

Identification of knowledge gaps for future testing in Jack Rabbit III: a European perspective

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Guidance - freely available to help people comply with health and safety law

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Outline

- Aims
- Survey of knowledge gaps and research priorities
 - Survey methodology
 - Top five research topics identified
 - Specific research questions
- Brief reviews of:
 - Relevant previous experiments
 - Ammonia incidents
- Summary
- Tentative proposal for some future work

Aims

- To conduct a survey amongst European experts of knowledge gaps in atmospheric dispersion of acute toxic hazards
- To help prioritise the key topics to study in the future Jack Rabbit III experiments

Jack Rabbit III

- Focus on anhydrous ammonia
- Experiments at medium scale in 2023 and large scale in 2024, with supporting wind tunnel and/or modelling work beforehand
- Led by DTRA and CSAC

Knowledge Gaps Methodology

Staged approach:

1. Pose open questions to gather information

- What is the issue?
- Why are we interested?
- What testing is needed?
- Example: Dry deposition
 - Some models predict it could have a significant affect on the hazard range
 - Lack of experimental data for dry deposition rates
 - Tests would involve measurements with different soil/vegetation samples downwind from large realistic release

Knowledge Gaps Methodology

2. Group common issues identified in the responses into topics and sub-topics

- Five topic headings:
 - Source terms
 - Dispersion
 - Physicochemical effects
 - Mitigation
 - Outcomes

Knowledge Gaps Methodology

3. Contributors vote on their top three sub-topics

– For example, sub-topics in dispersion:

- Obstacle effects
- Terrain effects
- Stable atmospheres
- Internal boundary layers
- Low wind speeds
- Transition from dense to passive
- Persistence in wakes/hollows
- Detailed turbulence

Assign vote value:
3 for top issue
2 for next issue
1 for lower priority

– Contributors also asked which topics should not be studied

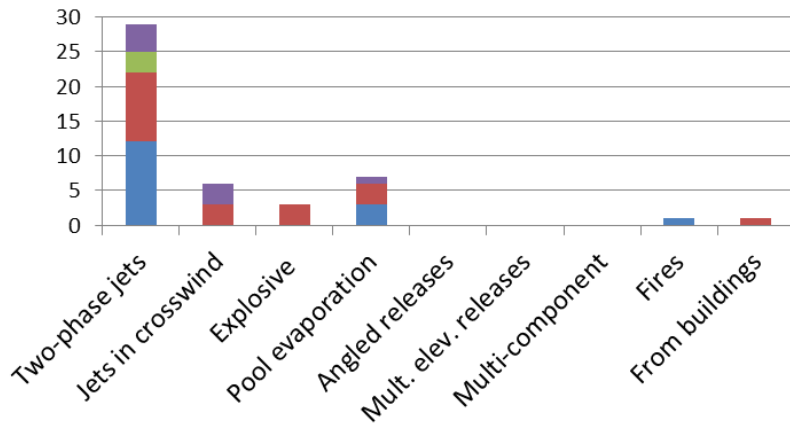
Knowledge Gaps Methodology

4. Collate responses from all contributors

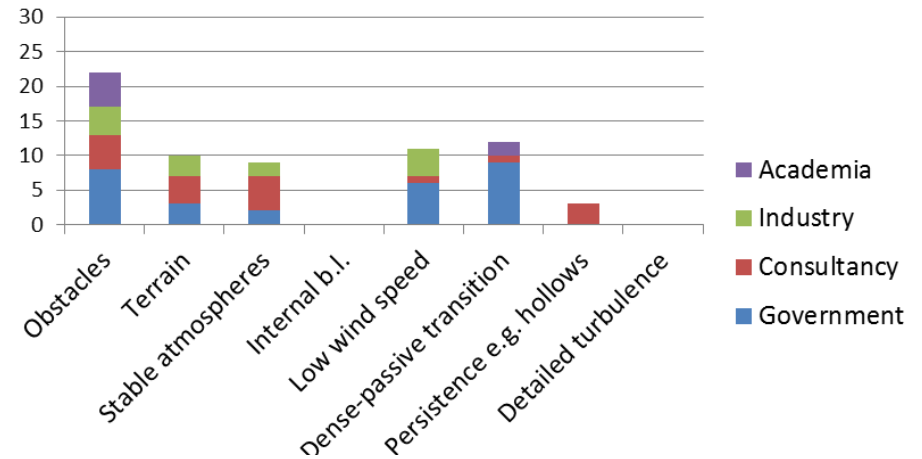
- Votes summed to find highest-priority research topics
- Specific research questions identified within the top five highest-priority sub-topics
- Findings circulated for feedback from the contributors prior to finalising these slides

