BESPOKE RESEARCH AND CONSULTANCY FROM HSE

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

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Acknowledgements

I would like to acknowledge Dstl, Met Office and PHE for making the time to assist me in the information gathering exercise

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Disclaimer

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What were the aims of the review?

A high level review of the dispersion of dense gases

The aim: A comprehensive summary of all aspects of dense gas dispersion knowledge relevant to industrial regulation and emergency preparedness and response

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The objective: define typical and plausible dense gas release scenarios supported by information required to interpret them.

Presentation outline

- Scope
- Contents
- Introduction
- The review
- Scenarios
- Future trends and emerging technologies
- Knowledge/data gaps

What was within scope?

The body of information should include

- Summaries of the physics of dense gas dispersion
- Past and potential future incidents involving dense gas releases
- Summaries of modelling approaches
- Experimental tests
- Mitigation measures

Also, 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 identifying future trends and emerging technologies.

Review contents

Introduction

Context

Physics

Incidents

Modelling

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Experiments

Mitigation

Scenarios

Discussion

Conclusions

Fun facts

- Current draft report is 347 pages in total
- Summaries of 69 incidents
- Information about 64 models or modelling packages
- Summaries of 63 experimental trials

INTRODUCTION

What’s in the introduction

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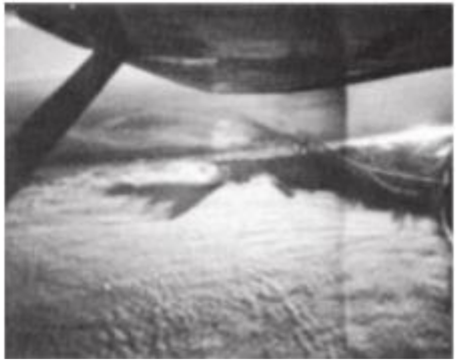
Why are dense gases important?

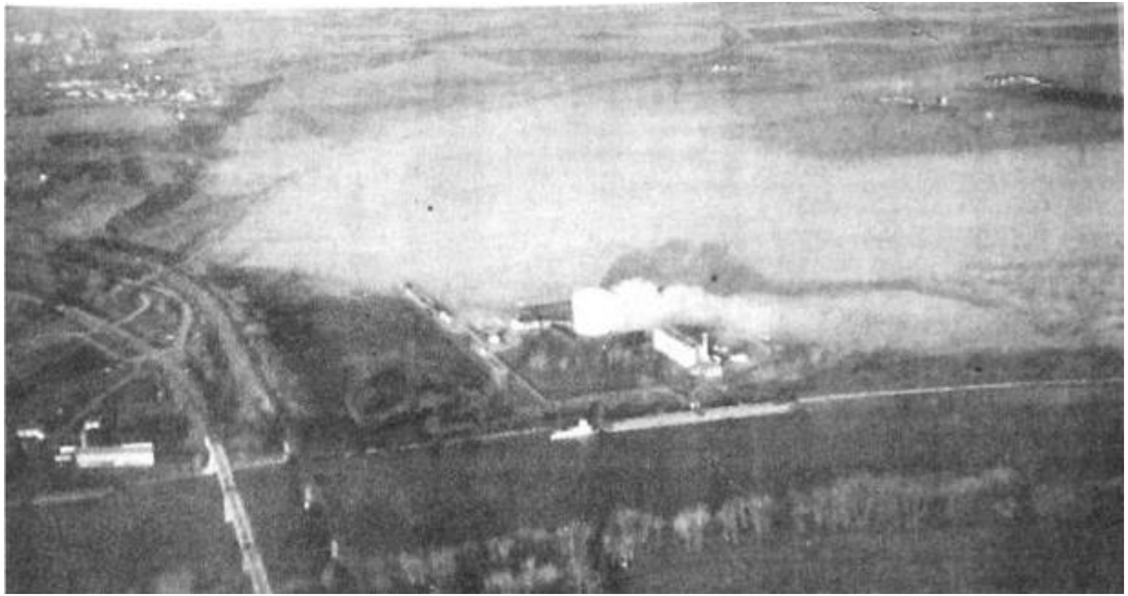
- Dense gases spread along the ground, even if they are released from height
- This can cause high concentrations to remain in the human-occupied atmospheric environment for longer
- ie higher concentrations in our breathing zones, higher chance of reaching sources of ignition at concentrations that will ignite
- Dense gases are not just transported by the atmospheric conditions and therefore they do not just disperse with the wind. They can flow independently of the wind

Examples

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 over-whelmed, unaware of the gas involved or its effects.

Blair Nebraska, 1970





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Houston, Texas 1976

Photograph taken by Texas Air Control Board (© Texas Commission Environmental Quality copyright 1976)

Buncefield, UK, 2005

(Images from Buncefield Major Incident Investigation Board, 2008)

Chelyabinsk, Russia, 2011

https://www.youtube.com/watch?v=sle-LkV3vPs

https://www.youtube.com/watch?v=OszIK-1xxuA

Barcelona, Spain, 2015

(https://www.practicosdepuerto.es/colegio-federacion/publicaciones/articulos-luis-jar/un-paso-complicado?page=3 Image © Naucher Global copyright 2015)

CONTEXT

What context is given?

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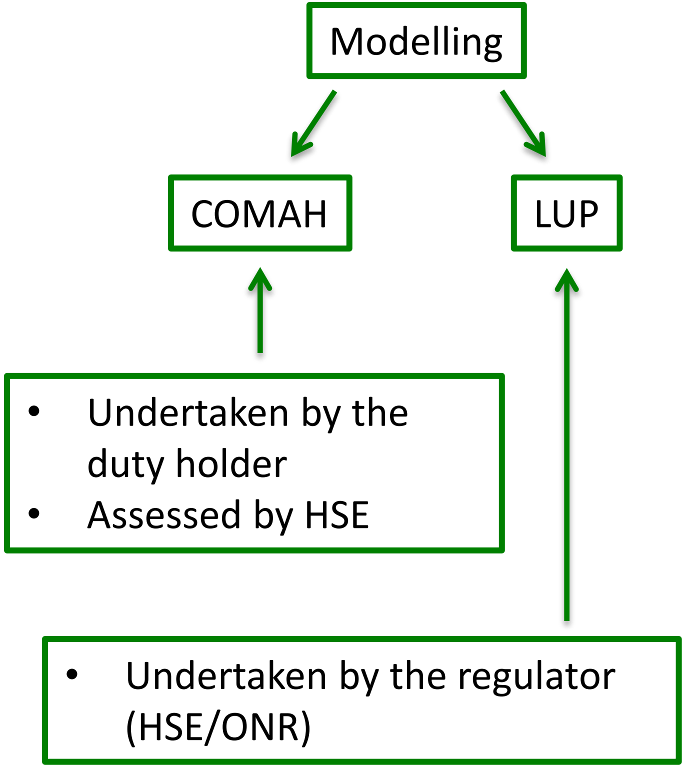
Industrial regulation

- Identify and regulate hazards in industry, by assessing the risks
- Put systems in place to ensure the safety of the nearby population and the environment
- Put in place plans for emergencies associated with the hazards of a specific industry

Static sites | Pipelines | Transport

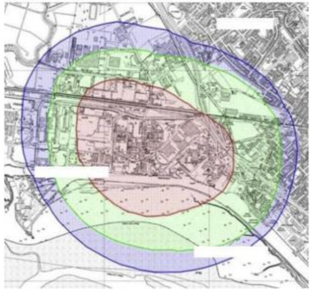


Dense gas modelling in LUP (HSE)

Appropriate assumptions are made in order to provide a cautious estimate

- Foreseeable and credible release scenarios and might include catastrophic releases and releases from a range of hole sizes.
- Four weather categories are simulated (D2.4, D4.3, D6.7 ad F2.4) and wind directions with probabilities assigned from Met Office weather data near to the major hazards site.
- Obstructions, such as buildings, are modelled as surface roughness.

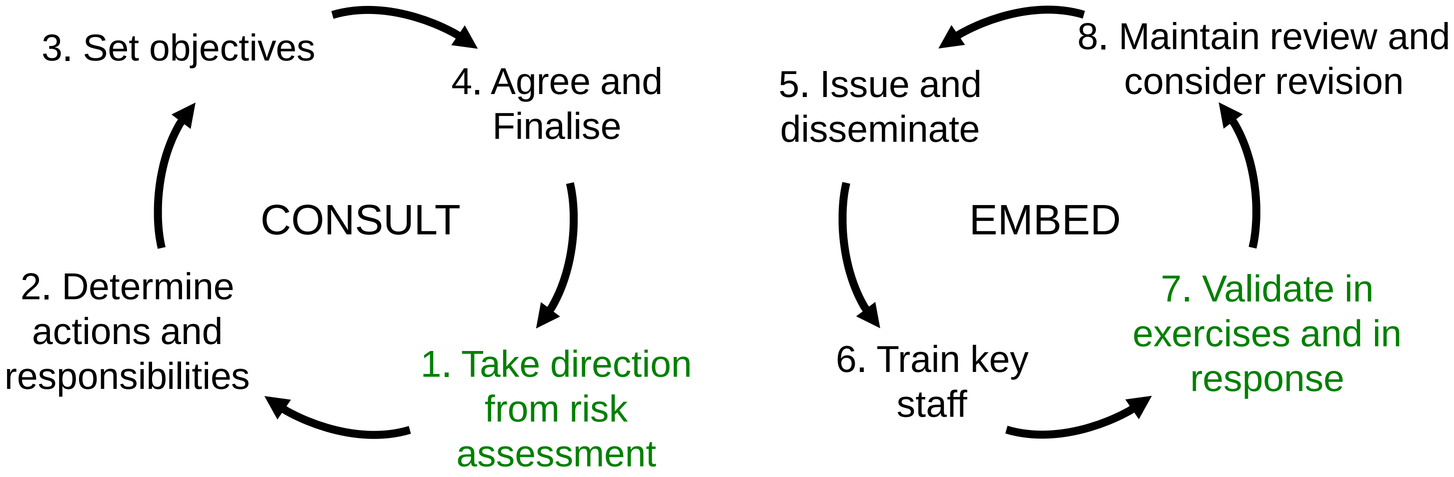
DRIFT



Balance between being too cautious resulting in constraints on the surrounding population and being not cautious enough, potentially resulting in mass casualties

