might be in operation so the site may be more heavily occupied around shift changeovers.

Potential dense gas incident sources and contributing factors

In a dense gas incident on a COMAH site there is a good chance that the source substance will be known. It may be possible to approximate release flow rates and maximum quantities released. The release type, instantaneous or continuous may also be readily approximated.

Most dense gas incidents on COMAH sites are likely to be associated with substances stored in pressure-liquefied, temperature-liquefied or cryogenic states. Compressed gas storage is also a possibility. Many different release conditions can result from these types of storage including single and two-phase jets and vaporising pools.

Several of the incidents in the present review involve failures of valves, vents and pipework. Releases from height are also reasonably common, such as a release from a stack or from elevated pipework or from elevated vents/valves.

Several of the incidents reviewed occurred during maintenance or downtime, i.e. under abnormal operation and when contractors might be involved. Substance transfer, e.g. loading and unloading can be a potential cause.

Tank-overfilling is also a potential source of dense gases. This can cause dense gas formation from substances that would not necessarily be associated with dense gas effects, such as gasoline.

The number of different substances on COMAH sites means that mixing of incompatible substances is a potential cause of a dense gas release. This might occur due to problems with a system, e.g. filling processes and loading and unloading, or after spillage, e.g. if incompatible substances are stored too close together or enter drainage systems. Large quantities of multiple substances also mean that the severity of an incident can escalate, potentially leading to a 'domino effect accident', which is an additional concern.

Human factors are important in any incident. Human error can lead to an inadvertent design flaw in relation to a Process and/or Operational Plant. Failures in training, executing safety procedures and mitigation measures, failures in communication and appropriate dissemination of information are all potential factors. Familiarity with the behaviour of dense gases could be a contributory factor to these.

Factors affecting dense gas dispersion

The degree of flatness and openness of the site may affect dense gas dispersion. Depending on the type of site and the site layout, buildings and other fixed structures such as tanks and warehouses may act as isolated obstacles or as obstacle arrays. This will depend on their proximity to each other.

Site features such as containment bunds and walls may act to channel, block or divert the dispersing cloud.

Ingress may occur into buildings, drainage systems and sewers.

Vegetation may increase deposition of substance from the gas cloud and potentially cause congestion. Areas of the site with dense pipework may also cause congestion.

Heat sources may increase convection and therefore increase dilution of the gas cloud.

The presence of a nearby water body may influence the atmospheric flow field, modifying the gas dispersion in its proximity.

Mitigation measures and emergency response

COMAH sites should have well-known and well-practiced emergency response procedures in place, including in situ controls and mitigation measures. In an emergency, the emergency response is likely to be undertaken by a combination of site personnel/responders and emergency response personnel. For small incidents, the site may be able to deal with it themselves.

Site personnel should have supplier details for information about particular substances which might assist in emergency response.

It is likely that there will be features such as containment bunds in place on a COMAH site. There may also be water sprays or vapour barriers in place. Sites may have detector systems on valves and vents and also across the wider site.

If there is enough time, a cordon should be put in place to restrict access to hazardous areas of the site. This may need to be extended if the gas cloud spreads off site.

A COMAH site is more likely to have the equipment available to stop the release at source. Emergency shut-offs and system shut downs are likely to be possible. However, there is sometimes reluctance to action this due to very large costs in start-up and shut-down.

As part of emergency procedures, it is likely that site personnel would have relatively fast access to appropriate PPE. The site may have sirens or loud speaker systems and designated shelters.

Modelling challenges

For emergency preparedness

The model requires the ability to simulate a range of substances and source conditions including multi-phase sources and both instantaneous and continuous releases.

In LUP, it is not appropriate to take all site details into account because most of them can change as the site evolves through the years but the same planning permissions may have to stand throughout this time. Exact details cannot be known about a potential incident, instead a representative set of conditions has to be selected. This presents a significant challenge.

Another challenge is determining which factors can be reasonably ignored or approximated and which features can be reasonably treated as generic. Selecting appropriate methods to account for these factors is also a challenge.

For emergency response

The emergency response should initially be guided by information given in the MAPP and COMAH Safety Report. The latter may include results from modelling work that considers various credible release scenarios.

If the hazard spreads off-site, the Met Office is frequently one of the first points of contact for the police or fire brigade. For prolonged incidents, a Science and Technical Advice Cell or Air Quality Cell may be set up (see Section 2.3.3). At present, none of the typical models used for off-site civil emergency response in Great Britain can model dense gases.

Therefore, the inclusion of many features would be considered a modelling challenge.

During emergency response to an incident it will be necessary to decide if a dense gas model is required and then to communicate with an organisation that has the means to provide this capability. This is a significant challenge when timeframes may be very short.

The following features are likely to be some of the modelling challenges encountered for a COMAH site scenario: complex source physics, deposition, terrain, thermal convection effects and chemical reactions.

For COMAH sites, it is reasonably likely that site features, the substance, some details of the source may be known, but other relevant information may not be readily available. Methods to deal with this uncertainty and conveying it in results will be important.

8.3.2 Scenario 2 – Static site (non-COMAH)

Introduction

A non-COMAH static site is defined here as a facility which would not be regulated under COMAH 2015, i.e. smaller quantities than those shown in Table 40. A static site handling dangerous substances but below the limits for the COMAH regulations to apply would still be subject to The Management of Health and Safety at Work Regulations 1999 (the Management Regulations) and various health and safety regulations such as Control of Substances Hazardous to Health (COSHH), Hazardous Area Classification and Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR).

Sites are likely to be all shapes and sizes. Examples might be smaller sites such as swimming pools requiring a small store of chlorine or ammonia refrigeration units but also large sites storing multiple substances that do not meet the COMAH 2015 threshold quantities.

The Wealdstone (Section 4.4.2), Ellesmere Port (Section 4.4.3) and Trubshaw Cross (Section 4.6.1) incidents are examples of this type of scenario in the UK. Worldwide, the following incidents in this review (with section numbers) might be considered to be examples of non-COMAH sites:

4.5.23 Geneva, Switzerland	4.5.46 Monchengladbach, Germany
4.5.39 Baden-Wurtemberg, Germany	4.5.47 Antwerp, Belgium
4.5.40 Richmond, California	4.5.51 Theodore, Alabama
4.5.43 Dalton, Georgia	4.6.4 Arkansas, US

Typical Features

Regulations such as COSHH and DSEAR still require employers to control substances hazardous to health. The hazards from the substances should have been identified and risk assessed. Substance safety data sheets should be clearly displayed and appropriate control measures should be in place including things like PPE, monitoring and employee health surveillance. Personnel should be trained in handling substances and any emergency response procedures.

There will likely be less typical features than for a COMAH regulated static site. A range of dangerous substances will be handled or stored in quantities below those regulated by COMAH. Some substances may be stored indoors and result in an indoor source, which could disperse outdoors for example via the ventilation system.

The smaller hazard means that non COMAH sites can be located within an urban area in relatively close proximity to high population densities. The location of the local population, indoors or outdoors, will depend on the time of day and the weather. The site may have contractors who may not be as familiar with the site layout and procedures. There may be a shift system so that the site is more heavily occupied at some times of day than others.

The site may be in an area with some topography present. There may be vegetated areas such as parks, fields and woodland near to the site. It may be near to water bodies such as the sea, rivers or lakes. The site may contain heat sources or be adjacent to heat sources. It may be adjacent to other sites handling hazardous substances.

There may be indoor or outdoor drainage or sewer systems into which ingress could occur.

Potential dense gas incident sources and contributing factors

Incident sources on non-COMAH sites are similar to COMAH sites, but should involve smaller quantities. As for COMAH sites, many incidents occur due to vent and valve failures during processing or storage of pressure or temperature-liquefied gases or from compressed gas containers. The source may be at an elevated position. Failure of liquefied gas storage may result in a liquid spill and an evaporating pool source.

There may be a number of different substances on site and mixing of incompatible substances is a potential cause of dense gas release. In some industries, mixing might be an intentional part of the site processes and system failure may cause a release. In other industries, dense gas releases might result from accidental mixing of incompatible substances.

Indoor sources are likely to be more common for the smaller quantities of non-COMAH sites, which might be stored in a warehouse, or store room. In these cases, features such as the layout and ventilation rate of the building will be important and presence of any basements or cellars.

Factors affecting dense gas dispersion

Factors affecting the dense gas dispersion for a non-COMAH site may be similar to those for a COMAH site. A particular difference is that unlike a COMAH site, a non-COMAH site can be located in a more densely populated urban environment. The site is also not as likely as a COMAH site to have been chosen for its flatness (for example to accommodate large storage tanks) and there may be topographical features such as hills and terrain dips.

The urban environment means that interaction of the atmospheric flow field and the dense gas cloud with buildings, other fixed structures and vehicles could cause channelling, diverting and blocking effects. Buildings, vehicles and other structures may also be infiltrated by the gas cloud. Ingress may occur into the sewer and subway network, if present.

Open spaces such as squares, car parks and parks may affect the atmospheric flow field and therefore dense gas dispersion. Parks, vegetation, hedgerows, woodland and shelter belts may provide surfaces for deposition.

Sites may be located on industrial sites, adjacent to other industry. There may be heat sources on site or nearby which may affect the gas dispersion.

Mitigation measures and emergency response

The site should have control measures in place in case of a substance release and trained personnel familiar with the substance and appropriate PPE. Substance data sheets should be available and there should be an emergency plan, which may include mitigation measures. While controls and emergency plans should be in place, there will be more variability in how well-developed and practiced they are when compared to COMAH sites.

The smaller quantities involved in a potential incident on a non-COMAH site may mean that mitigating the source is more achievable.

The potential location within an urban environment means that the general public could be in the immediate vicinity and communication and approaches for clearing the area may be critical very early on in an incident. Measures to mitigate the dispersion of the gas cloud once it is off-site may be required. Isolation zones may be required and shelter in place and evacuation may be necessary. Therefore, the emergency services are likely to be required.

Modelling challenges

For emergency preparedness

The site operator might see modelling as an expensive undertaking when it is not a requirement of non-COMAH sites.

The large number and variability of non-COMAH sites, means that undertaking modelling for LUP is unfeasible.

Emergency preparedness may be more informed by approved codes of practice, industry guidance and other information sources, such as the ERG (see Section 5.7.18).

For emergency response

As observed for the COMAH sites, at present, none of the typical models used for off-site civil emergency response in Great Britain can model dense gases. Therefore, the inclusion of many features would be considered a modelling challenge. During emergency response to an incident it will be necessary to decide if a dense gas model is required and then to communicate with an organisation that has the means to provide this capability. This is a significant challenge when timeframes are likely to be very short.