Knowledge Gaps: Results from votes

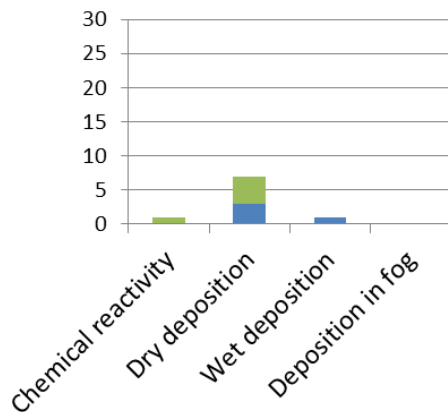
Source Terms



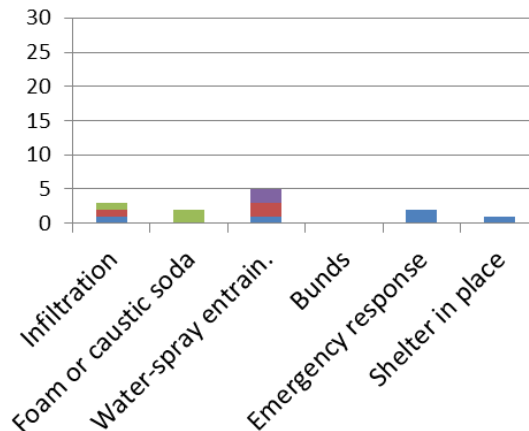
Dispersion



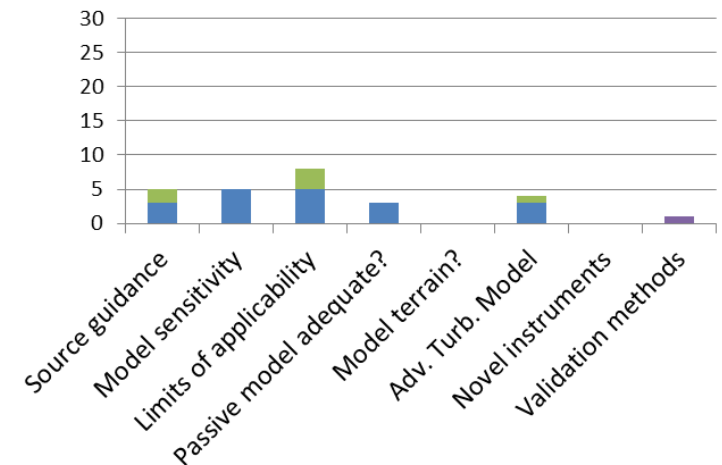
Physicochemical effects



Mitigation

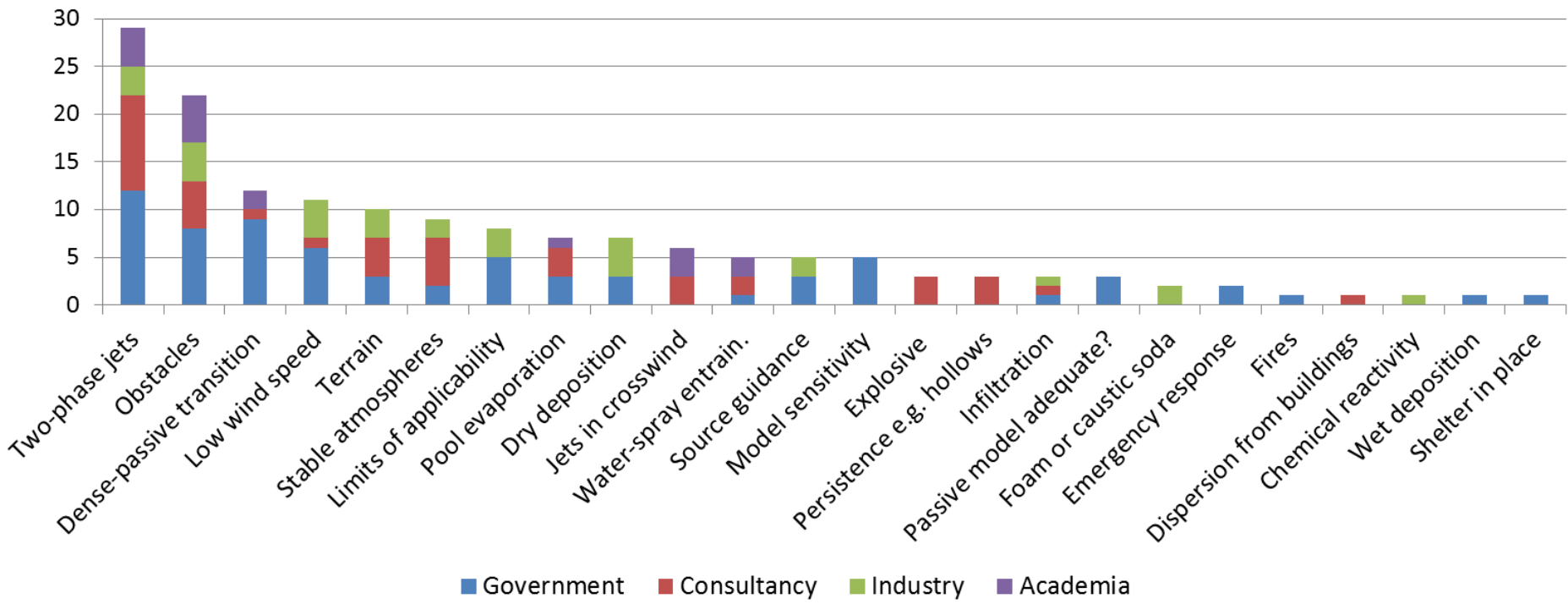


Outcomes



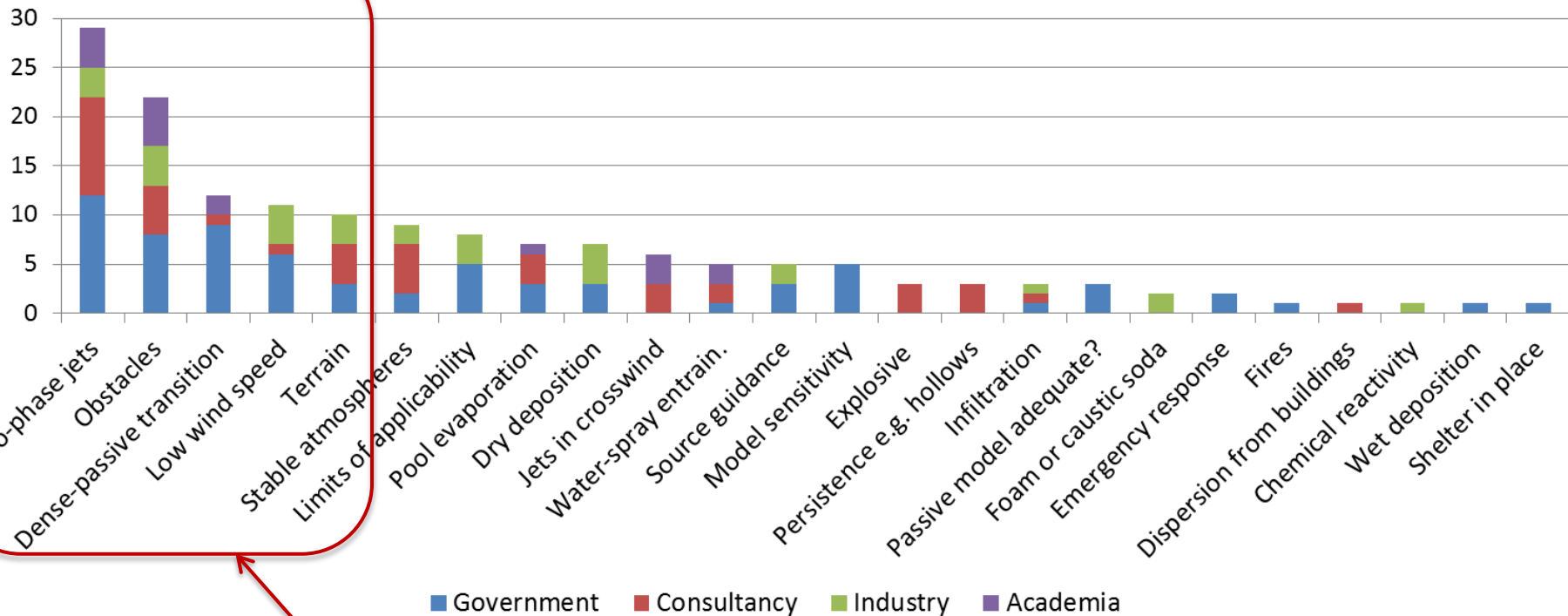
Knowledge Gaps: Results from votes

Overall Ranking



Knowledge Gaps: Results from votes

Overall Ranking



Next slides focus on top five sub-topics

1. Two-phase jets

- Critical issue studied in several previous projects (see later review)
- Lack of data for partitioning between airborne aerosol and liquid pool (i.e. rainout fraction)
- Validity of rainout approaches in operational models is uncertain
- Rainout fraction can have significant influence on dispersion, particularly in the near field
- Rainout is scale-specific: depends on geometry and release size
- Useful to consider range of conditions: hole sizes, release orientations, impinging, short releases (e.g. catastrophic vessel failure), long duration releases (e.g. pipeline)
- Uncertainty in post-expansion source conditions: jet velocity and liquid fraction (metastable or homogeneous equilibrium) – could be studied in laboratory-scale tests?
- Uncertainty in behaviour inside vessel (champagne effect)

2. Obstacles

- Limited field-scale data available for dense-gas dispersion with realistic obstacles
- At what size do obstacles become important such that they need to be taken account of in modelling?
- Are dense gas dispersion models for flat and rough terrain still applicable to built-up environments?
- Which is better: a building-resolved passive model or a dense gas model with surface roughness?
- How much do isolated or small obstacles affect dispersion?
- What is the impact of obstacles on persistence of the cloud?
- How effective are vapour barriers for mitigation?
- Do wakes from isolated tall buildings in city environments have a significant affect? Is it important to model them?

3. Transition from dense-gas to passive dispersion

- When is it necessary to use a dense-gas model instead of a passive model?
 - Is the current rule of thumb that says a dense-gas model should be used for releases of 1 ton or more accurate?
- Can testing determine if there is a threshold release size when a passive model is adequate?
- How rapid is the mixing between the dense cloud and the atmosphere that produces a passive cloud?
- Does near-field dense gas behaviour matter far downwind?
- How does the transition from dense to passive affect turbulence levels and toxic dose (non-linear toxic response to concentration)?
- What are the implications for infiltration into buildings, e.g. draining of dense clouds into basements?