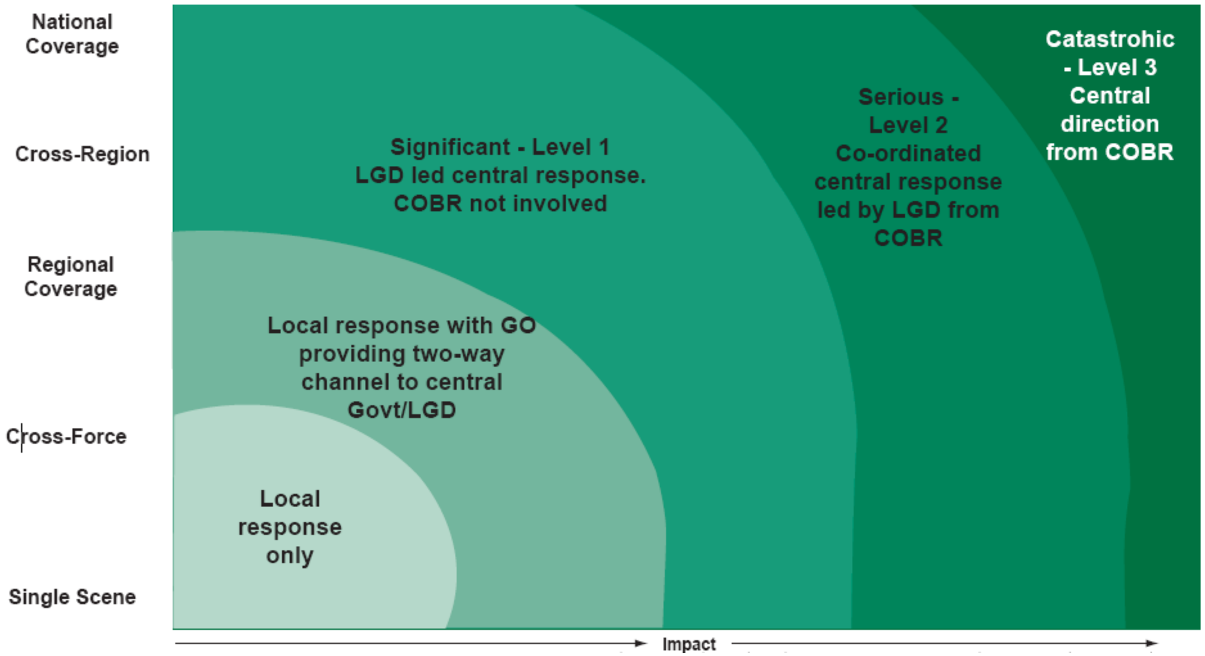
(Image for illustration purposes only)

Emergency preparedness



(Diagram from Cabinet Office, 2011)

Emergency response

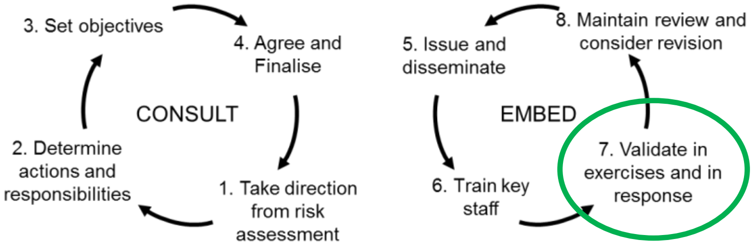


STAC
Science and Technical Advice Cell (local)

SAGE
Scientific Advisory Group for Emergencies (national)

(Image from https://publications.parliament.uk/pa/cm201011/cmselect/cmsctech/498/49806.htm#a9)

Modelling for emergency response



Simulated incident emergency conditions during validation exercises

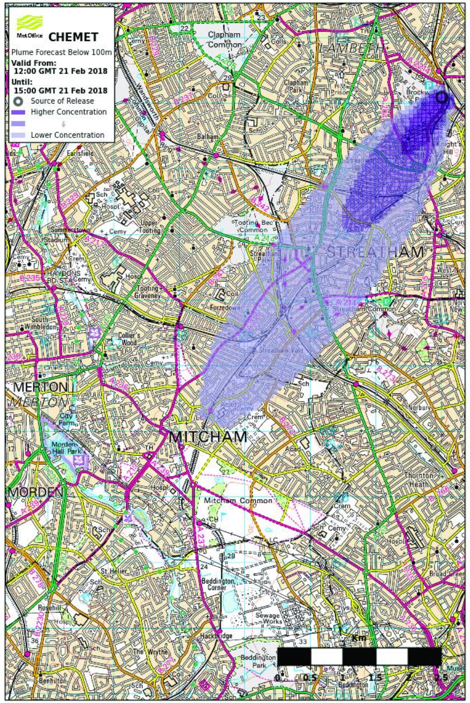
- For a release from an industrial site, initially the emergency procedures of the site will be actioned. For a few sites, this may include modelling to predict dispersion
- Once off-site, or for an off-site release, the Met Office is frequently one of the first points of contact for the police or fire brigade
- If the incident is prolonged and an Science and Technical Advice Cell or Air Quality Cell is set up then Met Office, and other participants in the cell with modelling capability, *may* undertake further modelling to refine initial estimates
- Time is very short and the uncertainty is very high in emergency response modelling

For a chemical release

- Met Office aims to provide a response within 20 minutes in the form of a CHEMET using the model NAME

- The CHEMET might be used e.g.
  - To apply cordons around restricted areas and
  - To position emergency vehicles and support centres

ID = 37_002_ExampleLocation_Event   For further advice, call EMARC on 01392 447947.



Met Office   CHEMET Forecast

Exeter Chemical CHEMET 001_001

Issued by Met Office Environment Monitoring and Response Centre (EMARC)

Tel: 01392 447947   Email: emarc@metoffice.gov.uk   Link to Hazard Manager

Plume forecast below 100m - map will be sent separately

Forecast Issued on Monday, 05 March 2018 at 12:55 local

To: Duty Officer   *of* Example Fire and Rescue Service

Tel: 01234 567890   **Email:** example@FRS.uk

Forecast for: G Smith's Recycling Facility   *due to* Waste Fire

Incident ongoing since: 09:00 05/03/2018

Forecast valid between: 09:00 05/03/2018   *and* 15:00 05/03/2018

Surface wind direction/speed: *Blowing from SSE towards NNW at 10 mph. Changes to blowing from SW towards NE at 15 mph from 1200.*

Weather conditions and effect on plume

Light rain may cause some deposition of smoke particles until 12:00

If incident continues beyond the validity period, the following weather conditions will affect the plume

Little change expected.

Please call 01392 447947 to request further updates if this incident is likely to continue or to discuss further.

Additional Information for Science and Health Agencies

Precipitation (type and intensity): Occasional moderate rain, until 1200.

Total Cloud amount: 8 oktas

Height of lowest significant cloud: 500 feet rising to 1200 feet after 1200.

Air temperature: 6 °C

Relative humidity: 90 %

Depth of mixing layer: 400 metres

Wind at top of mixing layer: Blowing from 160 to 340 degrees at 30 km/h, changing to blowing from 200 degrees to 020 degrees at 35 km/h from 1200.

Air stability: D   *(A=unstable, G=stable)*

Latitude and Longitude of source: 50.727 N, 3.474 W

Sensible heat flux: 5 W/m²

(Image from CHEMET User Guide, Met Office, 2018)

For other types of release

- Radiological and nuclear emergencies
  - PHE provide potential input for public health advice
  - Atmospheric dispersion modelling is undertaken with NAME
  - Joint Agency Modelling (JAM) program has been set up to assist in coordinating multi-agency response to provide assessments to UK Government on the potential impacts and protective actions following a radiological release anywhere in the world
- For a counter terrorism emergency any modelling required is undertaken by Dstl using the modelling suite HPAC

There are no dense gas dispersion models in operational use in the UK for real-time modelling during response to a civilian emergency

PHYSICS

What's covered in the review

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Causes of the density difference

- Molecular weight – released substance has a higher molecular weight than the environment

Substance	Molecular weight ($gmol^{-1}$)
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

More causes of density difference

- Aerosols – Frequently associated with releases from pressurised storage of liquefied gases or liquids of any molecular weight. Flashing causes clouds that are a mixture of aerosols and vapour. Examples include chlorine, ammonia, hydrogen fluoride and LPG

- 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 and hydrogen fluoride.

- Combinations – Density differences can be caused by several of these mechanisms at once

When is the density difference important?

- Density effects are important when they dominate over atmospheric conditions
- The best means of identifying when this is the case is via the Richardson number

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

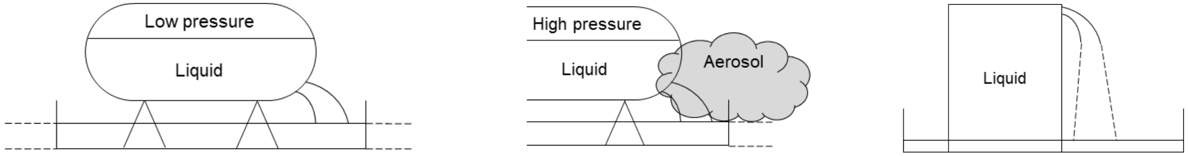
- Strictly speaking, density effects are important until the point when the cloud becomes effectively passive. This can be very near the source or it can be far downwind

Factors affecting dense gas dispersion

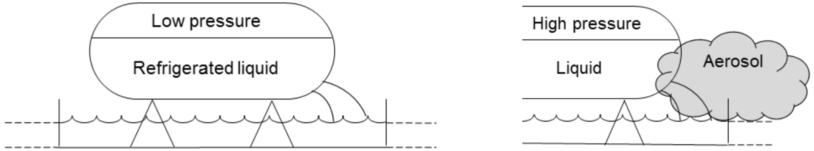
- Source geometry and conditions
- Atmospheric conditions
- Heat transfer and phase changes
- Deposition
- Surface conditions
- Fixed structures
- Topography

Source conditions

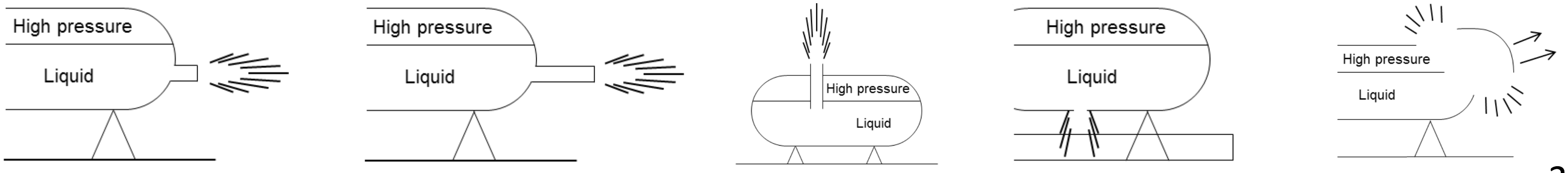
Spills of liquids with boiling point above ambient temperature



