Dispersion Behavior in Severe Vapor Cloud Explosion Incidents

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Objectives

- **Aim**: to review historical severe unconfined VCE incidents
  - Characterise the events and identify common factors
  - Improve our understanding of vapor cloud development and explosion
- **Motivation**:
  - Public concerns about potential for VCEs at LNG export terminals in USA
  - Recent VCEs at Buncefield, Jaipur, San Juan and Amuay produced unexplained high over-pressures in unconfined, uncongested areas

Buncefield (2005)

Jaipur (2009)

Puerto Rico (2009)

Amuay (2012)

Selection of VCE Incidents

- LNG export terminals handle:
  - LNG (predominately methane) ← Cannot produce severe unconfined VCEs
  - Refrigerants: ethane, butane, propane, ethylene (typically 100,000 US Gal)
  - Condensates: pentane, hexane (typically 500,000 US Gal)
- Only one recorded VCE incident at an LNG export terminal (Skikda, Algeria, 2004)
- Incidents reviewed from other LPG, LNG, gasoline and petrochemicals sites to assess potential VCE risk from refrigerants/condensates at LNG export terminals
- Similar combustion properties for C2-C6 hydrocarbons:

Gas	Laminar flame speed (cm/s)
Methane	40
Ethane	47
Propane	46
Butane	45
Pentane	46
Hexane	46
Heptane	46

VCE Incidents Reviewed

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Brenham, TX, 1992	LPG Storage
Newark, NJ, 1983	Gasoline storage
Big Spring, TX, 2008	Refinery (LPG)
San Juan, Puerto Rico , 2009	Gasoline storage
Skikda, Algeria, 2004	LNG facility
Buncefield, UK, 2005	Gasoline storage
Amuay, Venezuela, 2012	Refinery LPG storage
Jaipur , India, 2009	Gasoline storage
Austin , TX, 1973	LPG pipeline
North Blenheim, NY, 1990	LPG pipeline
Donnellson, IA, 1978	LPG pipeline
Ruff Creek, PA, 1977	LPG pipeline
Port Hudson, MO, 1970	LPG pipeline
St Herblain, France, 1991	Gasoline storage
Geismer, LA, 2013	Petrochemicals
Naples, Italy, 1995	Gasoline storage
La Mede, France, 1992	Refinery (LPG)
Baton Rouge, LA, 1989	Refinery (LPG)
Norco, LA, 1988	Refinery (LPG)
Pasadena, CA, 1989	HDPE
Flixborough, UK, 1974	Petrochemicals
Devers, TX, 1975	LPG Pipeline
Lively, TX, 1996	LPG Pipeline
Ufa, USSR, 1989	LPG Pipeline

Sources:

- Significant national incidents investigated by CSB, NTSB, HSE etc.
- Marsh insurance 100 largest losses

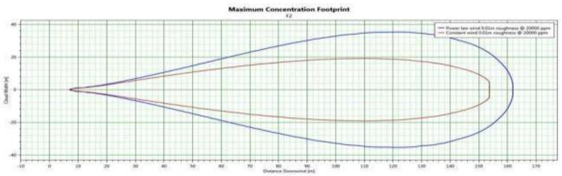
VCE Incidents Reviewed

- Unexpected findings:
  - Majority of incidents showed vapor clouds that spread in all directions around the source
  - Only a few incidents showed a burned area extending solely in the downwind direction

VCE Incidents: Common Factors

Approximate cloud radii shown

Burn patterns do not look like this

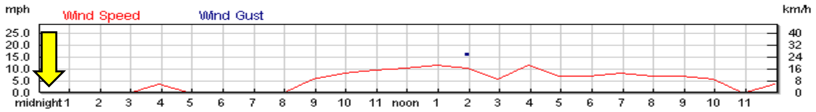


Dispersion in a 2 m/s wind (Pasquill Stability Class F)