4. Dispersion in low/zero wind speeds

- Lack of experimental data for large dense-gas releases in low/zero wind speeds
 - But there are examples of several severe incidents involving flammable dense-gas releases in low/zero wind, e.g. Buncefield and San Juan fuel storage depots
- How do obstacles and terrain influence the dispersion behaviour when the wind speed approaches zero?
- What are the implications of low/zero wind speeds for emergency response?
 - ERG provides protective action distance in downwind direction
 - ERG for ammonia has three wind speeds (low, moderate, high) for (<10 km/h, 10-20 km/h, >20 km/h)
 - What is the advice for very low or zero wind? Which direction is downwind? Are the ERG distances still valid?

5. Terrain effects

- Lack of experimental data for large dense-gas releases with terrain
 - Indications from incidents that even moderate slopes could have significant effect in low/zero wind
- At what scale does terrain become important for dispersion?
- What is the combined effect of the wind, the release direction and terrain on dense-gas releases?
 - Useful to have range of tests: e.g. releases upslope, downslope and cross-winds for a range of release sizes and slopes
 - Also elevated releases, e.g. for rooftop-mounted ammonia refrigeration tanks

Brief review of previous experiments

Brief Review of Previous Experiments

The next slides examine experimental data for the top five priorities:

1. Two-phase jets (only ammonia)
2. Obstacles
3. Transition from dense-gas to passive
4. Low/zero wind speed
5. Terrain

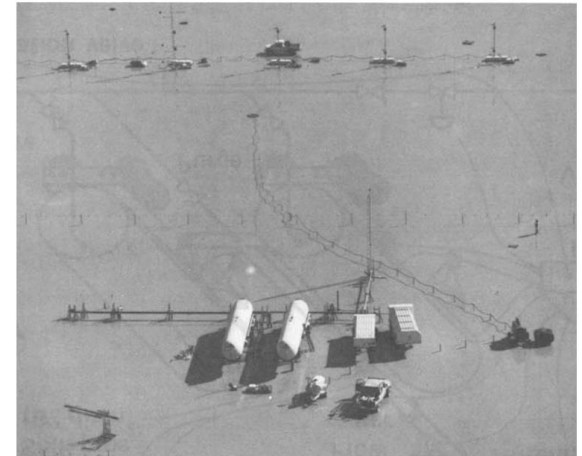
References to papers/reports cited in these slides are provided at the end of the presentation

Previous ammonia two-phase jet experiments

	Instantaneous	Continuous	Flashing jet	Evaporating Pool	Gas source	Unobstructed	Obstructions	Topography	Nil/low wind/stable	Concentration measured	Ingress	Mitigation
Desert Tortoise		•	•			•				•		
Ecole des Mines d'Ales		•	•	•						•		•
FLADIS		•	•		•	•				•		
ICI	•	•	•	•			•					•
INERIS		•	•	•	•	•	•			•		•
Jack Rabbit I		•	•	•		•		•	•	•		
Landskrona		•			•	•						
Resplandy		•	•		•	•	•		•		•	•
University van Kunstmest bv			•	•								

1. Two-phase jets: previous ammonia experiments

- **Desert Tortoise, 1983**
 - Frenchman Flat, Nevada Test Site
 - 10 – 41 tonnes pressurised liquid ammonia
 - Horizontal discharge from 81 or 95 mm diameter pipe at height of 0.79 m
 - Quasi-continuous release rates of approx. 81 kg/s – 133 kg/s
 - Little or no liquid rainout observed
 - Sensors at several heights on arcs at 100 m, 800 m, 1.4 km, 2.8 km or 5.5 km
 - Data included in MDA, REDIPHEN and SMEDIS databases
 - Goldwire *et al.* (1983)



Source: DesAutels & Schulman (2010)

1. Two-phase jets: previous ammonia experiments

■ INERIS, 1996-1997

- CEA/CESTA test site near Bordeaux, France
- 15 ammonia releases of 2-3 tonnes with discharge rates of 3-4 kg/s
- Release orientations: horizontal, vertically-down, annular, with/without impingement
- Six types of ammonia sensors on 150 masts at different heights on arcs from 20 m to 1700 m
- Atmosphere: stable to neutral
- Mitigation: effect of water sprays
- Data used to validate Phast model
- Bouet (1999)



Image © INERIS
Source: Bouet (1999)



1. Two-phase jets: previous ammonia experiments

■ Jack Rabbit I, 2010

- Dugway Proving Ground, Utah, USA
- Five 1 – 2 ton ammonia releases vertically downwards from 2 m AGL into 2 m deep, 50 m diameter depression
- 62 ammonia sensors in rings from 50 m to 2,500 m
- Some rainout and absorption of liquid ammonia into desert playa surface
- <https://www.uvu.edu/es/jack-rabbit/>



Image © CSAC, DHS

Source: Storwold *et al.* (2011)

1. Two-phase jets: previous ammonia experiments

■ FLADIS, 1993-1994

- Ammonia discharge rates from 0.25 kg/s to 0.55 kg/s through 4.0 mm and 6.3 mm diameter orifices
- Sensors on arcs at 20 m, 70 m and 240 m
- Analysis of aerosol and transition from dense gas to passive dispersion
- Data available in REDIPHEM and SMEDIS databases
- Duijm (1994), Nielsen *et al.* (1994), Nielsen (1998) and Nielsen and Ott (1996)



Photo © Kenneth Nyren, FOA
Source: Hall, Walker & Butler (1999)

1. Two-phase jets: previous ammonia experiments

■ Landskrona, 1982

- 11 field experiments undertaken in Landskrona, Sweden in 1982 by the Swedish National Defence Research Institute
- Vessel with 1,400 kg of ammonia at 6 bar and 9 °C
- Discharges from a pipe with diameter from 32 to 40 mm at height of 2 m AGL
- Jet touched down between 6 m and 10 m downwind
- No liquid ammonia rainout observed
- **No concentration measurements made**
- Nyrén and Winter (1983), Nyrén *et al.* (1983), summarised in Bouet (1999).