Spills of refrigerated liquids

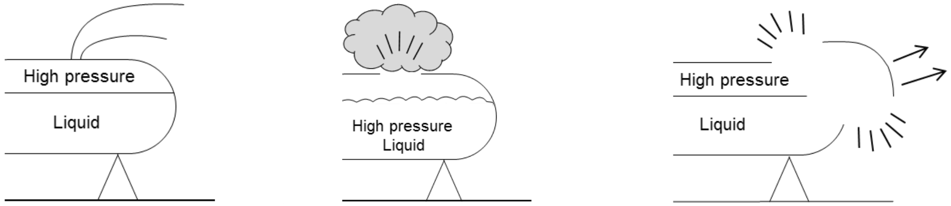


Releases of pressure-liquefied gases



More source conditions

Releases of pressurised vapours



Releases from drums and cylinders

Reactions

Reactions of chemicals with water or other chemicals can result in dense gases. Eg, hydrogen fluoride, uranium hexafluoride, titanium tetrachloride, sulphur trioxide and oleum

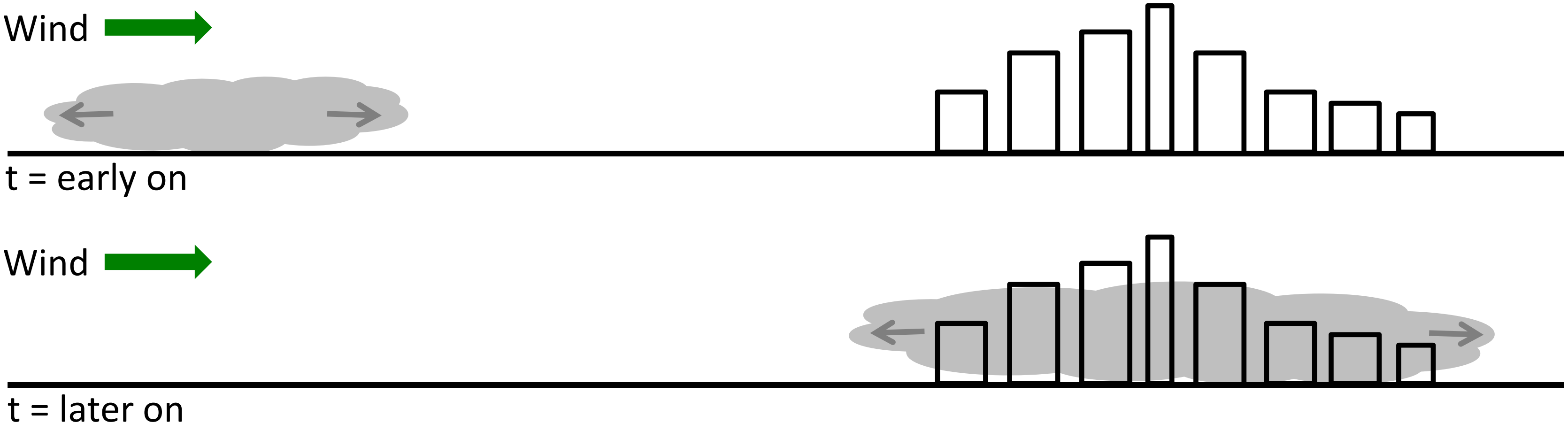
Acids + Hypochlorites = Chlorine gas

Acids + Sulphides = Hydrogen sulphide gas

Instantaneous

In an **instantaneous** release:

- The entire volume of gas is released in a very short, near instantaneous, period of time
- Along wind dispersion can be important

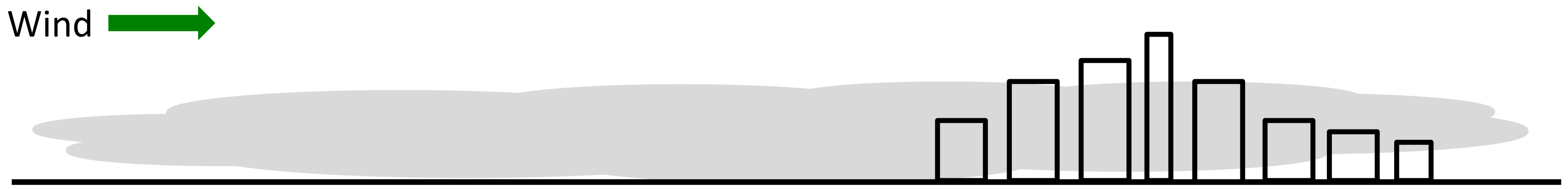


Continuous

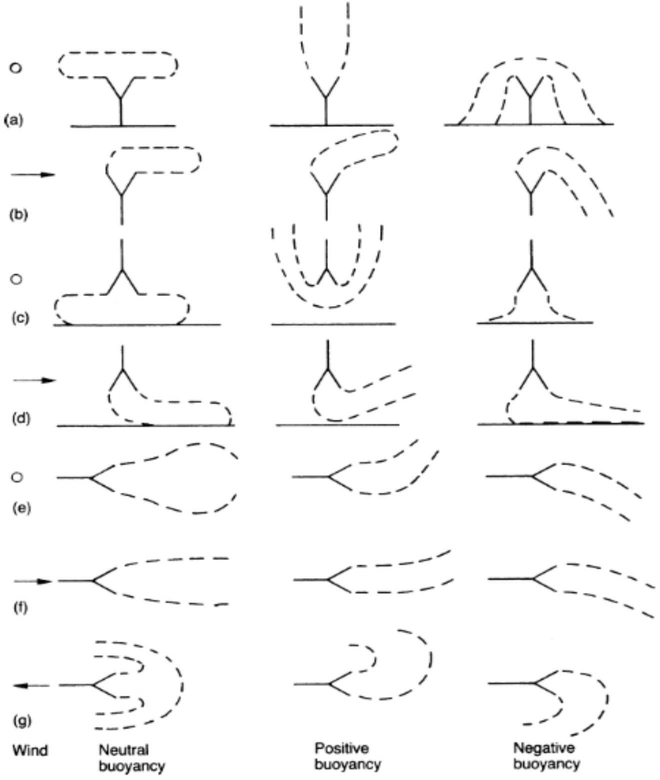
A **steady continuous** release typically has a constant flow rate over a long enough period of time that the gas disperses in a steady state.

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.

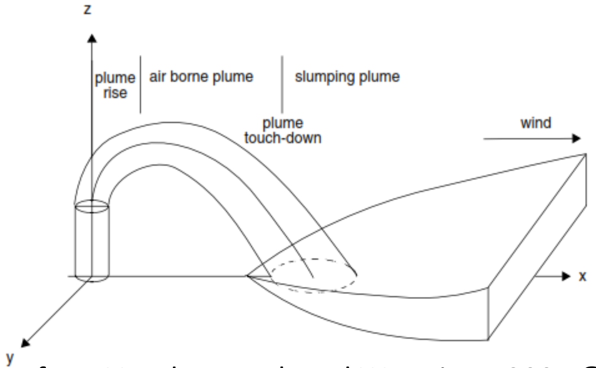
Note: short/finite duration continuous release can sometimes be better described as an instantaneous release for modelling purposes.



Jets and plumes



(Illustration from Mannan, 2012)

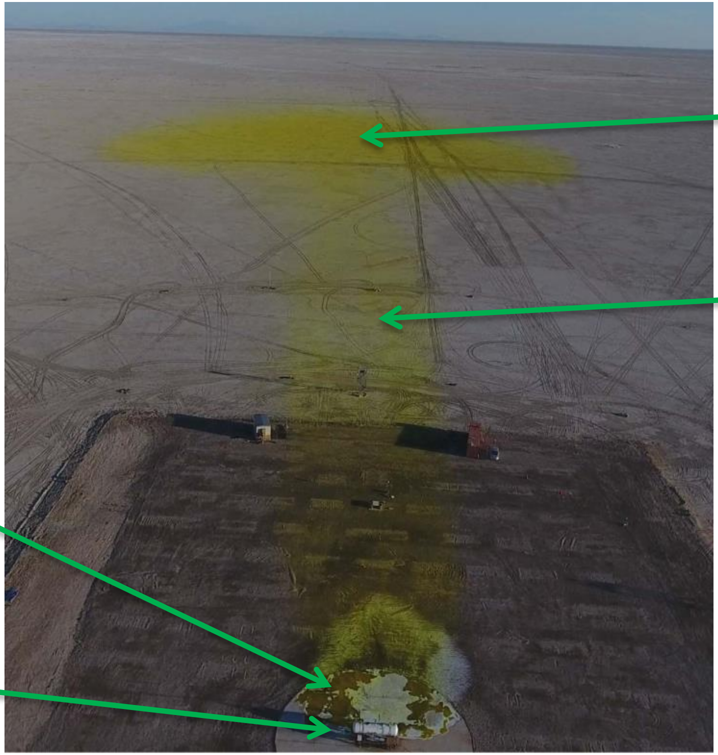


(Illustration from Van den Bosch and Weterings, 2005 © TNO copyright)

(Image from https://www.uvu.edu/es/jack-rabbit/ (© UVU copyright)

Complex sources

Jack Rabbit II Chlorine release



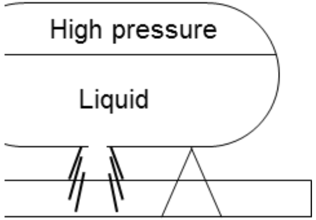
Finite duration dense gas cloud transported downwind

Continuous dense gas plume

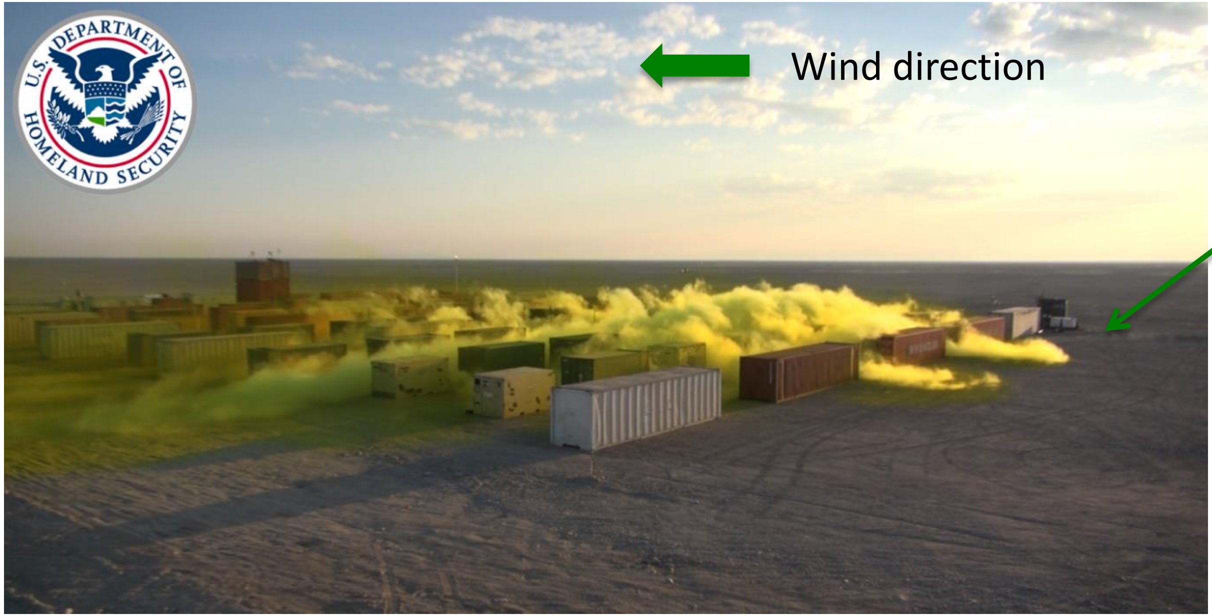
Evaporating liquid pool

Pressure-liquefied chlorine released from a railcar

(Jack Rabbit II Trial 7, Byrnes et al., 2016 © UVU copyright)