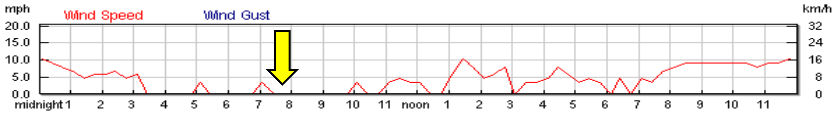
VCE Incidents: Common Factors

Wind speeds measure at nearest met stations

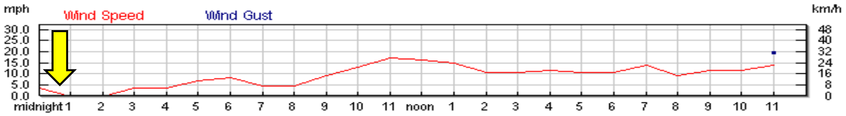
Brenham, Texas (7:00am)



San Jan, Puerto Rico (00:23 am)



Big Spring , Texas



Newark, New Jersey (0:10 am)

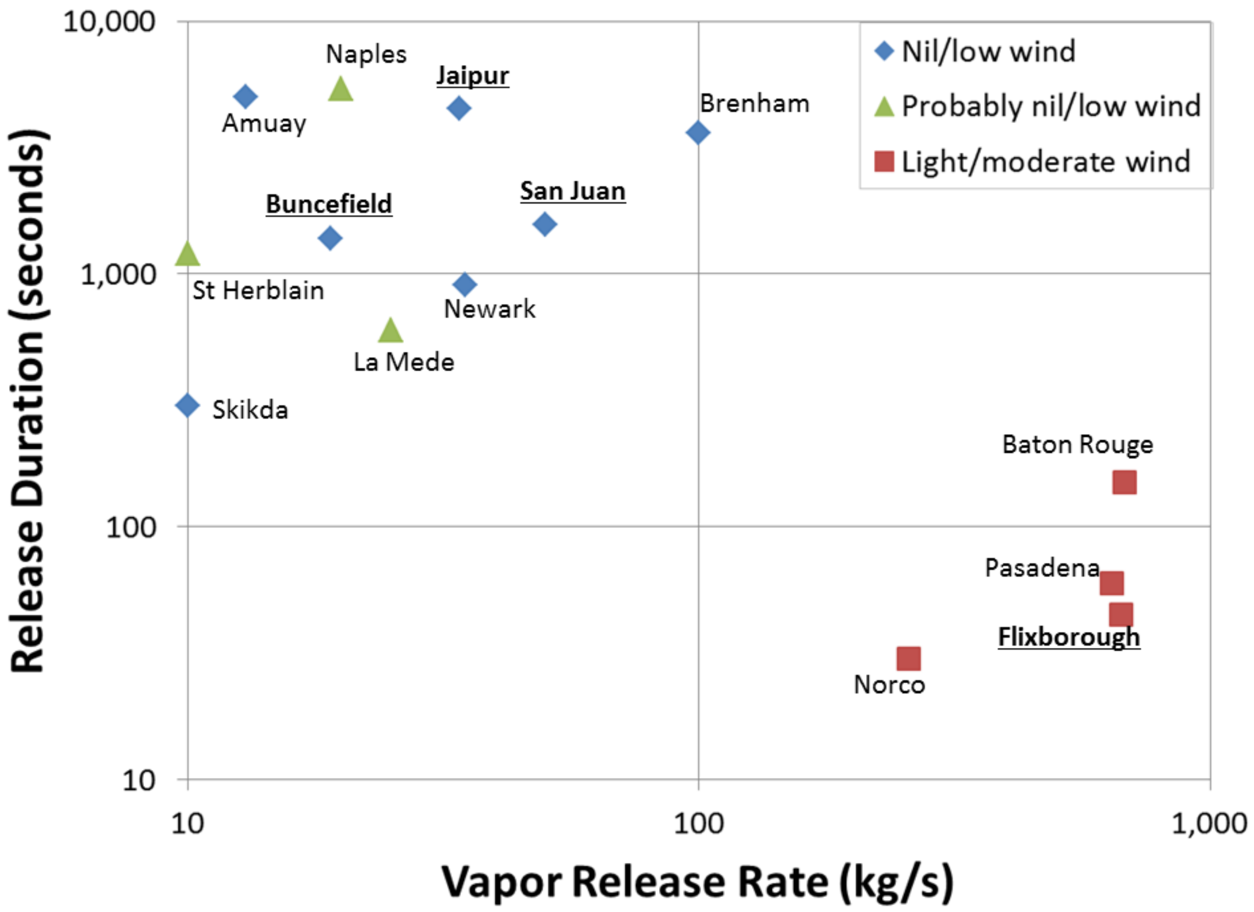
Vapor cloud structure

Dense vapor cloud spreads in all directions around the source in nil/low wind speeds