1. Two-phase jets: previous ammonia experiments

- **Resplandy, 1967**
 - Tests at two military camps in France
 - Liquid and gas-phase ammonia releases of between 300 and 1,000 kg over periods between 1 and 6 minutes
 - Vertical up/down releases from 1 – 2 inch pipe
 - Infiltration into caravan submersed in ammonia cloud
 - Containment in earth and cement retention basins
 - Interaction between water and ammonia.
 - **Data mostly qualitative and difficult to use for model validation**
 - Resplandy (1969) and Bouet (1999)

1. Two-phase jets: previous ammonia experiments

■ Ecole des Mines D'Ales, 1996

- One or two 44 kg ammonia bottles discharging downwards at height of 0.17 m
- Release duration approximately 2 minutes
- Purpose to test peacock tail water sprays
- **Ten concentration sensors** at 13 m, 25 m and 50 m downwind
- Bara and Dussere (1997)

■ ICI, 1974

- Instantaneous releases from ammonia cylinder 0.15 m in diameter and 0.45 m high containing 3.5 kg of liquid ammonia
- Long duration releases through a 1 mm diameter orifice located at 1 m from the ground and orientated horizontally, 'slightly' upwards and vertically downwards into a metal tray
- **No concentration measurements or quantities reported**
- Reed (1974)

2. Obstacles: previous experiments

	Substance	Field	Wind tunnel	Instantaneous	Continuous	Flashing jet	Topography	Nil/low wind/stable	Concentration measured	Ingress	Mitigation
AGA	LNG	•		•							•
BA Hamburg	SF ₆		•	•	•		•		•		•
BA TNO	SF ₆		•	•	•				•		•
BMT	Argon/Freon		•		•				•		
Bureau of Mines	LNG	•			•						
CHRC	CO ₂		•		•				•		•
COOLTRANS	CO ₂	•			•		•	•	•	•	
Eagle	Nitrogen Tetroxide	•			•				•		•
EMU-ENFLO	Unknown		•		•		•		•		
Falcon	LNG	•			•				•		•
FLIE	LPG	•			•	•					
Guldemond	Argon		•		•		•		•		
Hall et al.	BCF, argon		•	•	•			•	•		•
Hoot et al.	Freon/air mix		•		•			•	•		
ICHMAP	HF	•	•		•	•	•		•		•

2. Obstacles: previous experiments

	Substance	Field	Wind tunnel	Instantaneous	Continuous	Flashing jet	Topography	Nil/low wind/stable	Concentration measured	Ingress	Mitigation
ICHMAP	HF	•	•		•	•	•		•		•
ICI	Ammonia	•		•	•	•					•
INERIS	Ammonia	•			•	•			•		•
Jack Rabbit II	Chlorine	•			•	•		•	•	•	
JGA	LNG	•			•						
Kit Fox	CO ₂	•		•	•			•	•		
Lathen / BA Propane	Propane	•		•	•	•		•	•		
MODITIC	CO ₂		•		•				•		
Petersen and Ratcliff	TBC		•		•				•		
Resplandy	Ammonia	•			•	•		•		•	•
Schatzmann et al	SF ₆ /CO ₂ mixture		•		•				•		
Texas A&M	LNG	•			•				•		•
Thorney Island	Freon-12/N ₂	•		•	•			•	•		

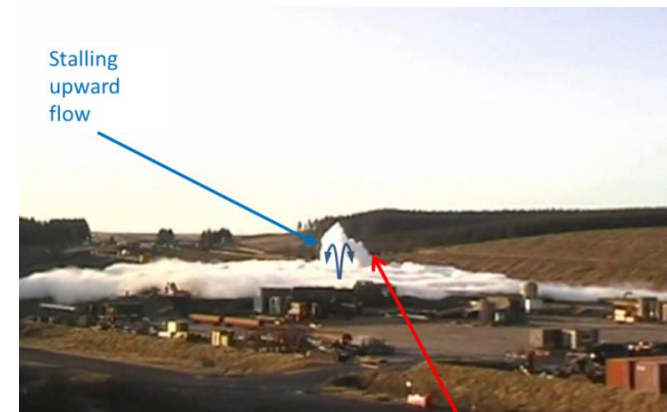
2. Obstacles: previous experiments

■ COOLTRANS, 2012 – 2013

- Pressure-liquefied CO₂ releases at DNVGL Spadeadam test site, UK
- Above-ground vertically-upwards and horizontal releases, below-ground releases from pipelines into craters
- Site mainly flat and open but some obstructions and slopes in largest tests
- Pipeline rupture tests: 230 m long, 6-inch pipe at initial pressure 150 barg
- Concentration measurements using 63 sensors upwind/downwind from -150 m to 500 m
- Ingress into two-storey Conex containers
- Data not yet fully released to the public
- Barnett & Cooper (2014)