Atmospheric conditions



(Image from https://www.uvu.edu/es/jack-rabbit/ © UVU copyright)

Chlorine cloud travels upwind in the Jack Rabbit II trials. Chlorine release point slightly right of centre and wind direction is from right to left

Nil/low wind

- During very stable atmospheric conditions (usually during the night or early morning) the wind can be low 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 remain near the source for a long time
- Gas cloud will spread out under gravity to form a thin ‘pancake’ cloud

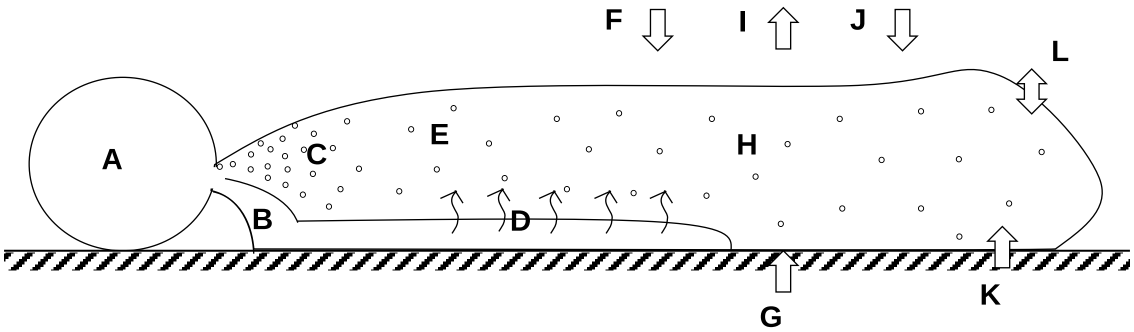
No wind

t = early on

No wind

t = later on

Heat transfer and phase change



A Ruptured vessel
B Liquid spill
C Cold temperature gas/aerosol mixture
D Evaporation and possibly aerosols thrown into the cloud by violent boiling
E Endothermic or exothermic chemical reactions
F Entrainment of warm ambient air, subsequent condensation of water vapour

G Ground heat flux to the surface
H Heat gain/loss due to condensation/ evaporation
I Heat loss due to radiation
J Solar energy input
K Convective heat flux from surface to the air
L Heat exchange by convection

(Based on Hanna et al., 1996)

What is the effect of topography, eg hills, valleys?

Generally the dense gas cloud will follow terrain features:

- Flow down hill
- Be channelled by valleys
- Pool in terrain dips
- Split and travel around high ground or pass over
- Spread out along the base of an upslope

Topography is more likely to impact on

- Large dense gas clouds
- Transport incidents

BUT

It depends on the atmospheric flow field. E.g.

- If there is an upslope wind, against the motion of the dense gas cloud, the cloud widens and dilution increases compared with dispersion over flat terrain
- When the wind is downslope the cloud is typically narrower and the dilution is decreased compared with dispersion over flat terrain

Topography examples

"…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 into the town resulting in a cloud approximately 1000 m long and 340 m wide."

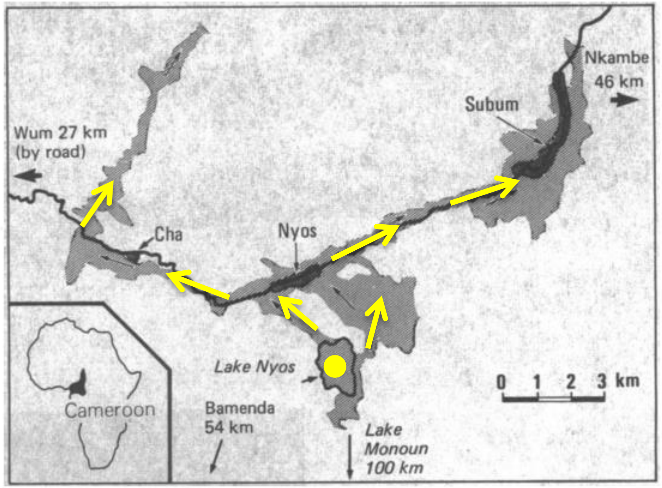


FIG 1—*Direction of flow of gas (arrows; stippled area) from Lake Nyos into adjacent valleys*

Baxter et al. (1989), © BMJ Publishing Group Ltd.

"…instantaneous release of a large amount of carbon dioxide from a volcanic Lake Nyos in Cameroon. The elevated position of the lake and the narrow valley structures leading down 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 due to oxygen depletion."

What is the effect of the urban environment?

- If the dense gas cloud is deeper than the urban environment then it will likely only be affected by the impact of the environment on the ambient flow field.
- Primarily, this means increased dilution compared with an open environment (but to a lesser extent than a passive gas cloud).
- If the dense gas cloud is significantly shallower than the average height of the buildings then it will be affected by the flow field within the buildings.
- Every city is different and the interaction or coupling between the street level flow field and the atmospheric boundary layer will depend on the layout of the city.

More effects of the urban environment

- Features such as street canyons (e.g. long boulevards), parks, open areas and street intersections may influence the flow fields in different ways.
- Vegetation such as trees, hedges, parks and shelter belts can affect the gas dispersion, providing surfaces for deposition and diluting the cloud.
- There is significant potential for ingress into buildings in the urban environment. This has the effect of temporarily removing mass from the cloud which will then exfiltrate later, increasing cloud persistence times.
- The effects of gravity on the dense gas cloud means that it naturally seeks low-lying areas. This means that it is likely to enter sewers, subways, basements, cellars and underground car parks etc.

What happens when dense gases enter buildings?

- Buoyancy effects mean that dense gases may be more likely than passive gases to enter a building during low or nil wind conditions.
- Under low wind conditions it is also more likely that the dense gas cloud will be more highly concentrated on arrival at the building than under windier conditions.
- Dense gases entering buildings from outside may be fully mixed on a room basis.
- Once the release has stopped dense gases are likely to preferentially disperse from upstairs first.
- Persistence is likely to be increased in lower levels such as basements and cellars.

What is the risk/impact of assuming the cloud disperses passively?

- The cloud may spread upwind
- Increased lateral spread
- Inaccurate cloud dispersion in topography
- Inaccurate cloud dispersion in obstacle arrays
- Inaccurate prediction of concentrations and toxic/flammable endpoints
- Subsequent inappropriate use of mitigation measures
- In terms of ingress, this could also lead to underestimation of the concentration of gas indoors, particularly during low wind conditions and in lower parts of structures

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Sources of information / Incident databases

- Looked for incidents involving dense gas dispersion to illustrate
  - Safety and Health contexts
  - Factors affecting dense gas dispersion
  - Ingress
  - Mitigation and emergency response
- Previous reviews and incident databases

eMARS	MHIDAS	MAIB	IChemE	ARIA
INRS EPICEA	ZEMA	PROCESSNET	FACTS	MInA
CSB	NTSB	PHMSA	OSHA	CCPS
NTSIP/HSEES	DGAIS	PUPAD	JST	RISCAD

Content for each incident summary

- Location, date, timings
- Source details
- Quantitative information
- Factors affecting dispersion
- Atmospheric conditions
- Ingress
- Terrain
- Health impacts
- Injuries, fatalities
- Hazard, e.g. fire, VCE, toxic cloud
- Emergency response
- Mitigation
- Reports
- Amount of information available
- Reconstructions
- Photos
- CCTV
- Modelling undertaken

Not exhaustive – there will likely be more information available than what I have included

Example

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 resulted in a deflection from the baseline reading and provided an estimation 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) comment 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 in Morabia et al. (1988).

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

Source

- Location of 91 patients at time of first symptoms
- Area in which toxicological assessment made
- Non-investigated area
- Visualisaton & positive tox. Measurements
- Assumed exposed area

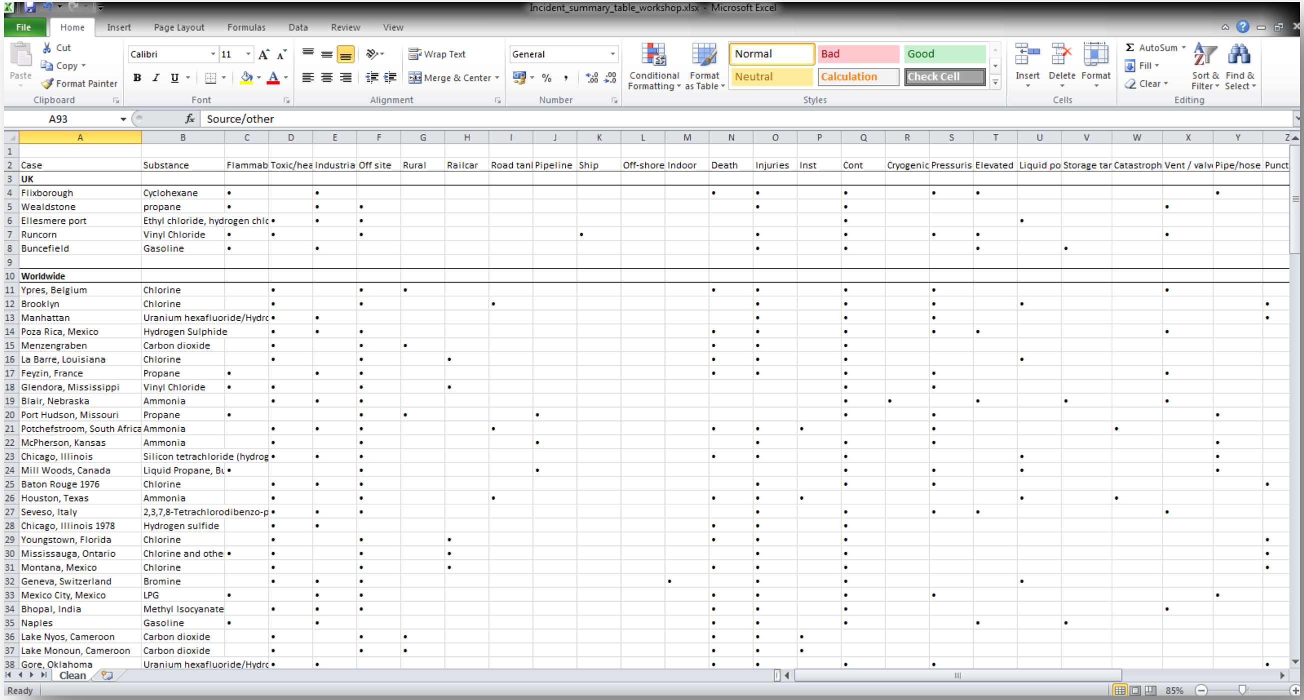
Morabia et al. (1988)
Image reprinted by permission of Oxford University Press on behalf of the International Epidemiological Association