The relatively high likelihood that a non-COMAH site would be in an urban environment means that a dense gas model that can account for the urban environment, including ingress and deposition, would be important.

8.3.3 Scenario 3 – Pipeline

Introduction

This scenario relates to pipelines regulated by the Pipeline Safety Regulations (PSR) 1996. This includes on and off-shore pipelines in Great Britain and in territorial waters and the UK Continental Shelf. This also includes Major Accident Hazard Pipelines, which convey oils, chemicals and gases, including substances such as ammonia, propane, butane, propylene, crude oil, LNG, vinyl chloride monomer and ethylene.

There were no dense gas pipeline incidents in the UK reviewed in the present work. Worldwide, the following incidents (with section numbers) involved pipeline releases of a variety of substances:

4.5.11 Port Hudson, Missouri
4.5.13 McPherson, Kansas
4.5.15 Mill Woods, Canada

4.5.31 Ufa, Russia
4.5.56 Yazoo County, Mississippi

Typical Features

Pipelines can transport substances over ground as well as underground and under water. They can be connected to off shore installations and on shore terminals and accessed at various metering and pumping stations and valves along their length.

They are typically used to transport large quantities at high pressures. Gases are often transported in a pressure-liquefied state. Pipeline diameters can range from 30 mm to 1000 mm, with pressures over 100 barg.

Pipelines can run along or near to railways and arterial roads but they also run through remote locations with significant topographical features such as valleys and hills. On the other hand, pipelines can run near to and through urban environments. They can run through or under bodies of water. There is likely to be very varied surface types and vegetation, hedgerows and shelterbelts. The potentially remote locations means that access to a leakage point for emergency response may not be easy and personnel may not be in the vicinity.

Underground pipelines can run near to other underground features such as sewer systems and natural geological cavities. Underground releases might result in dirt, debris or water blowing out of the ground and liquids bubbling up through the ground or bubbling in water. A high pressure release may create a crater in the ground around it.

Under PSR (1996), major accident hazard pipelines have special requirements, which include a major accident prevention document and arrangements for emergency plans. Several flammable liquids such as gasoline, hexane, kerosene and diesel do not meet the criteria of a 'dangerous fluid' and are therefore not subject to the regulations.

The length of some pipelines and varied terrain means that Land-Use Planning restrictions apply in each local authority that the pipeline passes through. As for COMAH regulated static sites, three zone maps are provided by HSE.

Escalation of the severity of the event is less likely than for releases on COMAH sites, unless the incident occurs at a pipeline terminal.

In a pipeline scenario, assuming the pipeline has been identified by the operator, the substance should be known. The pipe diameter and the standard operating pressure should be readily obtainable. It may be possible to approximate the quantity released.

Potential dense gas incident sources and contributing factors

The substance should be readily identified by the operator once a leakage is known. The pipe diameter and original operating pressure should be known and information about any pressure drops should also ultimately be available.

The release could be from a crack, hole or a full bore pipe failure. It is likely to be a continuous release and if emergency shut-offs are activated it will be of finite duration dependent on the time taken for the isolated section of pipeline to empty (likely to take several hours). Flow rates will depend on the conditions of the release but can be thousands of kilograms per second.

Direct inspection of the release point may be difficult due to location of the pipeline and, especially so, if the pipeline remains buried.

The source is likely to be a high pressure release of a liquid or a pressure-liquefied gas (for the cases considered here, i.e. releases producing dense gases). The high pressures mean that releases could rapidly produce large dense gas clouds.

Causes of incidents might be pipeline material or weld failures due to poor maintenance or damage during excavation work. Land-use planning protects against uninformed excavation near to some pipelines but not all of them, especially those which are not subject to the PSR.

Factors affecting dense gas dispersion

Large high pressure releases can result in a crater around the pipeline, which could affect the near-field dispersion behaviour. As well as potential craters at the release point,

significant topography may be present such as valleys and hills which could channel, block and divert the gas cloud as well as affecting the atmospheric flow field.

The variety of terrain which pipelines pass through or near, including water bodies, forests and urban environments, also presents very variable surface roughness and potential for deposition.

Releases from pipelines running through or under bodies of water may result in liquid and gas bubbling in water. Gas releases underground can spread through the path of least resistance and can enter into natural features and man-made structures such as sewer systems.

Mitigation measures and emergency response

If a pipeline has alarms and monitors and the leak is substantial enough to trigger them, the operator may be aware of the leak and initial emergency response may be actioned by the operator. Subsequent emergency response will involve emergency services. Otherwise, the leak may be first reported by the public and the local emergency response process should alert the operator.

Emergency shut offs should be in place to isolate sections of pipeline. These may be automatic or manually activated. Once these measures have been applied, this should mitigate the source to be a finite amount. The duration of the release may still be significant as depressurisation can take some time.

Mitigation measures are very substance dependent but for pipelines it should be possible to identify the substance by communicating with the operator. Or, local authorities should have this information as it should have been provided as part of emergency preparedness if it is a major accident hazard pipeline.

Mitigation measures to prevent dispersion will need to be mobile such as water sprays and fogs, and mobile monitors and detectors.

There may be a delay in the application of mitigation measures on site for remote sections of pipeline with the result that the area covered by the dispersing dense gas cloud may be larger. Because of this, an appropriate system of communicating with the public will be required and shelter in place/evacuation may need to be considered.

Modelling challenges

For emergency preparedness

The length of pipelines and the variety of terrain are significant challenges in modelling pipelines for emergency preparedness. Modelling pipeline releases also requires consideration of how the release changes over time as the pipeline depressurizes, which could be associated with phase change, for pressure-liquefied gas pipelines. These substances and also volatile liquid pipelines (e.g. crude oil) could produce evaporating sprays and spreading (evaporating) pools. Carbon dioxide pipeline releases may produce banks of dry ice particles that sublime into cold, dense carbon dioxide gas.

For emergency response

As noted in the previous scenarios, at present, none of the typical models used for off-site civil emergency response in Great Britain can model dense gases. Therefore, the inclusion of many features would be considered a modelling challenge. During emergency response to an incident it will be necessary to decide if a dense gas model is required and then to communicate with an organisation that has the means to provide this capability. This is a significant challenge when timeframes may be very short.

The substance may be known and it is likely to be a pressurised release of time varying finite duration. It may be difficult to get much physical information about the source beyond this and so the source will likely be poorly defined. If the release is underground or under water this could be very complex to model.

There is likely to be terrain including potentially complex topography and vegetation, forest canopies etc. The model may need to be able to deal with terrain at a range of scales and including (potentially) rainout and deposition effects, congestion effects and channelling, diversion and blocking, along with the potential impact on the atmospheric boundary layer, e.g internal boundary layers caused by water bodies, urban environments and forests.

8.3.4 Scenario 4 – Transport (road/rail)

Introduction

This scenario relates to substances transported by road or transported by rail. The substance could be contained in one large tank, or it could be contained in a series of smaller containers such as cylinders.

The carriage of dangerous goods by road or rail in Great Britain is regulated by the Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations (CDG) and either the European agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) or the Regulations concerning the International Carriage of Dangerous Goods by Rail (RID). These regulations apply to tankers and bulk containers and also smaller containers above specified thresholds.

The ADR prescribes what generic types of container can be used to transport dangerous goods. There are a wide variety of containers. These include assorted packagings, intermediate bulk containers (IBCs), portable tanks and multiple-element gas containers (MEGCs). At larger scales they include fixed tanks (tank vehicles), demountable tanks, tank-containers, tank swap bodies with shells made of metallic materials, battery-vehicles and fibre-reinforced plastics tanks.

Substances packaged in smaller containers can be a variety of sizes and shapes, including cylinders, tubes, pressure drums and cylinder bundles. As an example, carbon dioxide cylinders might contain only 2 kg for a small extinguisher and 34 kg for a larger industrial cylinder¹⁸⁹.

There are a variety of road and rail tanker sizes. For example, on the road, an LPG tanker with a rigid chassis might carry between 2 and 12 tonnes, while a semi-trailer might carry 18 to 24 tonnes¹⁹⁰. In Europe, typical load limits might be in the range of 50 tonnes to 65 tonnes for rail cars used for transporting flammable products and chemicals¹⁹¹.

There are no examples of dense gas dispersion incidents resulting from road or rail in the UK in this review. Worldwide, the following incidents in this review (with section numbers) involved road tankers:

4.5.2 Brooklyn, New York
4.5.17 Houston, Texas
4.5.19 Chicago, Illinois, 1978

4.5.34 Dakar, Senegal
4.5.42 Pennington, Alabama

The following incidents from this review (with section numbers) involved rail cars:

¹⁸⁹ <https://www.boconline.co.uk/shop/en/uk/carbon-dioxide-size-vk-40-vk> Accessed on 22nd September 2020

¹⁹⁰ <http://www.rtmtd.co.uk/new-lpg-tanker-manufacture> Accessed on 22nd September 2020

¹⁹¹ <https://www.qbrx.com/manufacturing/europe-rail/tank-wagons/> Accessed on 22nd September 2020

4.5.7 La Barre, Louisiana
4.5.9 Glendora, Mississippi
4.5.20 Youngstown, Florida
4.5.21 Mississauga, Ontario
4.5.22 Montana, Mexico
4.5.37 Richmond, Virginia, 1993

4.5.41 Festus, Missouri
4.5.44 Macdona, Texas
4.5.45 Graniteville, South Carolina
4.5.48 Viareggio, Italy
4.5.52 Chelyabinsk, Russia

Typical Features

Under the ADR, the packaging and vehicle should have the appropriate marking and/or placarding for its contents. A vehicle should be carrying transport documents and instructions in writing which contain basic information for use in an emergency.

Bulk road tankers carry one substance, which should be readily identified by marking and documentation but substances can also be transported by road in smaller containers with multiple substances in one vehicle. Trains pull many cars and so an incident may involve multiple substances. When there are multiple substances present, an incident could potentially suffer a delay in identifying the source and there is potential for escalation due to the delay and mixing of incompatible substances. Escalation due to fire is also possible.

Roads and railways have access to docks, railway sidings and airports for transfer of loads. They frequently pass near or through highly populated urban environments. An incident within the urban environment might result in significant ingress into buildings, other fixed structures and vehicles. Ingress into sewer networks and underground systems in the vicinity of the release is also likely.

An incident on a major road such as a motorway during busy times may result in relatively high population density and potential for ingress into vehicles. This will be affected by the time of day and the time of year. This could result in difficulty for emergency services reaching the scene of an incident.