VCE Incidents: Common Factors

Incidents that occurred in nil/low–wind conditions		Vapor release rate (kg/s)	Duration prior to ignition (s)
Brenham, TX, 1992	LPG Storage	100	3600
Newark, NJ, 1983	Gasoline storage	35	>900
Big Spring, TX, 2008	Refinery	not known	not known
San Juan, Puerto Rico, 2009	Gasoline storage	50	1560
Skikda, Algeria, 2004	LNG facility	~10	<300s
Buncefield, UK, 2005	Gasoline storage	19	1380
Amuay, Venezuela, 2012	Refinery LPG storage	13	>5000
Jaipur , India, 2009	Gasoline storage	34	4500
Incidents that probably occurred in nil/low-wind conditions			
St Herblain, France, 1991	Gasoline storage	~10	1200
Geismer, LA, 2013	Petrochemicals	not known	not known
Naples, Italy, 1995	Gasoline storage	20	5400
La Mede, France, 1992	Refinery	25	600
Incidents that occurred in light/moderate winds			
Baton Rouge, LA, 1989	Refinery	681	150
Norco, LA, 1988	Refinery	257	30
Pasadena, CA, 1989	HDPE	643	60
Flixborough, UK, 1974	Petrochemicals	670	45

VCE Incidents: Common Factors



VCE Incidents: Common Factors

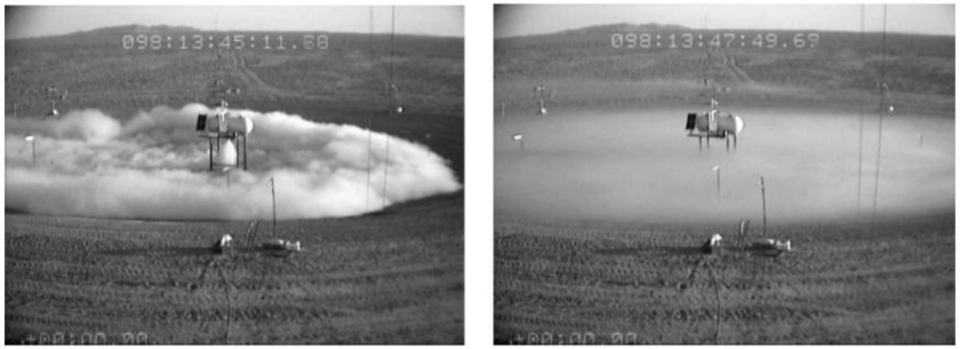
- Possible explanation for trends:
  - Nil/low wind speeds occur less frequently than windy conditions…
  - … but small leaks are much more likely than catastrophic failures
  - Incident sites lacked working gas detection/shutoff systems
  - Limited ignition sources (a large cloud could develop before igniting)

- Questions:
  - What are the characteristics of dense gas dispersion in nil/low wind speeds?
  - What models should be used to predict this dispersion behavior?
  - Should risk assessments account for releases in nil/low wind speeds?

Dispersion Characteristics

- Dense gas clouds become laminar in far field
  - Slow mixing and dilution, nearly uniform concentrations across wide area

Buncefield Incident



Jack Rabbit 1
Trial 2
Wind speed = 0.6 m/s

© DHS Chemical Security Analysis Center (CSAC)

Dispersion Characteristics

- Liquid nitrogen release in very low wind speed

Dispersion Characteristics

- Blast damage also indicates that gas concentrations were nearly uniform (within flammable range) across a wide area
- Uniform damage throughout cloud
- Similar damage across different incidents

Buncefield

Jaipur

Amuay

Test Explosion (1 bar)

Dispersion Characteristics

- Blast damage to empty tanks

San Juan

Jaipur

Buncefield

Amuay

Dispersion Characteristics

- Blast damage to drums

Jaipur

Test (2 bar)