Incident breakdown

- 69 incidents in total
  - 5 UK incidents
  - 57 worldwide incidents
  - 7 semi-confined incidents (3 UK based)

Reference table

Name
Substance
Flammable
Toxic/health
Industrial
Off-site
Rural
Railcar
Road tanker
Pipeline
Ship
Off-shore
Indoor
Death
Injuries
Instantaneous
Continuous
Pressurised
Elevated



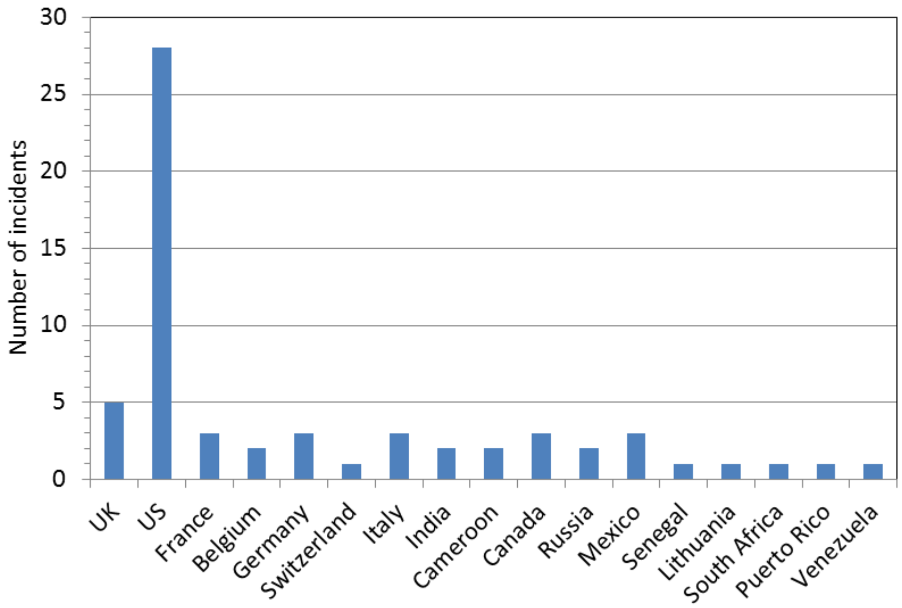
Case	Substance	Flammab	Toxic/hea	Industria	Off site	Rural	Railcar	Road tanl	Pipeline	Ship	Off-shore	Indoor	Death	Injuries	Inst	Cont	Cryogenic	Pressuris	Elevated	Liquid po	Storage tar	Catastroph	Vent / valv	Pipe/hose	Punct
UK																									
Flixborough	Cyclohexane	•		•									•	•		•		•	•					•	
Wealdstone	propane	•		•	•									•		•							•		
Ellesmere port	Ethyl chloride, hydrogen chlc		•	•	•											•				•					
Runcorn	Vinyl Chloride	•	•		•					•				•		•		•	•				•		
Buncefield	Gasoline	•		•										•		•			•		•				
Worldwide																									
Ypres, Belgium	Chlorine		•		•	•							•	•		•		•					•		
Brooklyn	Chlorine		•		•			•						•		•		•		•					•
Manhattan	Uranium hexafluoride/Hydrc		•	•										•		•		•							•
Poza Rica, Mexico	Hydrogen Sulphide		•	•	•								•	•		•		•	•				•		
Menzengraben	Carbon dioxide		•		•	•							•	•		•									
La Barre, Louisiana	Chlorine		•		•		•						•	•		•				•					
Feyzin, France	Propane	•		•	•								•	•		•		•					•		
Glendora, Mississippi	Vinyl Chloride	•	•		•		•									•		•							
Blair, Nebraska	Ammonia		•	•	•											•	•		•		•		•		
Port Hudson, Missouri	Propane	•			•	•			•							•		•						•	
Potchefstroom, South Africa	Ammonia		•	•	•			•					•	•	•			•				•			
McPherson, Kansas	Ammonia		•		•				•					•		•		•						•	
Chicago, Illinois	Silicon tetrachloride (hydrog		•	•	•								•	•		•				•				•	
Mill Woods, Canada	Liquid Propane, Bu	•			•				•							•		•		•				•	
Baton Rouge 1976	Chlorine		•	•	•									•		•		•							•
Houston, Texas	Ammonia		•		•			•					•	•	•					•		•			
Seveso, Italy	2,3,7,8-Tetrachlorodibenzo-p		•	•	•									•		•		•	•				•		
Chicago, Illinois 1978	Hydrogen sulfide		•	•									•	•		•									
Youngstown, Florida	Chlorine		•		•		•						•	•		•									•
Mississauga, Ontario	Chlorine and othe	•	•		•		•							•		•									•
Montana, Mexico	Chlorine		•		•		•						•	•		•									•
Geneva, Switzerland	Bromine		•	•	•							•		•		•				•					
Mexico City, Mexico	LPG	•		•	•								•	•		•		•						•	
Bhopal, India	Methyl Isocyanate		•	•	•								•	•		•							•		
Naples	Gasoline	•		•									•	•		•			•		•				
Lake Nyos, Cameroon	Carbon dioxide		•		•	•							•	•	•										
Lake Monoun, Cameroon	Carbon dioxide		•		•	•							•	•	•										
Gore, Oklahoma	Uranium hexafluoride/Hydrc		•	•									•	•		•		•							•

Liquid pool
Storage tank overfilling
Catastrophic failure
Vent/valve
Pipe/hose
Puncture/crack/hole
Obstructions
Topography
Nil/low wind
Concentration data
Ingress
Mitigation
ER/safety reg ignored/failed
Previous model validation
Potential model validation
Source description

Location

- Generally higher incidence in more developed countries
- Deaths and injuries are generally lower

Better enforcement of safety regulations in more developed countries



Incident stats

38 incidents originate from industrial facilities. In **26** of these cases, the gas cloud spreads off site therefore impacting the surrounding population/environment.

7 incidents could be considered instantaneous releases while the rest are continuous or finite duration

38 incidents (including semi-confined cases) result from a pressurised source

16 incidents result from modes of transport. Of these,

11 originate from railcars,

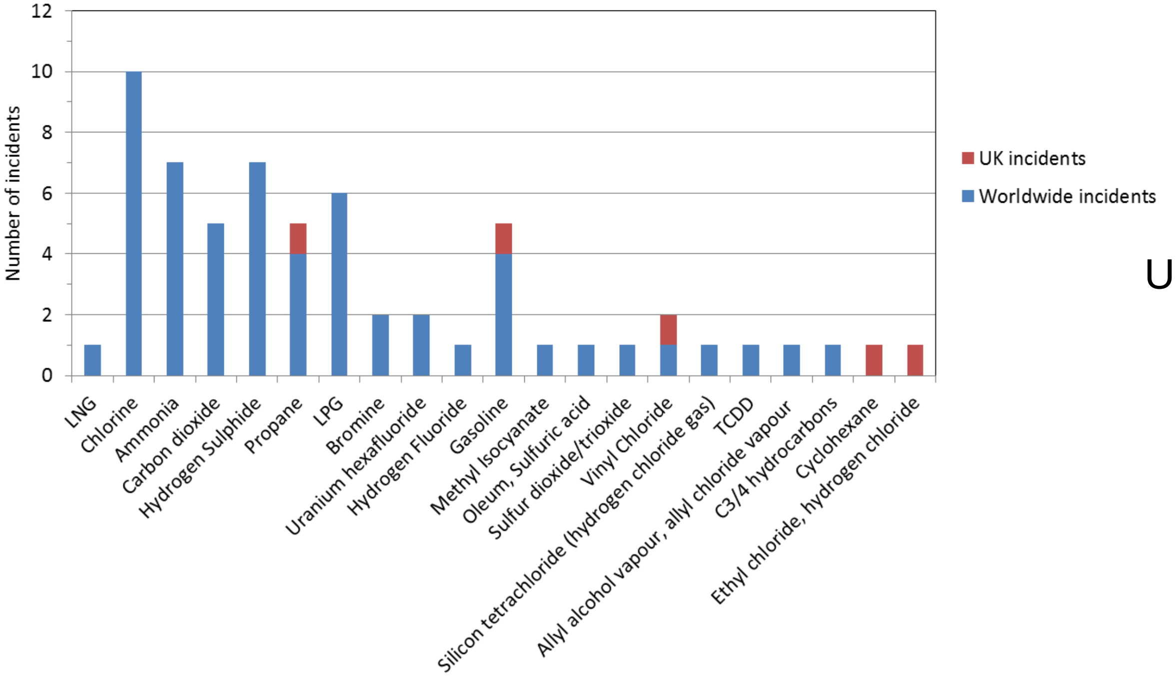
4 from road tankers and

1 from a ship

15 incidents occur due to issues with valves or vents

12 pipe or hose failures

Substances



Top five substances worldwide:

- Chlorine
- Ammonia &
- Hydrogen sulphide
- LPG
- CO_2 & Propane & Gasoline

UK substances

- Propane
- Gasoline
- Vinyl chloride
- Cyclohexane
- Ethyl chloride/hydrogen chloride

Indoor and semi-confined releases

- Substances in this review
  - Hydrogen sulphide
  - Carbon dioxide
  - Chlorine
  - Freon
  - Bromine

"…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)."

"There are only four indoor or semi-confined hydrogen sulphide example incidents listed here but Danielsson et al. (2009) highlights many more incidents with hydrogen sulphide both in confined and unconfined spaces."

"Several of the incidents are exacerbated by people coming to the aid of afflicted colleagues and succumbing to the hazard themselves."

Mixing of incompatible substances

- 5 incidents result from mixing of incompatible substances
  - 4 result in hydrogen sulphide release, 1 results in a chlorine release

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 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 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 H_2S. Within 5 minutes, an invisible cloud of H_2S 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 H_2S poisoning; seven other Burkes employees and one Davison Transport driver were injured due to H_2S 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 H_2S 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.