Fresh air entrainment possible around plume base



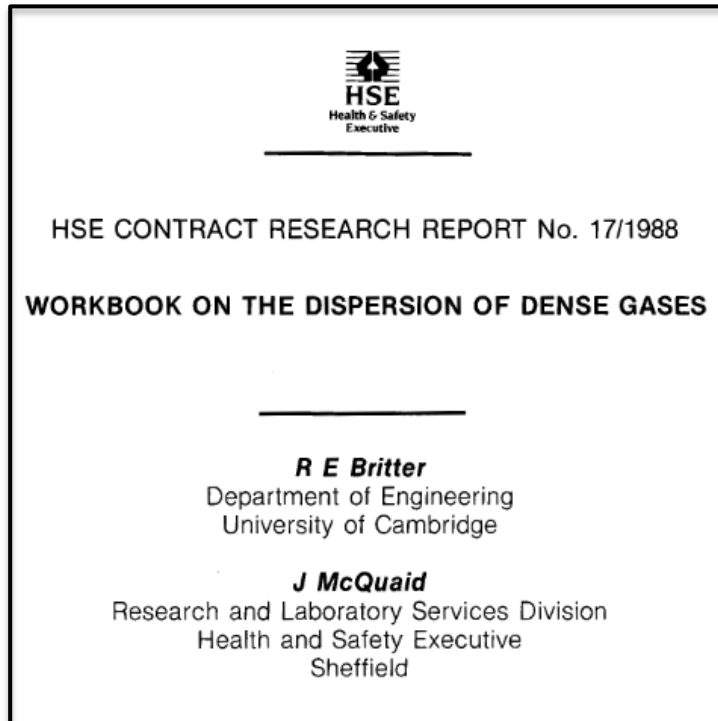
Crater is covered by vapour blanket – mixture released previously is drawn into flow

Photo © National Grid

Source: Cleaver *et al.* (2013)

3. Transition from dense to passive

- Transition from dense to passive dispersion studied previously in FLADIS and INERIS ammonia field-scale experiments



3.5 Criteria for Effectively Passive Behaviour

Under what conditions might a release be analysed using correlations from passive dispersion experiments that are widely available, have been well studied and exist in workbook form already (e.g. Turner, 1970; Clarke, 1979)?

For continuous releases of $q_o \text{ m}^3/\text{s}$ we recommend on the basis of Appendix A that the flow will be effectively passive and passive dispersion results may be used when

$$\left(\frac{g_o' q_o}{U_{ref}^3}\right)^{\frac{1}{3}} \leq 0.15$$

where U_{ref} is the velocity at $z = 10 \text{ m}$.

For an instantaneous release of $Q_o \text{ m}^3$ we recommend, also on the basis of Appendix A, that the flow will be effectively passive and passive dispersion results may be used when

$$\frac{(g_o' Q_o^{\frac{1}{3}})^{\frac{1}{2}}}{U_{ref}} = \left(\frac{g_o' Q_o}{U_{ref}^2}\right)^{\frac{1}{2}} / Q_o^{\frac{1}{6}} \leq 0.2$$

where U_{ref} is again the velocity at $z = 10 \text{ m}$.

4. Low/zero wind speeds: previous experiments

	Substance	Field	Wind tunnel/indoor	Instantaneous	Continuous	Flashing jet	Obstructions	Topography	Concentration measured	Ingress	Mitigation
Burro 8	LNG	•			•			•	•		
COOLTRANS	CO ₂	•			•		•	•	•	•	
ENFLO 2000	CO ₂ , krypton		•		•				•		
Hall et al.	BCF, argon		•	•	•		•		•		•
Hoot et al.	Freon/air mix		•		•		•		•		
HSE 1985	CO ₂	•			•				•		•
Jack Rabbit I	Chlorine, ammonia	•			•	•		•	•		
Kit Fox	CO ₂	•		•	•		•		•		
Lathen / BA Propane	Propane	•		•	•	•	•		•		
Maplin Sands	LNG/LPG	•		•	•	•			•		
Porton Down	Freon-12	•		•				•			
Thorney Island	Freon-12/nitrogen mixture	•		•	•		•		•		
URAHFREP	HF, HF/isobutane mix	•	•		•				•		
Wannberg et al	Propylene	•			•				•		