Roads and railways pass through all types of terrain. This can include dramatic topography including mountains and valleys using features such as bridges and tunnels. These could result in elevated or subterranean release scenarios.

The remote terrain can also result in a delay in arrival of the emergency services. The driver may be the only personnel present initially and they may have been incapacitated during the incident.

Potential dense gas incident sources and contributing factors

In a dense gas incident involving one large tank during road transport, the source substance may be known or readily identified. It may be possible to approximate flow rates and maximum quantities released. The release type is likely to be instantaneous or continuous of finite duration.

In an incident involving road transport of multiple substances, there may be complications identifying the source. It may be difficult to identify the source if more than one rail car is involved in a rail incident.

Most dense gas incidents by road or rail are associated with pressure-liquefied, temperature-liquefied or cryogenic substances. This means that many different release conditions can result from these types of storage including single and two-phase jets and vaporising pools.

Potential sources include failed valves and welds, cracks and holes in tank walls. Failure can be caused by road traffic accidents and rail accidents, which may involve derailment. Failure

can also be caused by overpressurisation from tank overfilling. Fire engulfment can result in failure of containment. Other sources include corrosion or fatigue failure.

Releases from pipework during loading and unloading can occur and have the potential for mixing of incompatible substances. This is also a potential issue with an incident involving multiple rail cars.

Factors such as heavy traffic or remoteness can contribute to the source and escalation of incidents.

Factors affecting dense gas dispersion

Road and rail incidents can happen in a variety of environments, which means that there are no typical factors associated with dense gas dispersion in this scenario.

If the incident occurs in an urban environment, the gas cloud may be channelled, blocked or diverted by vehicles, buildings and other structures. The atmospheric flow field will be modified and deposition onto the ground and buildings may occur. Ingress into buildings, fixed structures and other vehicles will affect the cloud along with ingress into sewers and basements.

Outside of urban environments, the dense gas dispersion may be affected by variable surface types and topography. Valleys and hills can divert the gas cloud and affect the atmospheric flow field.

Vegetation, hedgerows, shelterbelts and forests will increase deposition and affect the atmospheric flow field.

Incidents which occur in a large open area, such as an airport, or next to a water body may have a different atmospheric flow field.

Mitigation measures and emergency response

Initial emergency response will be from the driver, if they are not incapacitated during the incident. PPE should be available in the vehicle.

For a road incident, there may be road traffic collisions within the area affected by the hazardous release. Traffic will need to be stopped outside this area and a cordon will likely need to be put in place around the vehicle. Mobile measures may be required to mitigate dispersion of the gas cloud.

If the release occurs on an industrial site, particularly a COMAH site, the site should have procedures and trained personnel in place to deal with emergencies. This may be supported by the emergency services.

Off site, there will be a high dependency on the emergency services response.

Mitigating the source, for example by plugging a hole, may be possible if the release occurs on an industrial site or in a location where the required materials and trained and equipped personnel might be accessible. In other circumstances, this may be delayed, or not possible. For example, if it is too dangerous to approach the source, or the incident occurs in a remote location.

There is potential for high population density in the vicinity of road or rail releases and so prompt communications with the public will be important. Shelter in place or evacuation may be required.

Modelling challenges

For emergency preparedness

The very extensive road network and the variety of terrain through which the road and rail network pass are significant challenges in modelling road and rail scenarios for emergency preparedness. Isolate and protective action distances for road and rail transport of dangerous goods, based on a generic set of atmospheric conditions and environments, are given in the ERG (see Section 5.7.18). Other models, such as HPAC (see Section 5.7.29), have pre-defined source conditions for transport-related sources, to enable the model to be used either for emergency preparedness or response.

For emergency response

As noted in the previous scenarios, at present, none of the typical models used for off-site civil emergency response in Great Britain can model dense gases. Therefore, the inclusion of many features would be considered a modelling challenge. During emergency response to an incident, it will be necessary to decide if a dense gas model is required and then to communicate with an organisation that has the means to provide this capability. This is a significant challenge when time-frames may be very short.

Speed is always the main challenge. In the case of a road tanker or a rail car incident in an urban environment, where the population density may be high, the speed of response is all the more critical because of the proximity of the public.

A large number of factors could affect the dispersion behaviour. There may be terrain including urban environments, complex topography and vegetation, forest canopies, deposition effects, congestion effects and channelling, diversion and blocking, along with the potential impact on the atmospheric boundary layer, e.g. internal boundary layers caused by urban environments, water bodies and forests.

8.3.5 Scenario 5 – Transport (maritime)

Introduction

The UK undertakes a significant amount of trade by sea. It has several industrial ports with which large transport ships can operate. Substances such as LNG and ammonia are transported by ships.

The maritime transport of dangerous goods is covered under the International Maritime Organization's International Maritime Dangerous Goods Code (IMDG), which is regulated in Great Britain by the Maritime and Coastguard Agency while at sea and by HSE when ships are docked in port.

Liquefied gas carrier ships carrying substances such as LPG, ammonia or vinyl chloride typically have capacity in the range 15,000 m³ to 85,000 m³¹⁹². The largest carrier ships are probably LNG carriers, which to date have been constructed to carry up to 266,000 m³ of LNG.

No examples of incidents off-shore in the vicinity of the UK, where a large dense gas cloud played a significant part, were found in undertaking the present review. The Runcorn incident (Section 4.4.4) is an example of a maritime/port incident in the UK. The Southern Red Sea and Solent and Fraserburgh incidents (Sections 4.6.5 and 4.6.6) are maritime incidents, though they resulted from transport of substances for fire extinguishing (carbon dioxide) and refrigeration (Freon) functions on the boat, rather than the transport of dangerous goods per se.

¹⁹² <http://www.liquefiedgascarrier.com/Fully-Refrigerated-Ships.html> Accessed on 22nd September 2020

There are no offshore incidents elsewhere in the world included in this review. The Naples incident (Section 4.5.26), which occurred during tank filling from a ship in port is an example of an incident near a port.

Typical Features

The ship personnel should have an inventory of its cargo and therefore substances and quantities on board should be known. Ship personnel will likely be familiar with the layout of the ship and should be trained in emergency procedures.

There are particular shipping lanes at sea and on approach to ports, which influence the location of ships. These are typically based on prevailing winds, currents and depth of water. They are generally populated by larger, less manoeuvrable vessels. They are typically the busiest parts of the sea, which is a useful feature for rescue of personnel from passing ships but it also means that there are many ships potentially in the vicinity of an off-shore release.

Shipping activity is heavily influenced by time of day due to tides and also influenced by the weather. In proximity to land there are particular meteorological features such as on-shore and off-shore winds which can affect the ships positioning and also any gas release.

When near land the ship can be at anchor or it can be moored to a quay or jetty. Loading and unloading of cargo is likely to be by pipes and hoses between the land and the ship.

Port areas are often industrialised and have low population density. They can be made up of large industrial sites, which are regulated under COMAH, with similar considerations to Scenario 1.

Potential dense gas incident sources and contributing factors

Hazardous substances, which could result in dense gas behaviour, are most commonly transported by ship in pressure-liquefied or temperature-liquefied (or a combination) form. Releases are likely to be continuous of finite duration up to the quantity of a storage tank.

A source could result from holing of the ship near or below the water level due to grounding or striking another ship or object in the water. This could result in a liquid spill and an evaporating pool on the surface of the sea. In an extreme case, this could also result in ship break up.

One method of mitigating ship break up due to grounding is to jettison the cargo. This could be via a jet release from a pipe at elevation.

There is the potential for releases from pipes and vents at sea and during loading and unloading. These may also result in releases from height.

There is the potential for tanks to be overfilled and for failure of storage conditions.

Complex behaviour could result if the substance released onto water is water-reactive or due to rapid phase transitions (as demonstrated by the Coyote and Falcon trials with LNG).

Wind directions in coastal areas can be affected by land and sea breezes, with sometimes different wind directions near the surface and aloft.

Factors affecting dense gas dispersion

The surface of water is relatively smooth (as compared to urban terrain) and fairly uniform in temperature, as compared to ground surfaces that may fluctuate significantly in temperature due to solar insolation. These features mean that turbulent mixing may be relatively low and clouds could disperse over longer distances than on land.

Dense gas clouds originating from low temperature releases will evolve differently over large, deep water bodies because convection currents continually replenish the heat at the surface.

If the water body is shallow, the surface temperature cannot be maintained and cryogenic releases may cause the water to freeze, affecting both heat transfer and surface roughness.

Depending on the atmospheric conditions, the dense gas dispersion may be affected by flow fields generated by the presence of the ship. This could result in the ship being immersed within the dense gas cloud.

The differences in the atmospheric boundary layer between the land and the sea results in a transition region which could affect the dispersing cloud as it approaches land.

Mitigation measures and emergency response

Ships are fitted with a variety of detectors and alarms, both inside and outside of cargo tanks.

The ship should have appropriate PPE on board, and emergency response procedures and equipment that is appropriate for the substances carried. For example, LNG carriers may be fitted with water sprays, nitrogen purging and/or carbon dioxide systems to deal with a variety of release scenarios and fires.

A liquid spill at sea can be mitigated through the use of booms to try to prevent spread of the liquid and restrict the size of the pool, therefore mitigating the source by reducing the evaporation rate.

At sea, it is possible to jettison the load if a ship is grounded and at risk of breaking up. There are risks that the ship could be enveloped by any resulting cloud and if the ship is near to land there is a risk that the cloud could spread to land.

In order to mitigate exposure to those on board, the ship needs to position itself outside of the dense gas cloud if possible. This might be difficult in a flammable vapour cloud where the ship is a potential ignition source.

There is likely to be a considerable delay before assistance can be provided to a ship at sea. Any responding vessels/helicopters will need to take care not to enter the cloud and not to provide an ignition source if it is a flammable release.

If the dense gas cloud travels towards and over land, measures will be required to inform population in its path and to action shelter in place or evacuation.

If the ship is in port, any unloading or loading operations should be stopped and disconnected in the event of a release.

If one tank is damaged, if possible, cargo can be transferred to other tanks in order to stop the source of the release. This is unlikely to be possible once at sea because all tanks are likely to be full.

Modelling challenges

For emergency preparedness

There are several challenges for modelling dense gas dispersion for the purpose of emergency preparedness. Difficulties in characterising of the source include the time-varying location of ships and possible interactions between releases and water, e.g. due to the substance released being water-reactive (e.g. ammonia) or the occurrence of RPTs. Spills that spread on water may also be affected by tidal currents. For releases from ships in coastal areas or near ports, atmospheric conditions may be affected by land and sea breezes.