More incident stats

5 incidents result from pipelines

21 incidents mention nil or very low wind conditions

13 incidents clearly indicate that the topography at the incident location, or nearby, influenced the spread of the gas cloud

In 5 incidents, the dense gas originates indoors but is not contained

In 14 of the incidents ingress of gas is mentioned

There are 20 incidents where sufficient information may be available for a modelling exercise

Existing modelling studies have been found for 13 of the incidents

MODELS

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BESPOKE RESEARCH AND CONSULTANCY FROM HSE

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What are the requirements of models in industrial regulation and emergency preparedness?

- For Land-Use Planning, the models need to include a wide range of physics and source terms to model a range of hazardous substances and storage and release conditions
- The models
  - Do not need to run in real-time but needs to be fast enough to run multiple simulations (e.g. for different atmospheric conditions or release sizes) without being too onerous to meet LUP assessment deadlines.
  - Need to make appropriate assumptions in order to provide a cautious estimate
  - Need to output information easily for transferring into reports
- For regulatory research purposes and legal cases, timeframes are typically longer and a wider range of models are required

What are the requirements of models for emergency response?

- There are different types of model for emergency response with different end user requirements. E.g.
  - Specialists typically running models remotely, e.g. Met Office
  - Emergency responders running models on the ground
  - The industrial site use of models
- In general, the models need to be
  - Fast to run, preferably real-time or faster
  - Quick to set up, preferably with few inputs
  - Include detailed meteorological information
  - Ideally be able to account for topography and the urban environment, when relevant.
- Ability to extract required information quickly
- In a suitable format for use by decision makers, preferably with information on uncertainty
- Models for use ‘on the ground’ need to be developed in consultation with end users

Types of model

Empirical and nomograms

Shallow layer models

Box and integral models

Lagrangian particle and puff models

Computational Fluid Dynamics (CFD)

Zone

Gaussian plume models

Common assumptions and parameterisations

Source terms

Surface roughness

Atmospheric conditions

Flat world

The Boussinesq approximation

Homogeneous equilibrium

Content for each model summary

Who owns it?

Is it a package or a model?

Who wrote it?

Does it require a source term model?

Is it proprietary?

What does it typically output?

Who is it aimed at?

What's the QA like? Is there evidence of V&V?

Is it suitable for emergency response?

Can it model ingress of contaminants?

What met. does it take? Can it model nil wind?

Example

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.

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).

Models for use in emergency response

Model name	Type of model
Aeolus	CFD
ALOHA	Integral / box
ERG2016	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

When it is important to model terrain?

- Lack of clear guidance on when topography is likely to be important
- It is likely to depend on the prediction required and the case in question
- Literature on the use of surface roughness and the transition to obstacles is often confusing
- It is clear that there is a limit at which an aerodynamic roughness length is no longer an adequate means of parameterising the surface and the scale of the gas cloud to the obstacles becomes such that the street level flow field becomes important.

What are some of the current issues with models?

- Transparency of technical information on models and model validation
- What do we do when we don’t know the source?
- When is it important to model terrain?
- Few models for ingress – not enough data
- Ideally, models should not be used outside of their limits.
- How wrong is a passive model?

EXPERIMENTS

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Background

- Suitability of experimental datasets – Scale
- Model validation databases

Modellers Data Archive	SMEDIS
REDIPHEM	LNG model validation database

- Previous experimental reviews

Content for each experimental summary

- Location, date
- Name of trial if it has one
- Main references
- Objective
- Associated trials
- Atmospheric conditions
- Source
- Concentration
- Measurements undertaken
- Passive transition
- Source details
- Scale
- Substance
- Evidence of previous use for model validation
- Suitability for model validation
- Known uncertainties/ issues
- Ingress
- Mitigation

Not exhaustive – there will likely be more information available than what I have included

Example

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.

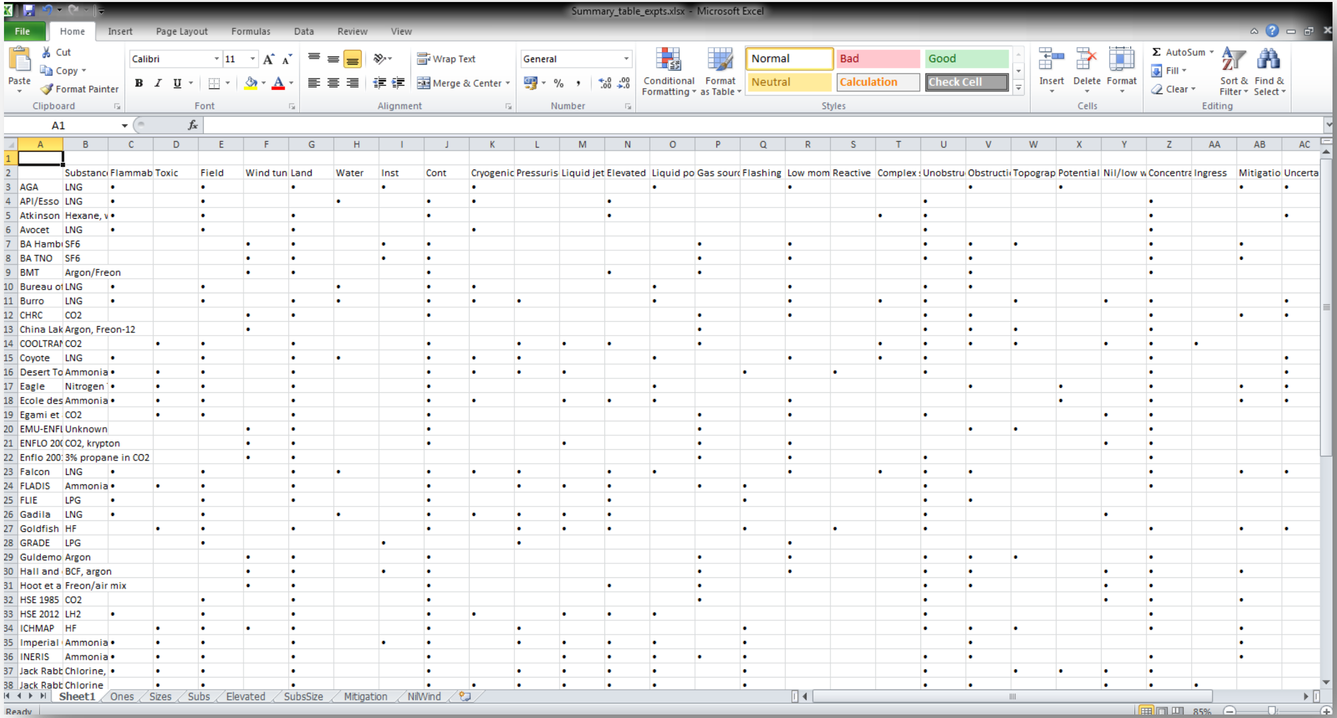
The buoyant gas used was ammonia, the neutrally buoyant gas was ethylene and the dense gas was propylene. Release rates ranged from 1 to 20 kg/h. Five tests of five minute duration were undertaken to represent puff releases of ammonia and ethylene and five tests of 20 minute duration were used to represent 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.

Reference table

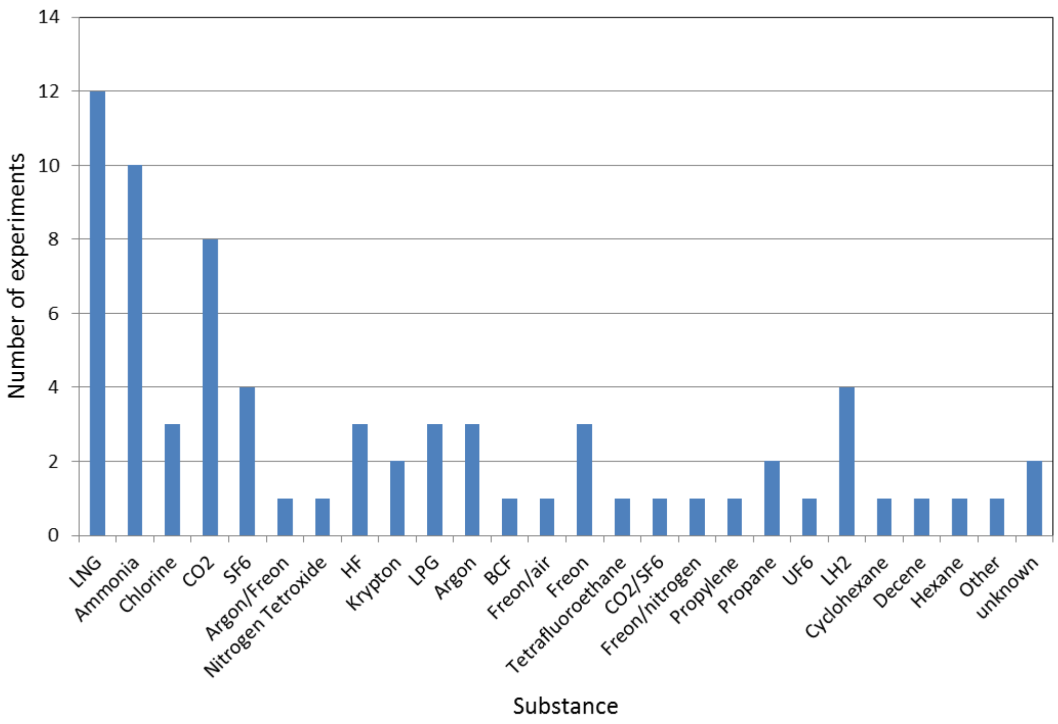
Name
Substance
Flammable
Toxic/health
Field
Wind tunnel
Land
Water
Instantaneous
Continuous
Cryogenic
Pressurised
Liquid jet
Gas source
Flashing
Low momentum
Reactive
Complex source