5. Terrain effects: previous experiments

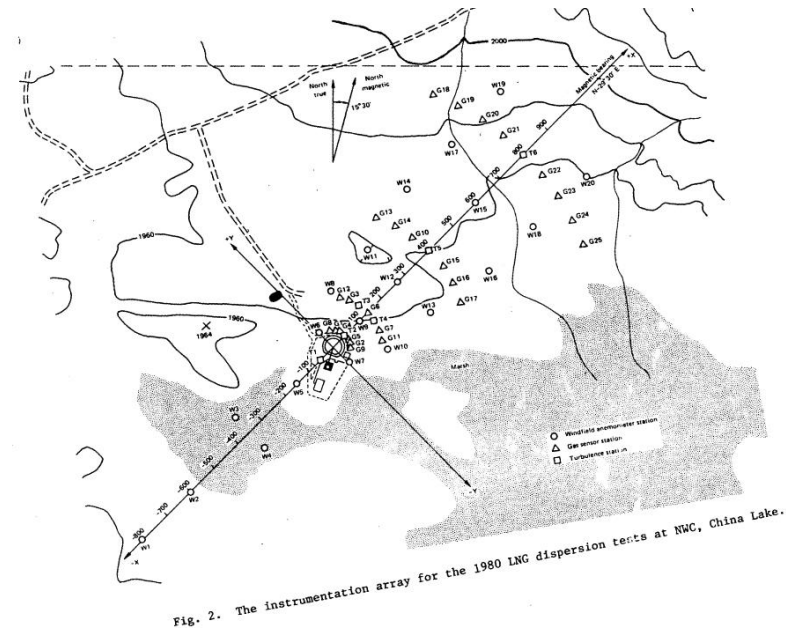
	Substance	Field	Wind tunnel	Instantaneous	Continuous	Flashing jet	Obstructions	Nil/low wind/stable	Concentration measured	Ingress	Mitigation
BA Hamburg	SF ₆		•	•	•		•		•		•
Burro	LNG	•			•			•	•		
China Lake (Meroney WT)	Argon, Freon-12		•				•		•		
COOLTRANS	CO ₂	•			•		•	•	•	•	
EMU-ENFLO	Krypton		•		•		•		•		
Guldemond	Argon		•		•		•		•		
Jack Rabbit I	Chlorine, ammonia	•			•	•		•	•		
Muller	SF ₆		•					•	•		
Porton Down	Freon-12	•		•				•			

Field-scale tests all have limitations:

- Burro: complex evaporating pool source
- COOLTRANS: data not yet fully available, terrain not mapped
- Jack Rabbit I: rainout/absorption into desert playa, only 2 m dip
- Porton Down: no concentration data, just dose

5. Terrain effects: previous experiments

- **Burro (trial 8), 1980**
 - Eight LNG spills of between 24 m³ and 39 m³ onto water at China Lake, California
 - 25 gas sensors at arcs from 57 m to 800 m downwind
 - Terrain downwind of spill pond sloped upward at about 7 degrees for 80 m before levelling out to about 1 degree slope
 - Burro 8: had lightest wind speed of 1.8 m/s with Pasquill Class E, cloud spread upwind and bifurcated downwind, exhibiting terrain effects
 - Koopman *et al.* (1982a,b), Ermak *et al.* (1982)



Source: Koopman *et al.* (1982a,b)

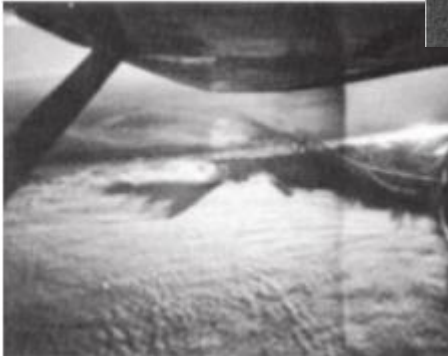
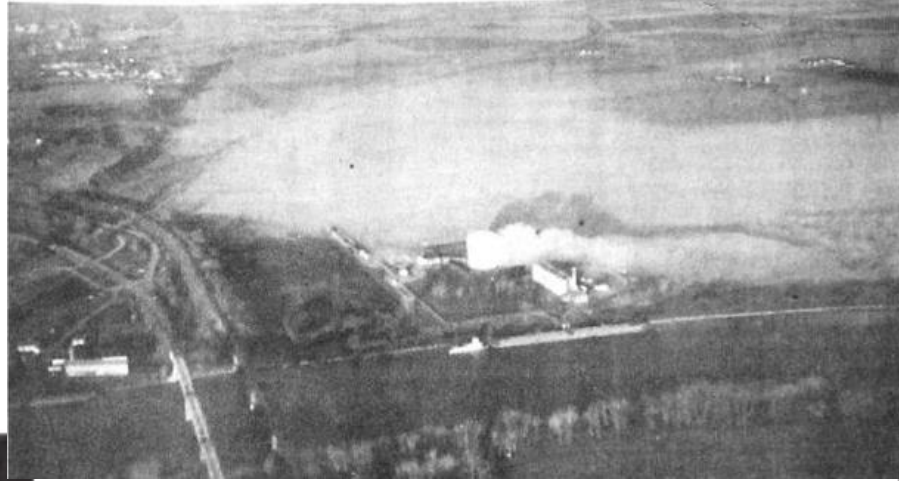
Brief review of ammonia incidents