For emergency response

As noted in the previous scenarios, at present, none of the typical models used for off-site civil emergency response in Great Britain can model dense gases. Therefore, the inclusion

of many features would be considered a modelling challenge. During emergency response to an incident it will be necessary to decide if a dense gas model is required and then to communicate with an organisation that has the means to provide this capability. This is a significant challenge when timeframes may be very short.

For an off-shore release, it may be difficult to obtain information about the source, which would rely on details and communication from the ship. As outlined for emergency preparedness, modelling the boundary layer above the sea and the transition between sea and land would be challenging.

8.3.6 Scenario 6 – Non-regulated, unknown source

Introduction

This scenario relates to unintentional or intentional releases, which do not fall into any of the previous scenarios and are not covered by any regulation.

In this sort of scenario the gas might be observed, smelled or be symptomatic before the source or substance is identified. Examples might be a dense gas release from an unknown location within a city. In an alternative scenario the release location might be known but the source details and substance are unknown.

An intentional release can result from, for example, a CBRN threat, or from sabotage.

There are no UK examples in the incidents reviewed in this work. Worldwide, the following incidents in this review (with section numbers) could be considered under this type of scenario:

4.5.1 Ypres, Belgium

4.6.2 Japan

4.5.6 Menzengraben, Germany

4.6.3 Cleveland, Ohio

4.5.54 Wisconsin, US

4.5.27 Lake Monoun & Lake Nyos, Cameroon

Typical Features

There are many unknowns in this scenario and few typical features. The substance and the quantity released are likely to be initially unknown; there may be multiple sources; the release could originate from indoors or outdoors.

If the release is intentional, such as a CBRN threat, then the source may be located in a position to maximise impact on its target and it may be intentionally difficult to identify.

An alternative type of intentional release is sabotage. In this case, the source may be located in a position where known hazardous substances are stored. It is likely that once the source location has been identified, the substance and other source information may be more readily obtained from the site operator.

An incident in the urban environment means that ingress into buildings, other fixed structures and vehicles is likely. Ingress into sewer networks, basements and subway systems is also likely. There may be high population density in the vicinity of the release.

Unlike some of the other scenarios where there may be trained personnel or automated systems in place to alert emergency responders to a release, releases in this type of scenario may initially go unnoticed for some time. Therefore, the dense gas cloud may be reasonably well established before emergency response personnel arrive.

The general public may be aware of the incident before the emergency services, which could result in relatively high levels of exposure and confusion or panic.

The response to this type of scenario will be based on the local authorities and emergency services plans for responding to such scenarios. If it is deemed a CBRN threat, it may involve UK defence organisations such as Dstl.

Potential dense gas incident sources and contributing factors

The details of the source are unknown. This means that the source could be any package or container located indoors or outdoors and potentially at an initially unknown location. It could be difficult to find or reach.

The source could result from a variety of storage conditions or due to mixing of substances. The source type might be instantaneous or continuous.

For an intentional release, the source geometry will have been designed to open and release the substance and may be quite different to unintentional release geometries.

Factors affecting dense gas dispersion

With no typical features, except for the lack of source information, there are many factors which could affect dense gas dispersion. Most factors discussed in the previous scenarios are also potential factors in this scenario.

Mitigation measures and emergency response

Emergency response will be provided by the emergency services and any local authorities' emergency planning.

Until the source is identified, generic measures to mitigate exposure will likely be required. Cordons will be applied as soon as possible to limit access to known hazardous areas. Traffic in the area will need to be managed. Shelter in place or evacuation may be advised.

If the incident occurs in a highly populated area, emergency response may be delayed by public confusion or panic and require good communication systems to deal with this. The number of people will depend on the day of the week, time of day and the weather. Factors such as these will dictate the population density and whether people are generally indoors or outdoors. The location of the population will also affect the numbers of people exposed to the hazardous gas.

Measures to mitigate the source and dispersion can be applied once the location and substance is known. Decontamination of exposed personnel and members of the general public may be required.

Modelling challenges

For emergency preparedness

There are very many uncertainties associated with this scenario, which makes it difficult to select representative cases for emergency planning.

It is possible that modelling may be undertaken during response exercises. Therefore the modelling challenges will be those associated with emergency response modelling.

For emergency response

As noted in the previous scenarios, at present, none of the typical models used for civil emergency response in Great Britain can model dense gases. Therefore, the inclusion of many features would be considered a modelling challenge. During emergency response to an incident it will be necessary to decide if a dense gas model is required and then to communicate with an organisation that has the means to provide this capability. This is a significant challenge when timeframes may be very short.

If the incident is deemed to be a CBRN threat then modelling may be undertaken in a counter-terrorism capacity by Dstl. This would likely involve the use of HPAC, which has dense gas modelling capability.

The lack of source information (location, substance, release conditions) is a significant uncertainty in this scenario. In addition, there is the potential for very many factors to affect the dispersion, in particular, the urban environment, vegetation, deposition, ingress etc. Any model used would ideally be able to accommodate all of these factors in some way, while remaining quick to set up and run.

Any predictions resulting from modelling will be very uncertain and will need to convey this uncertainty. The lack of information and necessity to understand the uncertainties will make it difficult to provide a fast response.

9 DISCUSSION

This chapter provides discussion on two aspects not yet covered in this review:

- Future trends and emerging technologies where dense gas dispersion may present a potential new, increased, or under-studied hazard for industrial regulation and emergency preparedness and response
- Potential knowledge or data gaps on dense gas dispersion, which have arisen from this study and other recent studies

9.1 Future trends and emerging technologies

9.1.1 Aging infrastructure and declining risk standards

Marsh (2020) found that plants older than 30 years are far more likely to experience losses and suggested that industry needs to look more closely at the risks of older refineries and petrochemical plants. They elaborate on the reasons for this: in the first ten years of a plants operation, most losses are caused by operations-related failures. As plant operations experience develops, the number of losses reduces, until age takes its toll and there is a steep rise in both loss frequency and magnitude in plants more than 30-years-old. In plants older than 30 years, failures related to mechanical integrity account for 65% of losses. The incident review in this study appears to corroborate this timeframe, with examples of incidents due to failed infrastructure increasing with age.

Marsh (2020) also stated that risk standards have declined in some areas over the past 12 years, which may also be a factor. For example, risk engineer surveys undertaken by Marsh (2020) found that "engineering standards" at refineries had declined over this period. Both gas processing plants and terminals/distribution have undergone an overall deterioration in risk quality over the past 12 years. The analysis suggests there could be an increased likelihood of incidents in the hydrocarbon industry, which may include dense gas releases (e.g. LNG, LPG, gasoline vapour, HF).

9.1.2 Reducing the carbon footprint

In order to reduce its carbon footprint, the UK must shift from using of high-carbon fossil fuels to low or zero carbon energy solutions. This is likely to involve an increase in production, storage and transport of a variety of substances, for which dense gas dispersion is a hazard. The following substances, which could form key components in a move to lower carbon footprint in the UK are discussed below: LNG, LPG and bioLPG, hydrogen, ammonia and carbon dioxide.

A revitalisation of the nuclear power industry in the UK is also part of the aim to reduce the carbon footprint and is also discussed below.

As rail has a lower carbon footprint than road, it is possible that in the future the transport of chemicals by rail could increase. Current forecasts over the short term (2023/4) and longer term (2033/4) suggest a modest increase of around 10% in chemical transport by rail from 2020 levels in several future scenarios¹⁹³.

¹⁹³ <https://www.networkrail.co.uk/running-the-railway/long-term-planning/> and <https://www.networkrail.co.uk/wp-content/uploads/2020/08/Rail-freight-forecasts-Scenarios-for-2033-34-and-2043-44.pdf> Accessed on 17th September 2020

9.1.3 LNG

There are various future trend analyses for LNG available online, which indicate that LNG use will continue to increase in the coming years, until beyond 2035-40¹⁹⁴ (Shell, 2020). Imports of LNG into the UK are likely to increase, meaning increases in LNG shipping.

There is also likely to be a move towards ships being fuelled by LNG¹⁹⁵, as shipping moves away from high sulphur fuels. Shell (2020) report that LNG use as a marine fuel could reach over 30 million tonnes a year by 2040.

9.1.4 LPG and BioLPG

LPG is used for a variety of applications in the heating, transport and industrial sectors. It is typically produced as a by-product of crude oil refining and natural gas processing. The government has plans to phase out the use of high-carbon heating fuels. LPG is a low carbon fuel emitting 33% less carbon dioxide than coal and 12% less than oil (Liquid Gas UK Ltd, 2019).

In the future, bioLPG has significant potential as a 'drop-in' fuel for similar applications to fossil-derived LPG (Liquid Gas UK Ltd, 2019), meaning that LPG infrastructure can be considered future-proof. Liquid Gas UK Ltd (2019) provides details of several market opportunities for LPG and bioLPG.

BioLPG can be generated in a variety of ways. Example technologies are fermentation of sugars to produce isobutene. There is a demonstration facility in Germany and a commercial scale facility in the planning stages in France, which will have expected capacity to produce 50,000 te of isobutene per year. At present there is no UK facility.

An example of bio-propane generation is hydrotreated vegetable oil. This is currently the only process for production of bio-propane that is operating at the commercial scale. The primary product of the process is bio-diesel but propane is produced as a by-product during hydroprocessing at a ratio of 100-111 kg per tonne of HVO biodiesel (Johnson, 2019). There are currently no units in the UK and the nearest facilities are in the Netherlands and France.

9.1.5 Hydrogen

Hydrogen has been highlighted by the Committee on Climate Change as a "credible option to help decarbonise the UK energy system" and its uses are discussed in detail in the CCC (2018) report. In the move away from carbon-based fuels, there is work already underway looking at more routine use of hydrogen in various sectors, e.g. as fuel in transport (including road¹⁹⁶, rail¹⁹⁷ and shipping¹⁹⁸) and its use in domestic and industrial heating across the UK¹⁹⁹. Projects such as HyNet are seeking to combine domestic and industrial use of hydrogen with carbon capture and storage²⁰⁰.

In the short term, hydrogen is likely to be generated by reforming natural gas, with a transition over time to renewable sources, e.g. from wind power. An example of the latter

¹⁹⁴ <https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-gas-and-lng-outlook-to-2035#> Accessed on 15th September 2020

¹⁹⁵ <https://www.mckinsey.com/industries/oil-and-gas/our-insights/forced-boil-off-gas-the-future-of-lng-as-a-fuel-for-lng-carriers> Accessed on 15th September 2020

¹⁹⁶ <http://www.ukh2mobility.co.uk/stations/> Accessed on 21st January 2021.