	Substanc	Flammab	Toxic	Field	Wind tun	Land	Water	Inst	Cont	Cryogenic	Pressuris	Liquid jet	Elevated	Liquid po	Gas sourc	Flashing	Low mom	Reactive	Complex :	Unobstru	Obstructi	Topograp	Potential	Nil/low w	Concentra	Ingress	Mitigatio	Uncerta
AGA	LNG	•		•		•		•		•				•			•				•		•				•	•
API/Esso	LNG	•		•			•		•	•			•							•					•			
Atkinson	Hexane, v	•		•		•			•				•						•	•					•			•
Avocet	LNG	•		•		•				•										•					•			
BA Hamb	SF6				•	•		•	•						•		•			•	•	•			•		•	
BA TNO	SF6				•	•		•	•						•		•			•	•				•		•	
BMT	Argon/Freon				•	•			•				•		•						•				•			
Bureau o	LNG	•		•			•		•	•				•			•			•	•							
Burro	LNG	•		•		•	•		•	•	•			•			•		•	•		•		•	•			•
CHRC	CO2				•	•			•						•		•			•	•				•		•	•
China Lak	Argon, Freon-12				•										•					•	•	•			•			
COOLTRAI	CO2		•	•		•			•		•	•	•		•				•	•	•	•		•	•	•		
Coyote	LNG	•		•		•	•		•	•	•			•			•		•	•					•			•
Desert To	Ammonia	•	•	•		•			•	•	•	•				•		•		•					•			•
Eagle	Nitrogen	•	•	•		•			•					•							•		•		•		•	•
Ecole des	Ammonia	•	•	•		•			•	•		•	•	•			•						•		•		•	•
Egami et	CO2		•	•		•			•						•		•			•				•	•			
EMU-ENFL	Unknown				•	•			•						•						•	•			•			
ENFLO 20	CO2, krypton				•	•			•			•			•		•							•	•			
Enflo 200	3% propane in CO2				•	•									•		•			•					•			
Falcon	LNG	•		•		•	•		•	•	•		•	•			•		•	•	•				•		•	•
FLADIS	Ammonia	•	•	•		•			•		•	•	•		•	•				•					•			
FLIE	LPG	•		•		•			•				•			•				•	•							
Gadila	LNG	•		•			•		•	•	•	•	•							•				•				
Goldfish	HF		•	•		•			•		•	•	•			•		•		•					•		•	•
GRADE	LPG			•				•			•						•											
Guldemo	Argon				•	•			•						•		•			•	•	•			•			
Hall and	BCF, argon				•	•		•	•						•		•			•	•			•	•		•	
Hoot et a	Freon/air mix				•	•			•				•		•					•	•			•	•			
HSE 1985	CO2			•		•			•						•					•				•	•		•	
HSE 2012	LH2	•		•		•			•	•		•	•	•						•					•			
ICHMAP	HF		•	•	•	•			•		•					•				•	•	•			•		•	
Imperial	Ammonia	•	•	•		•		•	•		•	•	•	•		•					•						•	
INERIS	Ammonia	•	•	•		•			•			•	•	•	•	•				•	•				•		•	
Jack Rabb	Chlorine,	•	•	•		•			•		•	•	•	•		•				•		•	•	•	•			
Jack Rabb	Chlorine		•	•		•			•	•	•	•	•	•		•				•	•			•	•	•		

Unobstructed
Obstructed
Topography
Potential porosity effects
Nil/ low wind/ stably stratified
Concentration data
Ingress
Mitigation
Uncertainties
Previous model validation
Potential model validation
Reference

Substances



Top five substances:

- LNG
- Ammonia
- Carbon dioxide
- Sulphur hexafluoride &
- Liquid hydrogen

Top five substances in incidents worldwide:

- Chlorine
- Ammonia &
- Hydrogen sulphide
- LPG
- CO_2 & Propane & Gasoline

Experimental trial stats

There are 63 experiments in total:

42 field experiments

21 wind tunnel experiments (there are more!)

11 field experiments investigate dense gas dispersion over water or from sources released onto water

28 tests include obstructions of some form

In 11 tests topography may influence the gas dispersion

At least 19 tests under low or nil wind conditions

28 experiments involve elevated sources:

3 ↑ 11 ↓ 9 → 8 ?

Ingress

Experiment	Substance	Structure
COOLTRANS	Carbon dioxide	Two storey structure
Jack Rabbit II	Chlorine	Vehicles and containers
Resplandy	Ammonia	Caravan

Leaks

Leak

(Images from Cleaver et al., 2016, © IChemE copyright)

16 tests including mitigation 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, steam spray, Carbon Dioxide, Freon-12, fine water mist, boric acid mist and an ionised dry air stream
Thorney Island	Freon-12/nitrogen mixture	Fenced enclosure
Meroney	Various	Vapour barrier for HF, water spray curtain

Knowledge / data Gaps

Discussed later…

MITIGATION

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Measures affecting the vapour source

- As for any gas cloud, stopping the cloud at source is the most effective means of stopping the subsequent dispersion and reducing risks of exposure.
- This will depend on the substance and the particular circumstances of the release

- Examples include:
  - Emergency shut down, emergency vents and valves
  - Containment bunds and impounding/retention basins
  - Fine water fog
  - Foam and other additives
  - Plastic sheeting

Measures mitigating the dispersion of dense gas

- Most measures revolve around increasing dilution or containment
- Increasing the cloud dilution so that the cloud is diluted below hazardous endpoints

- Examples include:
  - Containment bunds and walls
  - Water spray barriers
  - Steam curtains
  - Forced air mixing

Measures that mitigate exposure

- As a minimum mitigating exposure means appropriate PPE for emergency responders and site personnel. Water fogs and sprays can also assist. Detectors and monitors are key to identifying information such as the substance, concentrations and location and setting exclusion zones or cordons. Sirens and loud speakers can assist in conveying this information.
- A key factor in mitigating exposure is timing. Deciding when to impose shelter in place, either in residences or in designated shelters, and when to evacuate.
- Examples include:
  - PPE
  - Detectors / monitors / sensors
  - Exclusion zones / hot zones / cordons
  - Sirens and loud speakers
  - Water fogs or sprays
  - Shelter in place
  - Designated shelters
  - Evacuation

Some comments on mitigation

- It is important that the mitigation measure is appropriate for the substance and the situation, including the atmospheric conditions.
- Limited guidance
  - For the practical use of measures by site personnel or emergency response personnel.
  - To assist in positioning of mobile measures in relation to the hazard, expected efficiency of the measures, associated concentration reduction factors and any factors affecting the efficiency such as atmospheric conditions.
- Some experimental work has been undertaken but more is required to be able to derive guidance for fast operational use.
- Human factors are a big issue since nearly all mitigation measures rely on appropriate response from personnel or the public.

SCENARIOS

What's covered in the review

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Existing scenarios

- Hanna et al. (1996) – 7 theoretical worked examples, input data, example output
- Hanna et al. (2008) – 3 worked examples of chlorine incidents, input data, example output
- COST ES1006 – 3 scenarios (windtunnel, field trial, incident), some input data, example output
- US EPA (1993) – 8 theoretical worked examples, input data, example output
- NUREG (SAIC, 1998) – 8 theoretical worked examples, input data, example output

TABLE 9-2 Scenarios Data Archive (SDA) for Worked Examples, Containing All Input Data Sufficient to Run Models Listed in Table 9-1

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
SCENARIO DESCRIPTION	Continuous pressurized horizontal release of liquid chlorine	Continuous liquid (cryogenic spill of large tank of chlorine	Continuous liquid (noncryogenic spill of large tank of acetone	Continuous vertical dense gas jet of normal butane	Slow time-variable venting of sulfuric acid from building (passive dispersion)	Pressurized gaseous release of multi-component mixture of hydrocarbons	Transient (mitigated) area-source release of HF
MODELS TO BE APPLIED	DEGADIS, HGSYSTEM, SLAB	DEGADIS, HGSYSTEM, SLAB	ALOHA, DEGADIS, HGSYSTEM	DEGADIS, SLAB	INPUFF, ISC	ALOHA, HGSYSTEM, SLAB	DEGADIS, HGSYSTEM
PROPERTIES OF RELEASED MATERIAL							
Name	Chlorine (Cl_2)	Chlorine (Cl_2)	Acetone (C_3H_6O)	Normal Butane (nC_4H_{10})	Sulfuric Acid (H_2SO_4)	Major component: Ethane (C_2H_6)*	Hydrogen Fluoride (HF)
Molecular weight (kg/kmole)	70.91	70.91	58.1	58.12	98.08	30.07	20.01
Normal boiling point (K)	239.1	239.1	329.4	272.7	n/a	184.52	292.7
Latent heat of evaporation (J/kg)	287,840	287,840	545,000	363,000	n/a	489,360	373,000
Specific heat at constant pressure for vapor (J/kg/K)	498	498	1467	1715	n/a	1774	1450
Specific heat of constant pressure for liquid (J/kg/K)	926	926	2070	2054	n/a	2346	2528
Density of liquid (kg/m^3)	1574	1574	788	623	n/a	547	987
Molecular diffusivity (m^2/s)	1.22×10^{-5}	1.22×10^{-5}	1.23×10^{-5}	n/a	n/a	n/a	n/a
Kinematic viscosity (m^2/s)	4.48×10^{-6}	4.48×10^{-6}	1.10×10^{-5}	n/a	n/a	n/a	n/a
Mole fraction (%) in pollutant mix	100	100	100	100	100	60	100
SOURCE CONFIGURATION							
Storage temperature (K)	298	239.1	303	303	293	293	308
Release temperature (K)	239.1	239.1	303	303	293	293	292.7
Storage pressure (atm)	8	1	1	1	1	4	10
Storage phase	liquid	liquid	liquid	gaseous	gaseous	gaseous	gaseous
Release phase	2-phase	liquid	liquid	gaseous	gaseous	gaseous	2-phase
Rupture/stack/source diameter (m)	0.0381	0.0381	0.0508	0.75	1	0.1	24
Rupture/stack/source height (m)	1.5	1.5	1	5	20	1	0
Mass in tank (kg)	80,000	80,000	143,743	n/a	n/a	n/a	n/a
Tank diamter (m)	4	4	7.62	n/a	n/a	n/a	n/a
Tank height (m)	5	5	7.62	n/a	n/a	n/a	n/a
Fluid level (m)	4.04	4.04	4	n/a	n/a	n/a	n/a
Pipe length (m) for pipe rupture	3.81	n/a	n/a	n/a	n/a	n/a	n/a
Dike, centered at source, diam. (m)	n/a	n/a	21.9	n/a	n/a	n/a	n/a
Dike height (m)	n/a	n/a	0.914	n/a	n/a	n/a	n/a
Ground surface composition	n/a	concrete	concrete	n/a	n/a	n/a	n/a
Building height (m)	n/a	n/a	n/a	n/a	18		
Building width (m)	n/a	n/a	n/a	n/a	22.36	n/a	n/a
Mass fraction that flashes to vapor	0.189	n/a	n/a	n/a	n/a	n/a	0.104
Vapor/aerosol mix density (kg/m^3)	18.9	n/a	n/a	n/a	n/a	n/a	7.98
Source Richardson number	1.36×10^5	782	3.61	28100	n/a	106	957
Richardson number for down-wind effects for point source	3.45×10^4	n/a	n/a	4220	n/a	10.6	n/a
SOURCE STRENGTH	11.04	9.3 (pool radius = 20 m)	2.34 (effective radius = 10.27 m)	15	0.272 exponentially decaying to 0.044 over 1 hour	5	10 for first 60 sec. 1 for next 540 sec.
Type	steady-state	steady-state	ALOHA: transient HGSYSTEM and DEGADIS: steady-state	steady-state	INPUFF: transient ISC: pseudo-steady-state	steady-state	transient
Method of deactivation	calc. from above source config. (Fauske & Epstein)	calc. by LPOOL module of HGSYSTEM (ALOHA yields similar evap. rate but lacks pool radius)	calc. from above source config. for DEGADIS (Fleischer)	direct user-input	calc. from an assumed building exchange rate	direct user-input	direct user-input
METEOROLOGICAL CONDITIONS							
Temperature (k)	298	298	303	303	300	303	293
Measuring height of temp. (m)	10	10	10	10	10	10	10
Wind speed (m/s)	2	2	5	2	2	5	2
Measuring height of wind speed (m)	10	10	10	10	10	10	10
Stability class	F	F	D	F	C	D	F
Pressure (atm)	1	1	1	1	1	1	1
Relative humidity (%)	80	80	50	50	50	75	90
Monin-Obukhov length (m)	12.2	12.2	9999	14.3	–74.2	9999	14.3
Friction velocity (m/s) profile method	0.0808	0.0808	0.344	0.0986	0.303	0.511	0.0986
Wind speed at 1 m (m/s) profile method)	0.791	0.791	3.02	0.654	0.486	2.06	0.654

Multicomponent mixture: 60% (mole) ethane, 20% (mole) nitrogen, 10% (mole) propane, 10% (mole) oxygen. Weighted MW = 31.25 kg/mole. Weighted cp = 47.29 J/mole/K = 1513 J/kg/K.