Ammonia incidents

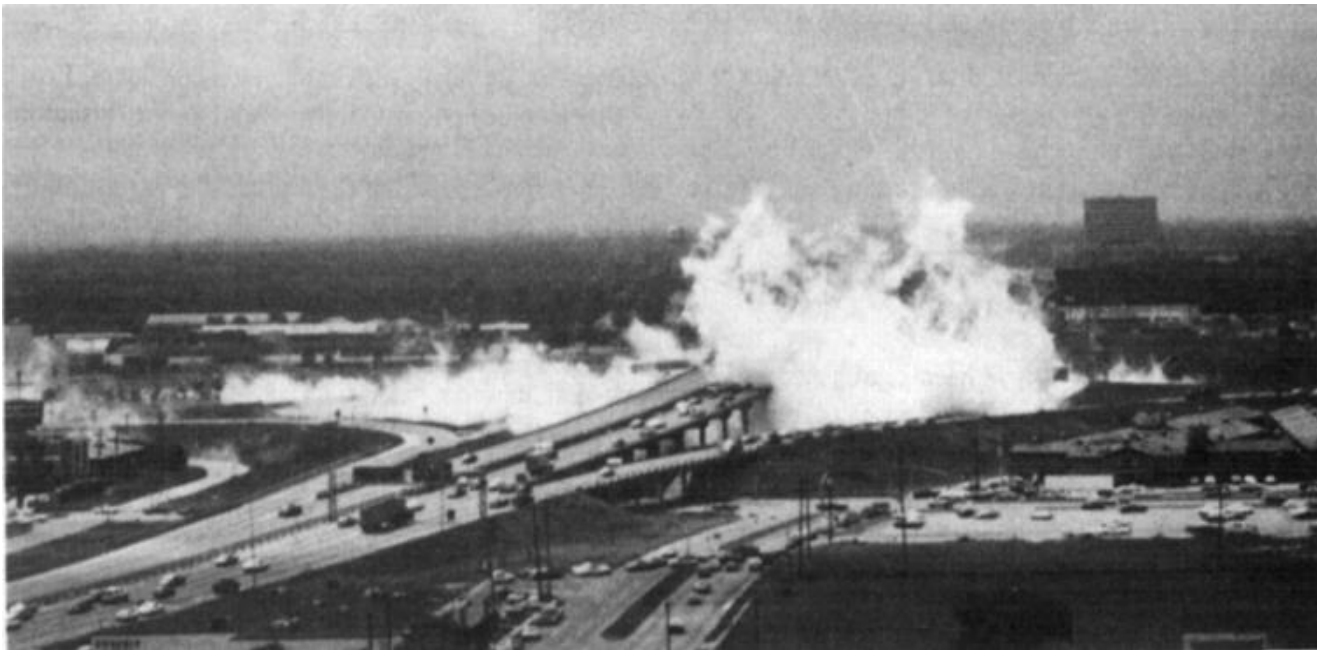
Location	Description	Deaths	Instantaneous	Continuous	Obstructions	Nil/low wind/stable	Mitigation	Previous model comparison	Potential use for model comparison?
Blair, Nebraska	Tank overfilling			•	•	•	•		•
Potchefstroom, South Africa	Partial tank failure and railcar failure	•	•			•	•	•	
McPherson, Kansas	Failed valve closed in pipeline leading to pressure build up			•			•		
Houston, Texas	Tanker fell off freeway	•	•		•	•		•	
Jonova, Lithuania	Liquid ammonia spill, quickly set alight	•		•		•	•		•
Dakar, Senegal	Road tanker overfilled causing vessel failure	•	•				•		
Theodore, Alabama	12" suction pipe fail			•			•		•
Lake County, Illinois	Farm tractor failure, 2 m ³ of liquid ammonia released				•	•	•		•

Also Larvik, Norway (2002): overfilled ammonia tank on farm, 1 death, 10 injured, 130 cattle killed, details limited

Blair, Nebraska, 1970



Houston, Texas, 1976



Lake County, Illinois, 2019



© Beach Park Fire Department, Illinois

<https://www.chicagotribune.com/suburbs/lake-county-news-sun/ct-lns-ammonia-spill-no-charges-st-0626-20190625-ikztowrhfhwhgym3lryjk4v2m-story.html>

With thanks to Sun McMasters (CSAC) for the information

Summary of knowledge gaps exercise for JR111

European Support for Jack Rabbit III

- European contributors asked if they would like to be involved in future Jack Rabbit III trials
 - Each organisation would need to be self-funded

- Provide modelling or wind-tunnel results to support JRIII?
 - 20 organisations said yes
 - ARIA, BAM, CEA, CERC, Demokritos, DSTL, EDF, FFI, FMI, FOI, Gexcon, GT Science & Software, HSE, INERIS, JRC, Mack/Spruijt, Shell, Silvia Trini Castelli, TNO, VKI

- Contribute to technical support group to help review plans and/or analyse results?
 - 17 organisations said yes
 - BP, CEA, Demokritos, DSTL, EDF, FFI, FOI, Gexcon, GT Science & Software, HSE, INERIS, JRC, RIVM, Shell, Silvia Trini Castelli, TNO, VKI

Summary

- Survey of 27 European organisations: government agencies, industry, consultants, academia
- Top five research priorities were:
 1. Two-phase flashing jets
 2. Obstacles (buildings, equipment, vegetation etc.)
 3. Transition from dense-gas to passive dispersion
 4. Low/zero wind speed dispersion
 5. Terrain effects
- Briefly reviewed specific questions, previous experiments and incidents
- More than a dozen organisations keen to provide in-kind support to JR11 trials, e.g. modelling, analysis of data

Tentative Proposal for Some Future Work

- **Proposal:** simulate previous ammonia incidents using different models, similar to the previous analysis of Graniteville, Festus, Macdonna chlorine incidents by Hanna *et al.* (2008)
- **Aims:**
 - To develop experience in modelling ammonia releases
 - To examine common factors in ammonia incidents
 - To see if we get similar over-prediction of casualties to that seen before in the chlorine study

Comparison of Six Widely-Used Dense Gas Dispersion Models for Three Recent Chlorine Railcar Accidents

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Any questions?

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