¹⁹⁷ <https://www.railway-technology.com/projects/hydroflex-hydrogen-train/> Accessed on 21st January 2021

¹⁹⁸ <https://www.bbc.com/future/article/20201127-how-hydrogen-fuel-could-decarbonise-shipping> Accessed on 15th January 2021.

¹⁹⁹ <http://www.h21.green/> Accessed on 15th January 2021.

²⁰⁰ <https://hynet.co.uk/> Accessed on 15th January 2021

technology is the Dolphyn project²⁰¹. To reduce carbon dioxide emissions, hydrogen produced from natural gas will need to be combined with carbon capture and storage.

In the UK, hydrogen is currently stored and transported as a compressed gas in road-going vehicles, with dispensing stations operating at either 350 bar or 700 bar. To supply hydrogen for domestic heating and industrial uses, it will be transported through the UK gas transmission and distribution network as a gas. Any releases from this infrastructure will therefore be lighter than air, rather than produce dense gas clouds.

Hydrogen is more likely to be stored as a cryogenic liquid for rail and shipping applications. Safety aspects related to releases of liquid hydrogen are being studied in the ongoing PreslHy project (Pre-normative REsearch for Safe use of Liquid Hydrogen)²⁰². Tests on liquid hydrogen releases were discussed in Section 6.5.32. At its boiling point of -253 °C, the density of hydrogen gas is 1.4 kg/m³, which makes it slightly denser than air²⁰³. The cold temperatures associated with cryogenic hydrogen releases can also cause condensation of nitrogen and oxygen from the air. Hansen (2020) showed that cryogenic hydrogen releases produce dense gas behaviour, and his analysis indicated that hazard ranges could extend further for liquid hydrogen bunkering than for LNG.

The CCC (2018) report notes that there is the potential for mass hydrogen production in the Middle East and other locations, which could be imported by ship either as hydrogen or as ammonia (see below). This suggests a potential rise in shipping in bulk of both hydrogen and ammonia. However, the CCC (2018) report also says that a large-scale international hydrogen market is unlikely to develop for the next 10-15 years.

9.1.6 Ammonia

Ammonia is used commercially to produce of fertilisers, plastics, synthetic fibres, dyes, explosives, pharmaceuticals and cleaning products, and as a heat transfer fluid in industrial refrigeration systems. Household and industrial cleaning solutions typically use solutions of 10 – 50% ammonia in water.

According to the Committee on Climate Change report (CCC, 2018), ammonia could be a crucial substance in enabling large-scale decarbonisation. Ammonia has a potential as a low-cost hydrogen carrier and directly as a hydrogen-rich fuel, at lower cost per MWh than hydrogen. There is potential for its use in power stations. This could result in large bulk transport of ammonia to the UK by ship and then either overland by road or by pipeline.

Several articles on the Ammonia Energy Association website²⁰⁴ indicate that there is increasing interest worldwide in ammonia as a fuel and as a hydrogen carrier. In its target to reduce emissions in shipping, the UK Government is aiming to launch a number of zero emission shipping ambitions, including a group of hydrogen or ammonia powered domestic vessels²⁰⁵.

Note that ammonia (like hydrogen) is lighter than air under typical ambient pressures and temperatures but it is often transported in a liquefied state which, when spilled, can cause the vapours to behave as a dense gas.

²⁰¹ <https://www.erm.com/news/erm-gets-go-ahead-to-develop-green-hydrogen-at-scale-from-offshore-wind/> Accessed on 15th January 2020.

²⁰² <https://cordis.europa.eu/project/id/779613> Accessed on 15th January 2021.

²⁰³ <https://encyclopedia.airliquide.com/hydrogen> Accessed on 21st January 2021.

²⁰⁴ <https://www.ammoniaenergy.org/articles/> Accessed on 21st January 2021

²⁰⁵ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815664/clean-maritime-plan.pdf Accessed on 15th January 2021.

9.1.7 Carbon dioxide

Carbon dioxide (CO₂) is used in many applications: as a chemical feedstock, an inert gas in welding and fire extinguishers, as a supercritical fluid solvent, as a refrigerant, and as an additive to beverages. It has been used for several decades (particularly in the USA) for Enhanced Oil Recovery (EOR), where CO₂ is injected at higher-pressure into oil reservoirs to help reduce the viscosity and improve the oil flow through wells.

Carbon capture and storage (CCS) could lead to a significant increase in the transport of CO₂ in the coming years. In the UK, various CCS projects have been proposed, starting in 2006-2007 with the BP Decarbonised Fuels (DF1) project²⁰⁶ and leading onto other projects such as White Rose²⁰⁷ in 2014-2016. These projects did not go ahead into the construction phase, due to lack of UK government support, but significant research efforts were devoted to investigating the potential risks of CCS infrastructure (see Gant et al., 2017). Further research is currently ongoing, coordinated by the Energy Institute and other organisations.

In the UK CCS projects, CO₂ was planned to be captured from power stations and other significant emitters and then transported over land by pipelines to compressors or pumping stations on the shoreline, before being transported offshore to sequestration sites under the North Sea. Several projects planned to repurpose existing offshore hydrocarbon pipelines for CO₂ service. Whilst the White Rose project proposed a new onshore high-pressure pipeline with the CO₂ in the dense-phase (liquid) state, other work has mostly focused on onshore pipelines operating at lower pressures with CO₂ in the gaseous state, which enables existing natural gas pipelines to be repurposed for CO₂ service (e.g. Feeder 10 in the Acorn project²⁰⁸).

In Norway, the Northern Lights CCS project²⁰⁹ led by Equinor has recently been funded by the Norwegian government. The project involves transport of CO₂ by ship from emitter sites near Oslo to a terminal on the west coast, from where the CO₂ will be transported offshore by pipeline. The project envisions future growth in transport of CO₂ by ship to Norway from other sites around the world. It is planned to be operational in 2024.

Carbon dioxide is not currently defined as a dangerous substance under the COMAH regulations or as a dangerous fluid under the Pipelines Safety Regulations and therefore, HSE does not provide Land-Use Planning advice for carbon dioxide capture, transport or storage. However, HSE is aware of the potential hazards from carbon dioxide²¹⁰ (HSE, 2011b) and the regulatory environment may change.

In addition to CCS, there is also carbon capture and utilisation (CCU), in which CO₂ is used to make chemicals or fuels, rather than being emitted to the atmosphere. The UK government is providing support for CCU demonstration projects²¹¹ and further information on ongoing CCU work can be found online, for example on the CO₂-WIN website²¹².

Risks posed by Carbon Capture Utilisation and Storage (CCUS) infrastructure could involve high impacts (i.e. large dense gas clouds) but such events would have a very low frequency of occurrence. In contrast, CO₂ fire extinguishing systems have been found to present a high frequency, lower impact risk. For example, between 1975 and 2000, the unintended release

²⁰⁶ <https://publications.parliament.uk/pa/cm200506/cmselect/cmsctech/578/578m26.htm> Accessed on 18th January 2021

²⁰⁷ https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/446600/H1_assessment.pdf Accessed on 18th January 2021

²⁰⁸ <https://pale-blu.com/acorn/> Accessed on 18th January 2021

²⁰⁹ <https://northernlightsccs.com/> Accessed on 18th January 2021

²¹⁰ <https://www.hse.gov.uk/carboncapture/major-hazard.htm> Accessed on 15th September 2020

²¹¹ <https://www.gov.uk/government/collections/funding-for-low-carbon-industry#carbon-capture-and-utilisation-ccu-demonstration> Accessed on 18th January 2021

²¹² <https://co2-utilization.net/en/> Accessed on 15th September 2020

of CO₂ from fire-extinguishing systems caused 72 deaths and 145 injuries, mainly in the marine industry.

9.1.8 Nuclear power

Nuclear power is of increasing interest again as the UK seeks to move away from high-carbon gas and petroleum products. At Hinkley Point C in Somerset EDF Energy are constructing two new nuclear reactors in the first of a new generation of nuclear power stations in the UK. Plans have also been submitted to build and operate at Sizewell C in Suffolk. Information about both can be found on the EDF Energy website²¹³. China General Nuclear Power Corporation and EDF are also at the pre-planning stage of developing a new nuclear power station Bradwell B at Bradwell-on-Sea in Essex. Information can be found on a project-specific website²¹⁴.

In the nuclear power industry the main risk with regards to dense gases arises from uranium hexafluoride, which results from the conversion of uranium to reactor fuel²¹⁵. Uranium enrichment produces large quantities of depleted uranium hexafluoride as a waste product. The long-term storage of depleted uranium hexafluoride presents environmental, health, and safety risks because of its chemical instability. When uranium hexafluoride is exposed to moist air, it reacts with the water in the air to produce uranyl fluoride (UO₂F₂) and hydrogen fluoride both of which are highly corrosive and toxic. The conditions of release can result in dense gas formation and dispersion (see SAIC, 1998).

9.1.9 Chlorine

While there have been no large-scale chlorine incidents in the UK to date, it is one of the most common toxic substances involved in incidents worldwide. It is stored and transported within the UK and at a wide range of scales from very large bulk storage tanks to road tankers and small containers, for example, used in cleaning products. As such, it is associated with both low frequency, high impact risks and high frequency, low impact risks. Chlorine gas can also be produced from mixing incompatible substances.

Chlorine has been used as a chemical weapon in Iraq and Syria in 2014 - 2018 and concerns about potential releases was one of the motivations for the Jack Rabbit project (see Section 6.5.36).

9.1.10 Hydrogen sulphide

Hydrogen sulphide (H₂S) is a COMAH named dangerous substance that is present in many sectors, including the geothermal industry, waste processing industry, bio-technology industry, chemical and oil and gas sectors and the process industries. The OECD report (Danielsson et al., 2009) noted that the most fatalities occur due to biologically generated hydrogen sulphide releases.

Danielsson et al. (2009) found that many of the accidents occurred during non-standard operating such as during start-ups, pauses in production for maintenance, and during loading and unloading. Many of the incidents occurred in confined or semi-confined spaces and were exacerbated by employees attempting to aid afflicted colleagues and succumbing themselves.