Buncefield

Test (2 bar)

Dispersion Characteristics

- Blast damage to buildings

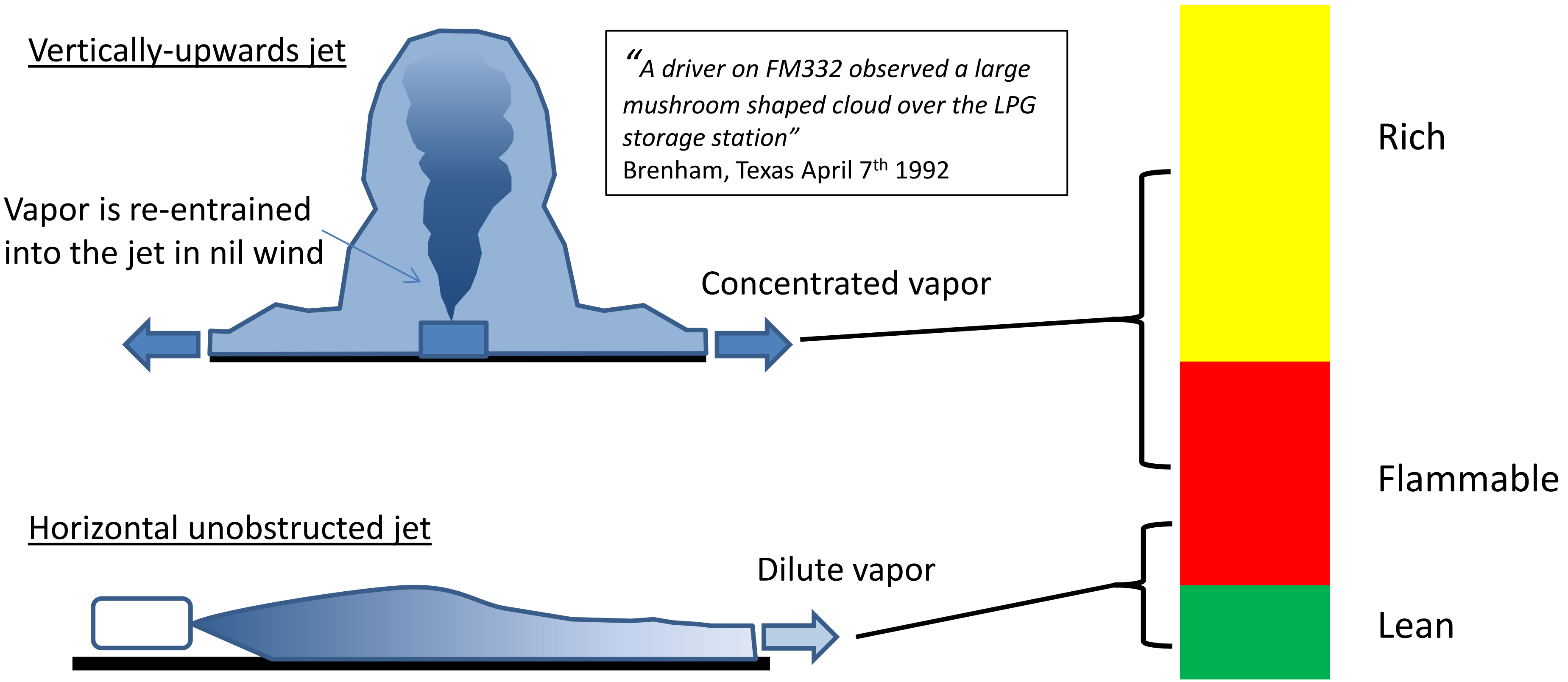
Buncefield

Amuay

Jaipur

Source Modeling Options

- Range of source conditions possible
- Limitation: models usually ignore re-entrainment of vapor



Vertically-upwards jet

> *"A driver on FM332 observed a large mushroom shaped cloud over the LPG storage station"*
> Brenham, Texas April 7th 1992

