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A review of very large vapour cloud explosions: Cloud formation and explosion severity

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ABSTRACT

This paper presents a review of Vapour Cloud Explosions (VCEs) to examine:

1. The relationship between weather conditions, source term and development of the flammable cloud.
2. The consequences of explosion in clouds with higher reactivity than methane.

The review identified that sustained small leaks in low wind conditions are associated with very large clouds and higher likelihood of ignition leading to a severe VCE. The examination of primary data from several LPG and gasoline incident investigations showed that in many cases severe overpressure effects extended to a high proportion of the cloud: damage was not confined to areas where there was congested pipework or vegetation. The analysis also suggests that radiation effects may be the key to understanding the explosion mechanism in many incidents.

The paper concludes with a discussion of how the new data on vapour cloud explosions that has become available over the last ten years may affect risk assessment and emergency planning in the future.

1. Introduction

A total of 24 incidents were selected for review with the assistance of PHMSA's independent consultants. Vapour cloud explosions were selected if

1. They were the subject of journal papers or high quality reports by national authorities.

Or

2. They appeared in the Marsh list of the 100 largest losses 1974–2013 (Marsh, 2014).

The explosion and fire at Min Al-Ahmadi (Kuwait) in 2000 appears on the Marsh list but was not included in the final review as insufficient data was available on the leak, vapour cloud or damage.

All of the vapour cloud explosions (LPG pipeline failures with delayed ignition) that were identified by Casella (2002) were also reviewed in detail.

The review collected data in the following areas:

1. Substances (gasoline, LPG, hydrocarbons used as refrigerants);
2. Source term (e.g. tank overfill, sprays, seal failure, hole size and release pressure);
3. Release size (duration of release, inventory);
4. Weather conditions (wind speed, stability);
5. Near field dispersion – especially the formation of a low entrainment, gravity-driven flow;
6. Cloud development (footprint, depth and influence of topography and surface roughness);
7. Explosion severity (flame speed and overpressure, distance of flame travel);
8. Blast damage to plant and other structures within and outside the cloud footprint;
9. Harm to on- and off-site personnel;
10. Information about the facility:

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   a. Location (latitude/longitude), characteristics (ports, urban, rural, industrial, etc.);
   b. Maps of facility showing the property and surrounding area;
   c. Category of facility (possible categories - refineries, petrochemical, gas processing, terminals and distribution and upstream), description of facility;
   d. Number of similar facilities in the world;
11. Information about the incident and the engineering practices at the site:
    a. Description and cause of the release (e.g. operator error, equipment malfunction, material failure, construction or design error, weld failure)
    b. Mitigation measures in place and their effectiveness

An additional objective of the review was, where possible, to make publicly available more detailed primary records of what happened in the incidents. These records include photographs of the aftermath and any video records of cloud accumulation and explosion. Four electronic multimedia packages have been prepared to allow wider access to primary data from the incidents at Buncefield (Buncefield Major Incident Investigation Board, 2007), Jaipur (MoPNG Committee, 2010), Flixborough (Flixborough Court of Enquiry (1975)) and San Juan (CSB, 2015). The authors are indebted to the Chemical Safety Board (CSB) for making available a large amount of data from their investigation at San Juan.

2. Findings on vapour cloud formation

The incidents reviewed are listed in Table 1; this table also includes information about the rate at which hydrocarbon vapours were added to the cloud and the time between the start of the release and ignition. The data in Table 1 have been classified according to the wind conditions at the time of the release. This wind data comes from meteorological records and analysis of the cloud shape. For example, cases where the cloud spread in all direction around the source to a roughly equal extent are presumed to correspond to very low wind speed conditions.

It is notable that the incidents studied fell into two distinct groups:

1. Large releases (>250 kg/s) in light or moderate winds. These catastrophic releases were ignited rapidly as vapour was convected downstream – typically within 100 s.
2. Smaller releases (<100 kg/s) in very low or nil wind conditions. These smaller releases accumulated over longer periods – typically several hundred or thousands of seconds. Vapour typically flowed away from the source in all directions – driven by gravity (Fig. 1).

The large proportion of incidents (71%) that corresponded to relatively small leak rates and accumulation of vapour in very low

Fig. 1. CCTV image of the vapour cloud at Buncefield - well away for the source. The flat upper surface indicates a laminarised flow at the top of the current.

Table 1
Summary of vapour transport conditions in the incidents reviewed. (mass release rates/durations included for non-pipeline failures – where known).

Incidents that occurred in nil/low–wind conditions		Vapour release rate (kg/s)	Duration prior to igniton (s)
Brenham, TX 1992	LPG storage	100	3600
Newark, NJ 1983	Gasoline storage	35	>900
Big Spring, TX 2008	Refinery	not known	500
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	67	4080
Jaipur, India 2009	Gasoline storage	34	4500
Austin, TX 1973	LPG pipeline		
North Blenheim, NY 1990	LPG pipeline		
Donnellson, IA 1978	LPG pipeline		
Ruff Creek, PA 1977	LPG pipeline		
Incidents that probably occurred in nil/low-wind conditions			
Port Hudson, MO 1970	LPG pipeline		
St Herblain, France 1991	Gasoline storage	not known	1200
Geismer, LA 2013	Petrochemicals	not known	
Naples, Italy 1995	Gasoline storage	20	5400
La Mede, France 1992	Refinery	25	600
Incidents that occurred in light or 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
Devers, TX 1975	LPG pipeline		
Lively, TX 1996	LPG pipeline		
Ufa, USSR 1989	LPG pipeline		