Danielsson et al. (2009) suggest that there is a lack of knowledge of where a hydrogen sulphide release could occur within an industry and the impact of a hydrogen sulphide release or the consequences of exposure. For example, a couple of the incidents in this

²¹³ <https://www.edfenergy.com/about> Accessed on 17th August 2020

²¹⁴ <https://bradwellb.co.uk/> Accessed on 17th August 2020

²¹⁵ A description of uranium hexafluoride properties and processing can be found here <https://web.evs.anl.gov/uranium/guide/uf6/index.cfm> Accessed on 15th September 2020

review demonstrated that hydrogen sulphide can result from mixtures of two incompatible substances, which is particularly a risk in drains and when incompatible substances are stored in proximity to each other. They suggest that there is a lack of awareness in some industries that there is no warning provided by the odour of hydrogen sulphide, as the ability to smell it disappears if a hazardous concentration is reached. However, other industries are much more aware of the risks, i.e. there is a lack of dissemination across different industries. Therefore, guidelines, recommendations, education and training and methods of disseminating information should be developed or improved.

Danielsson et al. (2009) also comment that recording of hydrogen sulphide incidents is not rigorous and improvements could be made in order to understand their causes and prevent repetition.

9.2 Potential knowledge/data gaps and future work

9.2.1 Previous knowledge gap analyses

A number of published studies have identified knowledge gaps in dense gas dispersion, as summarised below.

Britter (1998)

The review by Britter (1998) is now over two decades old, but several of the 'Major Outstanding Issues' that Britter identified are still relevant. The following technical issues were identified:

- A definitive view on aerosol formation and subsequent rainout
- Lack of information on real catastrophic releases as distinct from idealised experiments
- The effect of actual types of industrial release, for example, seal failures, flange leaks
- The effect of impingement on nearby structures
- Dispersion modelling within a chemical complex or nearby urban environment, in particular the appropriateness of current models
- Dispersion under stable, low wind or variable wind conditions
- Dispersion in complex terrain
- Modelling of the dispersion of materials undergoing complex transformations and multi-component/multi-phase releases
- Modelling of finite-duration releases (both steady and time-varying)
- Releases indoors, or within highly congested spaces such as a module of an offshore production rig
- The efficiency and design of various passive or active mitigation devices

Hanna and Chang (2008)

In preparation for the Jack Rabbit experiments, Hanna and Chang (2008) highlighted a number of gaps in toxic industrial chemical model systems, as follows:

- Incomplete knowledge of scenarios: lack of information preserved from incidents, in particular, limited information about the source (such as hole sizes, shapes and locations); lack of information on local topography, buildings and obstacles and the underlying surface type; lack of local or on-site meteorology.
- Uncertainties in source term models: in particular, the complexity of two-phase sources, which still have uncertainties remaining such as droplet sizes and subsequent rainout.
- Modelling dispersion of large, very dense gas clouds released in light winds, which will not be strongly affected by the ambient air flow and may persist near the source.
- Lack of ability to model very low or nil winds
- Modelling of dense gas dispersion over complex terrain

- Modelling of chemical reactions and removal processes, which have been shown to significantly affect dispersion distances
- Outdoor to indoor dispersion
- Human exposure, including knowledge of the population distribution and its movement outdoors, indoors, daytime, nighttime.

SAIC (2010)

The SAIC (2010) report summarised a gap analysis undertaken for the US Chemical Security Analysis Center (CSAC) on understanding of source emissions, dispersion and deposition for large scale releases of Toxic Inhalation Hazard (TIH) chemicals. It is a valuable reference because it goes beyond listing the knowledge gaps to provide ranked recommendations to assist in prioritising future experimental and modelling work and analyses for understanding the behaviour and consequences of large scale TIH releases. The context is mainly transportation of chemicals.

The chemicals identified to pose the greatest risks by transportation due to volume, toxicity and volatility were chlorine, ammonia, hydrogen chloride, sulphur dioxide, hydrogen fluoride, ethylene oxide and hydrogen cyanide. Bromine, phosgene and sulphuric acid were also identified as high risk, but were not included in the analysis.

The report provides detailed analyses of discussions, rankings of recommendations, expected outcomes and benefits to stakeholders. The knowledge gaps identified were collated into the following topics:

- Understanding source terms
- Aerosols and rainout
- Large scale tests
- Terrain
- Atmospheric chemistry
- Deposition
- Integration of dispersion and biological models
- Predictive vs protective hazard exposure standards
- Understanding variability

Each topic has several knowledge gaps associated with it and recommendations for addressing them. The analysis then collated the recommendations to provide eleven prioritised areas of study, as follows:

1. Large scale tests of TIH chemicals
2. Determination of a range of mass fluxes
3. Rainout from flashing flow
4. Roughness, slope and obstacles
5. Chemical reactions
6. Specification of local conditions
7. Understanding variability
8. Improved consequence modelling
9. Deposition in urban areas
10. Expert groups and literature surveys
11. Remaining recommendations not included in the above

Further details and descriptions of the individual knowledge gaps, collated topics and recommendations can be found in the SAIC report.

Watson (2018)

Watson (2018) produced a transcript of a workshop discussion by several interested parties on urban dispersion in the US. It included various comments on knowledge gaps for

emergency response and in particular for urban dispersion modelling. It does not specifically consider dense gas dispersion, but many of the points are relevant.

Potential knowledge gaps for emergency response are summarised as follows:

- There is not enough simple guidance available for emergency response. There is a benefit to having 'rules of thumb' and 'no regrets' information
- More dialogue is required between the people who are creating models and those who are using them. Model output should be considered from the perspective of the incident commander, not from the perspective of the developer or the modeller. How will the models be used and interpreted in the field?
- At present it is difficult to know which models are the 'best' models. This leads to contentious discussions between developers and users. It would be useful if there was a way to overlay output from all models so that they can be compared and so that strengths and uncertainties can be understood. There is also a disconnect between organisations, with each group running their own models during an event. Understandably, organisations want to run the models they are familiar with but this situation results in multiple predictions, which do not always agree.
- There are significant difficulties in getting information from the response community during an event.
- It is suggested that a product that incident command can use to make decisions about shelter-in-place or evacuation and to decide how long to shelter-in-place would be of use. Models could also be targeted at providing information on transport pathways where exposure could occur during evacuation.

Watson (2018) noted that there are significant challenges in using a model in real time to support incident command during a chemical release because of such short durations and reaction times. There was a query about whether models are better used in preparation and planning, with information stored at incident command centres for reference and to assist decision making.

Potential knowledge gaps were primarily related to urban dispersion modelling, as follows:

- What is the appropriate level of complexity for urban dispersion models? What processes can be safely neglected? What are the right spatial and temporal resolutions? How much of the city do we need to model? How much knowledge do we need about the flow at various levels in the atmosphere?
- There is a lack of knowledge about transmission of contaminants between indoor and outdoor environments. For example, what are the consequences of venting a CBRN agent from a subway? How do particles get into and out of buildings? What is the appropriate zoning within a building? How are particles indoors and outdoors deposited? What is the effect of coagulation and humidity? When is a well-mixed assumption justified? Very few quick-running models (perhaps only QUIC and MSS) can provide pressure fields on the outside of buildings as input for indoor models such as CONTAM. Watson (2018) pointed out that it is possible that relevant datasets may exist in other disciplines such as architecture or structural engineering.
- There are significant uncertainties in meteorological information for urban environments. Meteorological information from a weather station, such as an airport, is unlikely to be representative of the conditions within the urban centre. There is an ongoing theme in the document in favour of accumulating meteorological datasets within cities. For example, the New York Police Department (NYPD) has been installing meteorological stations in lower Manhattan to improve datasets for input to models. However, there are knowledge gaps in how the neighbourhood-scale meteorology affects gas transport, and the connection between the local and the regional scales. There is limited understanding of how flow regimes on one scale are coupled to the next, and the implications for gas dispersion.

- Is it necessary to resolve small scale features, such as cars and trees, in a model? Is high resolution meteorological data required?
- Very little is known about transitional boundary layers, e.g. sea to land and open to urban environments.
- Meteorological measurements over water is a gap in current knowledge.
- Understanding of urban turbulence during the night time and under stably stratified conditions is limited.
- The impact of vegetation in urban areas is not well understood in terms of flow processes and deposition.
- Information about deposition on surfaces of buildings is required.
- There are very few experiments that have included human exposure measurements.

Watson (2018) noted that experimental datasets need to be very high quality in order to have confidence in the data. Pre-testing trials should be undertaken to ensure issues like measurement device saturation do not occur. Duplicate samples at locations assist in assuring quality of results.

Hort et al. (2019)

In 2019, the Atmospheric Dispersion Modelling Liaison Committee conducted a survey of knowledge gaps to help prioritise research projects for future funding (Hort et al., 2019). The key findings were split into six categories: modelling improvements, validation, logistics, sensitivity and uncertainty, guidance and communications. Members of the ADMLC, representing 14 UK Government departments, identified the following four topics as being highest priority:

1. Deposition modelling
 - Review of dry/wet deposition modelling of gases and particulates
2. Modelling of sources in an emergency
 - When there is limited information available
3. Fire source terms and plume rise
 - Including landfill, chemical and nuclear fires
4. Understanding the impact of meteorological uncertainties

Items 1, 2 and 4 in this list are relevant for dense gas dispersion.

Jack Rabbit III

Recently, several knowledge gaps exercises have been undertaken in North America and Europe in preparation for the forthcoming Jack Rabbit III trials (which are due to take place in 2023 and 2024). Summaries were presented at the 2020 George Mason University Conference on Atmospheric Transport and Dispersion (Fox et al., 2020; Hanna, 2020b; Gant et al., 2020). Work is currently ongoing at the Chemical Security and Analysis Center to compile these exercises into recommendations.

Gant et al. (2020) collated results from a survey of knowledge gaps and research priorities in atmospheric dispersion and acute toxic hazards proposed by academia, industry, consultancy and Government across Europe. Five main were identified topics:

- Source terms
- Dispersion
- Physicochemical effects
- Mitigations
- Outcomes

Contributors were asked to vote on the collection of sub-topics and rank their choices in order to seek the highest-priority research topics. The top five topics were as follows:

- 1) Two-phase jets
 - Including rainout, uncertainty in post-expansion source terms, uncertainty in behaviour inside the vessel
- 2) Obstacles
 - Including lack of field scale data with realistic obstacles, uncertainties in when buildings need to be resolved, impact on cloud persistence, vapour barriers and wake effects
- 3) Transition from dense-gas to passive dispersion
 - Including when a dense gas model is required, impact of near-field behaviour far downwind, impact of transition on turbulence and toxic dose and implications for infiltration
- 4) Dispersion in low/zero wind speeds
 - Including lack of large field scale dense gas releases in low/zero winds, impact of low/zero winds when terrain/obstacles are present and the implications of low/zero wind on emergency response (e.g. are ERG, 2020, distances valid in low/zero wind)
- 5) Terrain effects
 - Including lack of large field scale dense gas releases with terrain, uncertainties in scales at which terrain becomes important for dispersion and the combined effect of the wind, release direction and terrain on dense gas dispersion

Hanna (2020b) revisited the studies of SAIC (2010) and Hanna and Chang (2008) to provide an up to date summary of knowledge gaps that have been filled along with any additional gaps identified since. The main gaps identified are as follows:

- Lack of information available from incidents resulting in incomplete knowledge of the scenario, particularly for modelling
- Uncertainties in source emission models. In particular, in flashing jets, post-expansion physics, rainout and impaction. Pool evaporation should be revisited
- Inadequate transport and dispersion model algorithms for jets encountering obstacles, cloud formation and persistence in light winds, local terrain effects, meteorological information, transition to passive dispersion and removal mechanisms
- Biases and uncertainties in health risk models, which are based on little data and significant extrapolation.