Vapor is re-entrained into the jet in nil wind

Concentrated vapor

Horizontal unobstructed jet

Dilute vapor

Rich

Flammable

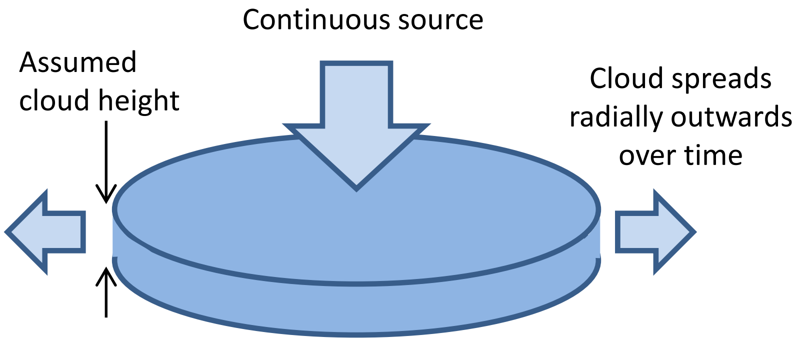
Lean

Dispersion Modeling Options

1. Simple vapor cloud assessment method
2. Integral dispersion models
3. Shallow-layer models
4. Lagrangian particle/puff models
5. Computational Fluid Dynamics (CFD)

Simple vapor cloud assessment method, e.g. FABIG Technical Note 12

http://www.fabig.com/video-publications/TechnicalGuidance



Dispersion Modeling Options

1. Simple Vapor Cloud Assessment method
    - Useful scoping tool that gives results in good agreement with Buncefield and other incidents
    - Makes simplifying assumptions e.g. no dilution, flat terrain, no obstructions
2. Integral models
    - Popular models like PHAST are unable to model nil/low wind speeds
    - Possible to use DEGADIS or DRIFT for nil wind, but only for flat unobstructed terrain
3. Shallow-layer models
    - Good potential, not widely used, further development required (several years?)
4. Lagrangian particle/puff models
    - SCIPUFF and QUIC not currently widely used in oil/gas/chemical process safety industry
    - Useful to investigate further models like SCICHEM
5. Computational Fluid Dynamics (CFD)
    - Able to model dense gas dispersion in nil wind with terrain/obstacles
    - Costly, complicated and user-variability issues
    - Lack of model validation

Possible Future Directions

- Define nil/low wind speed criteria
- Develop/validate source models, e.g. re-entraining two-phase flashing jets
- Simple Vapor Cloud Assessment method
  - Analyse dilution effects and residence time (e.g. Briggs)
- Integral and shallow layer models
  - Validate for low/nil wind and develop models, e.g. HSE GasSplot model
- Lagrangian puff models
  - Assess capabilities of SCICHEM
- Computational Fluid Dynamics (CFD)
  - Validate models and develop best practice guidelines
- Review experimental data for low/nil wind dispersion of dense gas:
  - BA-Hamburg tests: SF_6, sloping terrain in nil wind
  - Porton Down (Picknett *et al*. 1976), freon, wind speed <0.5 m/s at 2m height (Test 8)
  - Jack Rabbit 1, chlorine, wind speed = 0.6 m/s at 2 m height (Test 2)
  - Thorney Island 47, freon/nitrogen, wind speed = 1.5 m/s at 10 m height
  - Burro 8 (LNG), wind speed = 1.8 m/s at 2 m height

Possible Future Directions

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- Vapor Cloud Explosions
    - Lack of consensus among experts on prediction of VCEs in these incidents
    - Evidence shows severe explosion in open, unconfined areas
    - Damage to structures suggests explosions involved high-speed deflagrations, not detonations
    - However, some experts believe there must have been a detonation for a severe explosion in open areas
    - New explosion mechanism?

- Possible experiments
    - **Large-scale tests**:
        - 100m+ radius vapor fence filled with flammable vapor from LPG fountain
        - Study effect of elements that might trigger transition to severe explosion (sheds, pipework etc.)
        - Also useful for LPG source terms and low wind dispersion - both urgently needed

    - **Small-scale tests**:
        - Detonation tests on columnar objects (struts, small pipes, etc.)
        - Fundamental studies of the fluid mechanics of flow driven by a localized explosion - boundary layer detachment and roll up, lofting of particles etc.

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