More existing scenarios

- PRACTICE – several scenarios for exercises in response to CBRN incidents, descriptive
- NOG – 26 scenarios to assist in identifying the knowledge, control measures and actions needed to combat the hazards of that particular scenario

New scenarios

- Scenario 1 – Static site (COMAH)
- Scenario 2 – Static site (non-COMAH)
- Scenario 3 – Pipelines
- Scenario 4 – Transport (road/rail)
- Scenario 5 – Transport (maritime)
- Scenario 6 – Non-regulated, unknown source

New scenarios content breakdown

8.3 SCENARIO 1 – STATIC SITE (COMAH) 285

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- About 5 pages
- Descriptive
- References incidents

Scenario 1 – Static site (COMAH)

Description

1.1 Scenario 1 – Static site (COMAH regulated)

1.1.1 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 regulations[1] can be seen in Table 1. The competent authority for COMAH sites is HSE and the relevant environment agency from the devolved governments.

Table 1 Examples of the lower and upper tier quantities (in tonnes) of some named substances under the COMAH 2015 regulations

Substance	Lower tier (te)	Upper tier (te)
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

Quantities

Examples

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 [X]. From Great Britain, examples of incidents at sites subject to COMAH regulations include Flixborough and Buncefield.

Worldwide, the following incidents from the present review would likely be subject to COMAH regulations:

Scenario 1 – Features

What procedures might be in place

What substances might be expected

Personnel/ populations present/ nearby

Topography

Overlap with other scenarios

1.1.2 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.

Scenario 1 – Dense gas sources and dispersion

What might be known

1.1.3 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.

Potential storage/ release conditions

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.

Potential sources

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.

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.

Contributing factors

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.

The number of different substances on COMAH (Ctrl) ns 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.

1.1.4 Factors affecting dense gas dispersion

Topography and obstructions

The degree of flatness and openness of the site will 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.

Where could ingress occur

Ingress may occur into buildings, drainage systems and sewers.

Other factors…

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.

Scenario 1 – Mitigation measures and emergency response

Potential state of emergency response procedures and personnel

Potential mitigation measures

1.1.5 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.

Potential for substance information

Scenario 1 – What modelling might be done?

Brief description of modelling for emergency preparedness

Brief description of modelling for emergency response

1.1.6 Use of modelling

Modelling for emergency preparedness (COMAH)

Models are used within COMAH reports for demonstrating aspects such as the potential 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.

Modelling may be undertaken as part of emergency response exercises, if this is part of the emergency plan.

Modelling for emergency preparedness (LUP)

For LUP, modelling is undertaken by the HSE. It involves a range of pre-defined representative release conditions and meteorological conditions undertaken with pre-defined models. For dense gas dispersion the DRIFT model is used.

The output is a set of LUP zones: inner, middle, outer and a public information zone. The inner to outer zones have different conditions on LUP relating to the sensitivity of the population.

Modelling for emergency response

Modelling may not be undertaken at all. Whether or not modelling is required will depend on the timeframes of the incident and who is involved.

The choice of model may depend on the speed at which modelling is required and the likely duration of the event.

A minimal modelling approach adopted might be to use 'look up' information such as that supplied in NOG, EAC and ERG2016. Met Office may be contacted for a CHEMET, or similar, using the model NAME.

If modelling is undertaken, there are a variety of responders who may have some form of predictive capability, for example

- The site itself
- The emergency services
- Met Office
- Other parties in STAC/SAGE (if convened) such as EA, ONR, academics or other specialists

- What might be done
- Who might do it

Scenario 1 – Modelling challenges

Wide range of variables

Speed

Wide range of variables

1.1.7 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. In particular, a genericised method for accounting for terrain is required.

For emergency response

Speed is a significant challenge in emergency response modelling. This is not solely related to the speed in which the model runs. It also relates to the speed with which information can be communicated, input into a model and how quickly results can be output from a model in a form that is suitable for timely use by decision makers.

At present, none of the typical models used for civilian 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.

Reasonable assumptions for longevity

Not currently possible

Uncertainty

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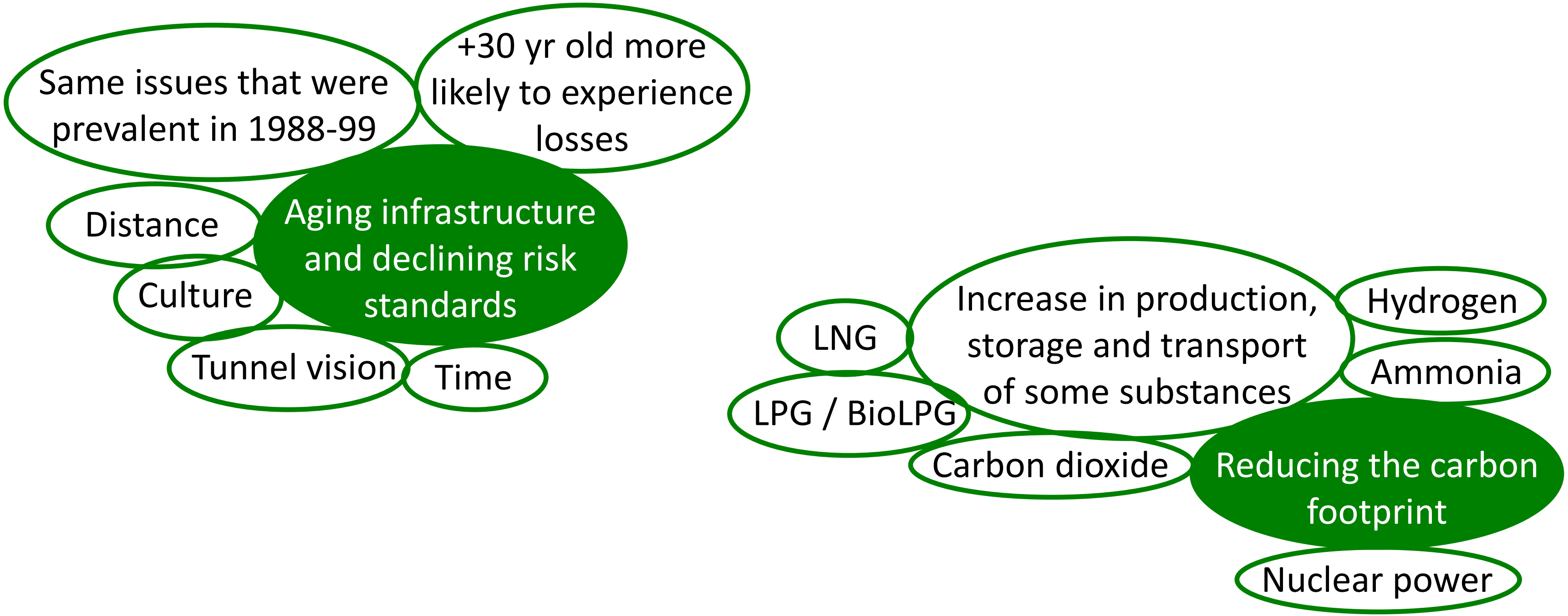
FUTURE TRENDS and EMERGING TECHNOLOGIES



Example - Ammonia

Current uses:

- Commercially to make household cleaners and refrigerants and to make other chemicals
- To make fertilizers for farm crops, lawns, and plants and applied directly into soil on farm fields
- Manufacture of explosives

Potential uses:

- As a low-cost hydrogen carrier
- Directly as a hydrogen-rich fuel, at lower cost per MWh than hydrogen
- UK Government is aiming to launch a number of zero emission shipping ambitions, including a group of hydrogen or ammonia powered domestic vessels

Timeframe:

Bulk transport of hydrogen/ammonia to the UK would require a large-scale international market, which Committee on Climate Change says is unlikely in the next 10-15 years.

KNOWLEDGE/DATA GAPS

EXPERIMENTS

- Ideal conditions
- Sources
- Infiltration and ingress
- Full scale industrial/urban environment
- Non-ideal conditions
- Vertically orientated releases from height
- Indoor to outdoor releases
- Congestion
- Deposition
- Topography
- Mitigation measures

KNOWLEDGE/DATA GAPS

Incident analysis
Revisit existing experiments
Effective passivity and passive transition
Richardson numbers
Other criteria

Statistical analyses
Incident analyses and quantitative scenario generation
Knowledge gaps
Model comparison exercises

REVIEWS

Help with clarity
Storage and transport
Substance-specific
Knowledge gaps
Reactions
Mitigation measures

In consultation with emergency response services
Mitigation measures
Incident analysis

Information gathering

Looking backwards:
Could more be done with existing incident and experiment information?

Going forwards:
Could more be done to collect and store information during emergency recovery?

Provide data to…
…Improve physical understanding of releases and dispersion
…Improve understanding of safety and emergency procedures
…Make it easier to determine lessons learned and good practices
…Be assimilated for use, for example, by incident analysts, epidemiologists and atmospheric dispersion modellers
…Provide hard evidence for determining areas of concern and knowledge gaps

THANKS FOR LISTENING!

References

For complete references and further information please see report:

Batt, R. 2021. Review of dense-gas dispersion for industrial regulation and emergency preparedness and response. UK Atmospheric Dispersion Modelling Liaison Committee.