November 2015

SAPHEDRA - Building a European Platform for evaluation of consequence models dedicated to emerging risk

List of experimental campaigns and information available to be used to evaluate existing tools or new tools

S A P H E D R A

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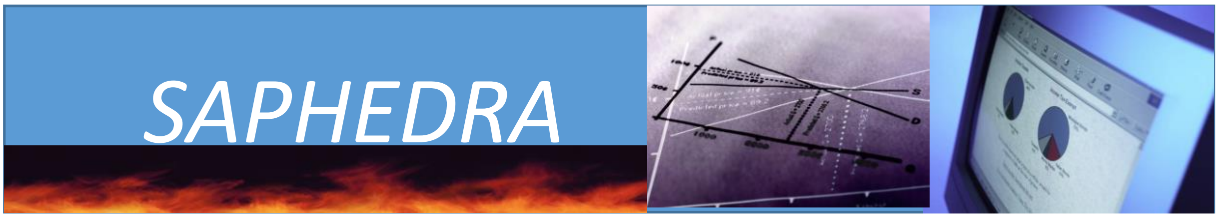

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1 Introduction

Work package 4 of the Saphedra project, “Building a European Platform for evaluation of consequence models”, is aimed at an identification of existing experimental campaigns for the validation of the tools for consequence modelling identified in WP1 of this project. On the basis of the classification into various phenomena proposed in WP 1, the identified experimental campaigns will be described in the following.

The following chapter contains a description of experimental campaigns associated to typical phenomena resulting from the release of hazardous materials. The results of the analysis of these experimental campaigns is then summarised in form of a spreadsheet. This spreadsheet is to be seen as an integral part of the report of WP4.

2 Classification of experimental campaigns in the families of phenomena

In this chapter a short overview of experimental campaigns is given, that provide experimental data for each of the identified phenomena. A more detailed description of the campaigns is then given in the following chapter.

2.1 Families of phenomenon as defined in WP1

In WP1 the typical consequences to be assessed in consequence modelling have been divided into 4 main phenomena. As the experimental campaigns presented here are intended for the validation of the consequence models identified in WP1, the same classification will be used. The 4 main phenomena categories and their subdivisions are:

1. Release
    - liquid
    - gaseous
    - pressurised liquefied
    - flash and evaporation
2. Fire
    - jet fire
    - pool fire
    - fire ball
    - flash fire
    - warehouse fire
3. Explosion
    - pressure vessel burst
    - vapour cloud explosion
4. Dispersion
    - jet release
    - light gas or neutrally buoyant
    - heavy gas

The further subdivision of these families as proposed in WP1 is also mainly used. Especially for the Dispersion category a slightly different subdivision has been done for the experimental campaigns, as the criteria used in WP1 are directly related to the different (mathematical) type of models, which is not relevant in the experimental campaigns. Nevertheless the main physical phenomena standing behind the subdivision of WP1 can also be found here. Other than for the consequence models which have clearly defined affiliation to each family and subcategory, some of the experimental campaigns can be found in more than one category. This is due to the fact, that some of the phenomena of interest can be investigated in one and the same trial. For example, the release of gas can be combined with the gas dispersion and a subsequent ignition of the formed gas cloud, so that one experimental campaign would be found in at least three categories.

2.2 Release

According to the classification adopted in this project, a total of 18 experimental campaigns have been identified as release experiments.
The release of liquids has been investigated in 9 experimental campaigns conducted mainly in the 1970's and 1980's. The substances released in these experiments vary from Water, Hydrocarbons, Chlorine and Refrigerants. Considering only the released substances it is clear that releases under ambient conditions will already cover the whole range from pure liquid release to two phase flows. Experimental campaigns of Fauske (1965) dealt with the discharge of saturated water from tubes resulting in a liquid / two-phase discharge, as the saturated Water will begin to vaporize at the moment it's exposed to ambient pressure. Similar experiments were conducted by Fletcher (1984), where the refrigerant R11 was released through orifices and pipes, leading also to a liquid / two-phase release.
The work of Fletcher investigating the release out of tubes and orifices covers the two main fields of interest when talking about liquid source terms, as the main reasons for the accidental release of a liquid are either the occurrences of leaks (represented here by orifices) or the rupture of pipings/failure of shutdown valves (represented here by the outflow from pipes). The investigation of liquid releases through leaks can hardly be done, as the shape and properties of each leakage are very specific and mainly unknown. Therefore, as most of the source term models are based on assumptions and findings from the investigation of the flow through nozzles, a lot of release experiments have been carried out with nozzles. Sozzi and Sutherland (1975), Boivin (1979), Lee and Swinnerton (1983), Simoneau and Hendricks (1984) as well as Veneau (1995) carried out investigations on the discharge from nozzles. While the first three investigated the behaviour of critical and subcooled Water leading to a two-phase flow, Simoneau and Hendricks investigated Methane and Nitrogen as cryogenic releases and Venau used Propane for his experiments.
Other release experiments dealt with the flashing release of liquids and the fraction of liquid that will rainout. Johnson and Woodward (1999) carried out such aerosol release experiments with Water, CFC-11; Chlorine, Methylamine and Cyclohexane. Allen (1998a, 1998b) measured the velocity profiles (1998a) as well as the droplet size repartition (1998b) in two-phase flashing propane jets using a laser-based non-intrusive measuring technique.
A very special case of liquid releases was covered by the experiments of Dodge (1980) who investigated the release of liquid Isopropyl alcohol, Methylchloride and Isopentane from a submerged vessel, covering the scenario of a sunken tanker.