These are very similar to the gaps identified in the studies above, even dating back to those of Britter (1998), and it can be concluded that while progress has been made, the gaps are large and further work is required. Hanna (2020b) highlights that perhaps the biggest existing knowledge gap is the question of why there have been relatively few casualties after large TIC releases despite both modelled and experimental concentrations (and therefore toxic endpoints) predicting that there should have been significantly more.

Fox et al. (2020) discussed the choice of ammonia for the Jack Rabbit III trials and the knowledge gaps associated with this choice. The study identifies anhydrous ammonia as the top chemical of choice in a potential threat assessment and the most serious hazardous material threat to communities (in the US). They highlight the growing ammonia market, particularly in green energy. By canvassing opinion through surveys and interviews, Fox et al. (2020) identified that, for the US in particular, transportation and emergency response to ammonia were the greatest safety concerns. Training was identified as the most useful tool to improve ability to deal with anhydrous ammonia or other HAZMAT emergencies.

Fox et al. (2020) also summarised modelling gaps that could potentially be addressed in the forthcoming Jack Rabbit III trials. These were as follows:

- Uncertainties in source term models
- Inadequate transport and dispersion models
- Chemical removal from the atmosphere due to gravitational settling, dry deposition and chemical reactions
- Infiltration of TICs into buildings/structures

The very recent paper by Hanna et al. (2021) collates many of these previous analyses into one document summarising current gaps in modelling of toxic industrial chemical releases.

9.2.2 Experiments

The experimental summary Section 6.6.2 discussed potential gaps in experimental data. The following topics were identified:

- Experimental trials in ideal conditions and in a range of atmospheric conditions, including transition from dense to passive dispersion behaviour
- Experimental trials involving changing meteorological conditions
- Wind tunnel and full scale dense gas dispersion over topography
- Full scale dense gas dispersion in the industrial/urban environment
- Vertically upwards orientated releases from height
- Infiltration and ingress
- Indoor to outdoor dense gas dispersion
- Sources
- Congestion
- Dry deposition

9.2.3 Reviews

Specific substances

This document presents a high-level review of dense gas dispersion for industrial regulation and emergency response. There are various other reviews on similar high-level topics (e.g. Hanna et al., 1996; Britter, 1995). Since these reviews are so broad in scope, it is difficult to discuss details of particular issues. It could be beneficial to focus reviews on particular substances to enable such detailed analysis. The choice of substance could be guided by some form of hazard index, to determine which are the highest-priority substances.

Substance-specific factors include types of transport and storage, source types, and reactivity. Reviews of particular substances could focus on current guidance and knowledge gaps for that substance, and identify worst-case scenarios and mitigation measures. To an extent, this approach was taken for chlorine with Jack Rabbit I and II. Efforts are underway now with ammonia in preparation for Jack Rabbit III.

Transition from dense gas to passive dispersion

It would be a useful exercise to revisit experiments and collate information on transition from dense gas to passive dispersion. This might involve calculation of Richardson numbers and other criteria, and identification of when or where transition occurs. This could also be attempted for incidents, where enough information is available.

This information would assist in compiling a broad picture of the duration and extent of the cloud within which density effects are important. This would be useful to inform whether passive models used for emergency response, such as the NAME model used by the Met Office for CHEMETs²¹⁶, are sufficiently accurate for the majority of incidents, or whether specific dense-gas dispersion capabilities are needed.

²¹⁶ <https://www.metoffice.gov.uk/services/government/environmental-hazard-resilience/chemical-meteorology-chemet>, Accessed 18 January 2021

Incident analyses and scenario generation

Several collections or databases of incidents were identified in Section 4.7.2. They typically only present high-level information such as financial loss, deaths, numbers evacuated etc., and rarely present quantitative information such as details of the source conditions (hole size, release pressure, inventory), meteorology, terrain maps, and locations of casualties. Such information is needed to feed into exercises like the chlorine railcar study by Hanna et al. (2008) and the COST ES1006 AGREE scenarios (COST, 2015c). It could also help to plan realistic national-level training exercises and feed into knowledge gaps exercises for future experiments. Collecting and storing information could be made a priority during emergency recovery and feed into the emergency planning cycle (see Figure 3 in Section 2.3.2).

Mitigation measures

There appears to be a gap with respect to the performance of mitigation measures used in incidents involving dense gas dispersion, e.g. releases of chlorine, ammonia and HF. A review would be useful to assess the lessons learned and feed into good practices and guidelines. This work could be conducted in parallel to substance-specific reviews (see above). Ideally, any reviews of mitigation measures should be undertaken in consultation with emergency response services.

10 CONCLUSIONS

This work has been undertaken with the goal of providing a high-level review of dense gas dispersion in the context of industrial regulation, emergency preparedness and emergency response.

The report began with a summary of the frameworks for industrial regulation, emergency preparedness and emergency response in the UK, and described how models are used in that context. In the main body of the report, features of dense gas dispersion were explored through a review of current knowledge on the physics of dense gas dispersion, incidents, models, experiments and mitigation measures.

The review of physics focused on factors that affect the cloud evolution and on the ingress of dense gases into structures. Causes of the density difference, which result in dense gas dispersion, were summarised. Factors affecting dispersion behaviour were identified as being the source geometry, atmospheric conditions, heat transfer, phase change, deposition, surface conditions, fixed structures and topography. Factors that affect ingress included the type and location of openings, ventilation systems, atmospheric conditions, thermal effects, proximity of structures to the source and the type of structure.

A brief summary of 69 dense gas dispersion incidents is presented, covering a range of hazardous substances and sources. These incidents demonstrate various factors affecting dense gas dispersion behaviour. Where possible, the incidents were used to illustrate the effectiveness of emergency preparedness and response measures.

The review of dense gas dispersion models considered the different types of models available and some of the more common modelling assumptions. Important topics, such as model evaluation, were discussed and existing good practice guidelines were summarised. The features of 64 dispersion models were described, including models for predicting ingress.

A collection of 63 dense gas dispersion experiments were summarised briefly, covering both field trials and wind tunnel studies. For each experiment, details were provided for the substance, location, release conditions and type of measurements, along with references for further information. Where possible, an indication was given of the quality of the dataset and whether it has been used in model evaluation exercises.

Mitigation measures were summarised based on their impact on either the source, on the dense gas dispersion behaviour or on mitigating personal exposure. Where possible, reference was made to the use of mitigation measures in incidents and experiments reviewed earlier in the report.

These six chapters (regulatory/response frameworks, physics, incidents, models, experiments and mitigation) were then drawn together into six scenarios illustrating dense gas dispersion in industrial regulation and emergency preparedness and response in the UK. Finally, future trends and emerging technologies were discussed, along with potential knowledge gaps.

Key questions that have arisen during this review are discussed below.

Why are dense gases important?

Dense gases tend to spread along the ground, even if they are released from height. They can lead to high concentrations in the human-occupied atmospheric environment remaining for long periods of time, i.e. increasing potential human exposure to toxic gases and/or increasing the chances of flammable gases reaching ignition sources.

Many serious incidents (e.g. Bhopal, Seveso, Buncefield) have involved dense gas dispersion. A significant number of hazardous chemicals in widespread use have the potential to produce dense gas clouds, e.g. chlorine, ammonia, LPG, LNG, carbon dioxide, hydrogen fluoride and gasoline vapour.

What causes the density difference?

Many hazardous gases are denser than air due to their molecular weight (e.g. LPG, chlorine, carbon dioxide). Other gases are stored in a liquid state at either high pressure or at cold temperatures (or a mixture of the two), which results in the gas being dense when it is released (e.g. LNG). Some substances behave as dense gas due to the presence of aerosols (e.g. ammonia). Chemical reactions resulting from two incompatible chemicals mixing can also produce dense gases (e.g. acids and hypochlorites reacting to generate chlorine).

When is the density difference important?

Density effects are important when they dominate over atmospheric conditions. The best means of identifying this is via the Richardson number or a related quantity (e.g. buoyancy flux). Some rules of thumb exist to classify when dense gas effects are significant (e.g. when more than 1 tonne of a hazardous substance has been released), although the origins of these rules are uncertain.

What enhances dilution or reduces concentration?

As the dense gas cloud moves through the atmosphere, it entrains air, which dilutes the cloud. The interaction between the flow of dense gas and surface roughness, topographical features, obstructions, fences etc. also causes air to mix into the dense gas cloud and enhances dilution. Unstable atmospheric boundary layers and heat sources can help to disperse and dilute the dense cloud, due to convection currents.

Dry and wet deposition, chemical reactions and photolysis can reduce concentrations in dispersing clouds of some substances. Deposition can occur on vertical and horizontal surfaces, such as the ground and buildings, and on vegetation. Deposition can also occur indoors on surfaces and other materials such as clothing.

Active mitigation measures such as fans and water sprays can reduce concentrations, both by mixing in air and reacting with certain substances, such as ammonia and hydrogen fluoride.

What are likely worst-case conditions?

For long duration or continuous releases of dense gas, low or zero wind speeds and stable atmospheric conditions are the worst-case conditions, in terms of producing high concentrations far from the source. These conditions often occur at night and are more prolonged in winter.

For short duration or puff releases, higher wind speeds are the worst case and give higher concentrations downwind than calm conditions. This is because in light winds, puff releases of dense gas spread out in all directions, under the action of gravity, without moving far downwind. Higher wind speeds advect the concentrated cloud downwind faster than it can spread out and dilute itself under gravity, producing higher concentrations downwind.

Dry conditions are the worst case for water-reactive substances such as ammonia and hydrogen fluoride. In humid conditions, the reaction between these chemicals and humidity is exothermic, which increases the cloud buoyancy and can cause the cloud depth to increase, or the cloud to lift off the ground, enhancing dilution.

What is the effect of topography, e.g. hills, valleys?

Terrain can have both direct and indirect effects on dense gas dispersion behaviour. In terms of direct effects, terrain features such as slopes and valleys act to direct dense gas down slopes. If a dense gas is released at the base of a hill, it may still flow uphill to a degree (depending on the wind direction, release direction and buoyancy forces), but buoyancy forces will act to spread the cloud around the base of the hill. If there is a wind blowing up a sloping valley, a dense gas may be able to flow down the sloping valley, against the wind, due to the force of gravity. If there are depressions or hollows, dense gases can pool in them and persist for long periods of time, particularly in low wind conditions. When wind flows over the surface of these depressions it causes detrainment from the upper surface of the pool of dense gas.

In terms of indirect effects, terrain can influence the local atmospheric conditions, which then influence the dense gas dispersion behaviour. For example, valleys can provide shelter from high winds, and hilltops can cause wind speeds to locally accelerate over their summit, which can influence dilution rates. Katabatic and anabatic flows (downhill and uphill) are produced by solar heating in hilly terrain, which may force the cloud in different directions. Similarly, land and sea breezes near coastlines may also affect dense gas dispersion behaviour.

What is the effect of the urban environment?

In low wind speeds, large obstructions (greater in height than the cloud) can deflect the cloud so that it spreads in directions that are not necessarily directly downwind (due to blocking effects and channelling along street canyons). The urban environment can also produce complex patterns in wind speeds at ground level, where the dense gas disperses, with localised areas of high and low wind speeds, and recirculations in the wakes of buildings. Dense gases could persist in these wake regions for long periods of time.

If the dense gas cloud originates from outside the urban environment and spreads towards it, when it encounters the urban environment, the dilution of the dense gas cloud is likely to increase due to increased atmospheric turbulence. However, the effects of gravity on the dense gas cloud means that in urban environments it is also likely to drain into sewers, subways, basements, cellars and underground car parks, where it may persist for a long time. The gas will also infiltrate into buildings.

What happens when dense gases enter buildings?

Infiltration of dense gas into buildings (and its later exfiltration) will tend to result in reduced peak concentrations inside the buildings, as compared to the outdoor concentrations, but also increase cloud persistence times inside the buildings. Persistence could be particularly increased in lower levels of buildings, such as basements and cellars. Analysis of some of the very limited data available has shown that models that assume full-mixing within a room give good agreement with measured indoor concentrations. Published shelter-in-place advice for dense gas releases advises occupants to close all doors and windows, turn off any HVAC and seek poorly ventilated spaces (ideally without windows) upstairs in buildings.

What is the potential impact of using a passive dispersion model for a dense gas release?

Passive dispersion models do not account for the gravity-driven spreading of dense gas clouds, which will be most pronounced near the source, where gas concentrations are highest (once any initial momentum from pressurised releases has been lost). This initial spreading will increase the effective source area. Gravity effects may cause dense gas releases to spread upwind from the source and cross-wind at a faster rate than predicted by passive models. Cloud spread in the vertical direction will be limited for the dense gas cloud, resulting in higher concentrations at ground level. Sloping ground will tend to have a more

significant effect on the dense gas cloud. This could change the direction of the cloud spread, as compared to the direction of the equivalent passive cloud. Persistence times for clouds in depressions and hollows could be much longer for dense clouds compared to passive clouds.

How can you mitigate against exposure from a dense gas cloud?

It is important that the mitigation measure is appropriate for the substance released and, to a certain extent, also the atmospheric conditions.

Reducing the release rate at its source soon after the release has started is the most effective means of reducing risks of exposure downwind. This will most likely depend on the particular circumstances of the release, but might involve emergency shut-offs and methods to prevent evaporation, such as plastic sheeting, foam and fine water fog.

Most measures to mitigate dispersion of dense gas clouds aim to increase dilution rates or provide containment. Methods include containment bunds, water spray barriers, steam curtains and forced air mixing. Water spray barriers are especially effective for water-reactive substances, such as ammonia. Creating a barrier to contain the cloud can be effective, but this will increase concentrations behind the barrier.

Other means of mitigating exposure includes PPE for emergency responders and site personnel. Detectors and monitors can provide important useful information, such as the substance, concentrations and location, and they can help decision makers to set exclusion zones or cordons. Sirens and loud speakers can assist in conveying this information.

A key factor in mitigating exposure is timing, i.e. deciding when to impose shelter in place, either in residences or in designated shelters, and when to evacuate.

What are the requirements for dispersion models in industrial regulation?

For Land-Use Planning (LUP) in the UK, the regulator requires models that can include a wide range of physics and source terms in order to model a range of hazardous substances, storage and release conditions. The model does not need to run in real-time but it needs to be able to run fast enough so that running hundreds or thousands of simulations (for different atmospheric conditions and different types of release) can be accomplished in a reasonable time-frame. The model does not need to account for specific details of the terrain, since LUP assessments endure for the period of consented operations, which could be for 20-30 years on a given site, during which time there may be some changes to nearby buildings and hedgerows. Models need to account for different classes of atmospheric conditions, i.e. typically several stable and neutral conditions in different wind speeds.

Models used to inform site operators of the risks of operations are typically re-run on a more frequent basis than for LUP (for COMAH sites, a maximum of every five years). The focus is more on understanding current, specific operations. Integral models such as PHAST are commonly used, but CFD may occasionally be used to account for the effects of specific obstacles or slopes in some cases.

What are the requirements of models for emergency response?

There are different types of dispersion models used for emergency response. They include models that are run in advance of an incident to inform site operator's emergency plan, or to feed into look-up tables (such as the Emergency Response Guidebook, ERG, 2020) that are used by decision makers in emergency response situations.

They also include models that are run during an incident itself to provide forecasts for the next few minutes, hours and days. Examples include the Met Office CHEMET service and Dstl / US DTRA Reachback. To be effective, these types of models need to run faster than real-time and be quick to set up. They need to include detailed meteorological information,

ideally based on current weather predictions, and also provide results that are easy to interpret, preferably with some information on uncertainties, in a suitable format to be used by decision makers.

What is the current state of modelling for industrial regulation and emergency preparedness and response in the UK?

In the UK at present, dense gas dispersion models are used for industrial regulation (LUP and COMAH), emergency preparedness and counter terrorist emergency response, but not necessarily for civil emergency response.

For LUP, HSE uses the dispersion model DRIFT, and for emergency preparedness, industrial site operators typically use results from integral models such as PHAST. In counter-terrorism emergency response, Dstl uses HPAC. All of these models account for dense gas dispersion behaviour, when necessary.

In civil emergency response, site operator's emergency plans provide guidance that is often based on results from dispersion models such as PHAST. The UK National Fire Chiefs Council's National Operational Guidance (NOG) provides look-up tables for initial cordon distances. For downwind protection zones, NOG recommends using either direct measurements/observations or modelling. The modelling advice refers to the Emergency Response Guidebook (ERG), ALOHA, Chemdata, FireMet and CHEMET. PHE also provides public safety advice using the R91 model. A limitation with this approach is that neither the PHE R91 model nor the CHEMET (which uses results from the NAME dispersion model) have the capability to simulate dense gas dispersion and instead they assume chemicals disperse passively (as neutrally-buoyant gases). FireMet provides weather forecasts rather than dispersion model predictions. It appears that ALOHA is rarely used. There does not appear to have been any work done to establish the validity of the American ERG guidance to the UK context.

One of the recommendations from this review is to address these shortcomings by:

- Reviewing current practice for response to chemical incidents (involving all of the agencies typically involved in incidents: FRS, LRF, PHE etc.)
- Assessing the need for dense gas dispersion modelling capabilities
- Assessing the options available for addressing that need (and the feasibility of implementing those options)
- Running a joint exercise involving a significant chemical release (e.g. a large chlorine or ammonia spill) to understand how results from dispersion models would be used in practice and their requirements in terms of operational capabilities
- If necessary, developing proposals to improve current modelling capabilities

What are the main knowledge gaps with dense-gas dispersion models?

Several studies of knowledge gaps are discussed in this report. Key issues include:

- Lack of information available from incidents resulting in incomplete knowledge of the scenario, particularly for modelling
- Uncertainties in source emission models. In particular, flashing jets, post-expansion physics, rainout, impaction and uncertainty in behaviour inside the vessel.
- Uncertainties in transport and dispersion models including chemical removal from the atmosphere due to gravitational settling, dry deposition and chemical reactions
- Uncertainties when buildings and terrain effects are important and need to be resolved in models, including wake effects and the impact on cloud persistence, particularly in light winds
- Impact of low/zero winds on emergency response advice, particularly when terrain and obstacles are present
- Uncertainties in health risk models, i.e. toxicological effects.

What are the main gaps in experimental dense gas dispersion datasets?

This review and the knowledge gaps exercises have identified several gaps in existing experimental datasets:

- Wind tunnel and full scale dense gas dispersion over topography
- Full scale dense gas dispersion in the industrial/urban environment
- Source uncertainties in measurement and in characterising real-life incidents
- Infiltration and ingress of TICs into structures
- Indoor to outdoor dense gas dispersion
- Dry deposition
- Vertically upwards orientated releases from height
- Congestion (e.g. hedgerows, complex pipework)

Experimental trials in ideal conditions and in a range of atmospheric conditions, including transition from dense to passive dispersion behaviour, would also be useful and, in addition, experimental trials involving changing meteorological conditions, including humidity.

Are there any further recommendations arising from this review?

Through the course of this review, the author's discussions with experts at PHE, the Met Office and Dstl have indicated that there appears to be limited communication between experts in the UK involved in industrial regulation, emergency preparedness and emergency response on the subject of dispersion of hazardous chemical releases. In the UK, there are a diverse range of organisations involved, including site operators, the Fire and Rescue Service, Local Resilience Forums, PHE, HSE, the devolved environment agencies of England, Scotland and Wales, the Met Office, Defra, Dstl, BEIS, Cabinet Office and CPNI. Relevant parties currently share information via the Resilience Direct website on a need-to-know basis. However, there does not appear to be a forum that brings together all of the relevant parties to discuss recent experience from chemical incidents, to identify knowledge gaps, and to learn about new scientific and technological developments. An annual forum to bring together these organisations would be useful. In addition to helping to coordinate UK activities and establish closer links between experts across different organisations, such a forum could also look outward to specialists overseas, to learn how other countries coordinate their activities, to assess the strengths and weaknesses of different approaches and share good practice.

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