McIntosh (1995) investigated the gaseous release of water from a dump tank used to separate gas and liquid phase. Unfortunately experiments aimed at simply defining the source term of a gaseous release are not easy to find. This might certainly be due to the fact that the more interesting in gaseous releases is the dispersion of the gas cloud. Therefore gas release experiments are mainly conducted for the aim of evaluating the gas dispersion and in these cases a fixed mass flow is given or measured but generally with no respect to the orifice geometry. For substantial validation data sets for the gaseous source term, it would be necessary either to identify more experimental series investigating the gaseous release, or to try to extract from the dispersion experiments the information about the source term and try to use these data as validation data. The case of pressurised liquefied outflow is actually not covered by any specific experimental campaign. Nevertheless it is covered in the gas dispersion experiments (release of LNG for example) as well as in the liquid source term experiments when releasing substances that are supercritical under ambient conditions.

After the release of a liquid the formation of a pool can occur or the liquid will flash. Okomato (2010, 2012) investigated the evaporation of liquids from a small scale / lab scale pool with a surface of 0.1 m². In the experiments of Fingas (1997, 1998) comparable pool sizes from 139 mm diameter up to 0.015 m² were investigated. Whilst most of the evaporation experiments deal with pure substances, these two experimental campaigns investigated the evaporation behaviour of mixtures from different hydrocarbons and organic solvents. Okomato investigated the evaporation in absence of wind, whilst Fingas carried out tests with and without wind. One of the most well-known experimental series is the one of Mackay and Matsugu (1973), where the evaporation of cumene and gasoline was investigated in pans of 1.5 m² and 3 m² under outdoor conditions. These experiments were used to formulate a new Evaporation model, the Mackay/Matsugu model. Feldbauer et al. (1972) investigated the spill of LNG on water and its behaviour during vaporization and the subsequent gas dispersion for pools under atmospheric conditions and with sizes up to 14 m diameter. Comparable test series were done by Puttock, Blackmore and Colebrander (1982) in the Maplin Sands experiments, where LNG and Propane were spilled in dyked areas resulting in a pool radius of approximately 10 m.
The release of substances like LNG under ambient conditions will not only form a boiling pool, but a considerable part of the released mass flow will directly form a gas cloud due to flashing of the liquid. Pettitt (1990) explicitly concentrated on the flashing release by shattering glass spheres filled with Freon 11. Comparable tests with glass spheres were done by Schmidli (1992) who released R114, R12 and propane. Maurer et al. (1977) also conducted tests with near instantaneous flashing release of Propylene from bursting tanks. But the aim of these experiments was more to determine the resulting gas cloud size and not characterize the source term. Eventually the gas clouds were ignited, so that this test campaign covers more than one phenomenon category.

2.3 Fire

2.3.1 Jet fire

In 1987 Cook et al. (1987) published their work on jet fires. At the Brithis Gas Spadeadam Test site, 57 experimental series were carried out with LNG. The Test site provided a 100 x 100 m concrete platform, in the center of which the flares were installed, so that building influences on the wind field could be excluded. In these series release rates up to 89 kg/s were carried out, resulting in flame lengths of up to 90 m. In these tests subsonic and sonic releases were investigated. Data on the size, shape and radiation characteristics have been obtained.

Bennet (1991) carried out large scale experiments also at the Spadeadam test site with LPG and LNG with mass flows up to 55 kg/s and resulting flame lengths of 50 m. In these experiments, the incident radiative flux as well as the SEP was measured.

Acton and Ewans (1996a, 1996b) investigated unconfined horizontal oil and gas jet fires in 12 experiments. Herein 6 free jets with exit pressures of 7 and 20 bar were investigated as well as 6 jets impinging on a wall situated at distances of either 9 m or 15 m. The released substances were pure oil with mass flows of 5 kg/s and a mixture of gas and oil with respectively 1-2 kg/s and 4-3kg/s. Flame lengths and surface emissive power were recorded as well as video recordings of the flame behaviour.

Chamberlain et al. (2008) investigated 15 confined jet fires with condensate fuel (except for 1 test where propane was used) with mass flow rates of 0.3 to 1 kg/s in test rigs of 135 m^3 and 415 m^3. The rigs were equipped with different targets and the jet orientation was varied between horizontal and vertical. The objective of the tests was to understand the influence of vent size and location, release nozzle height, release pressure and deluge.

2.3.2 Pool fire

Mudan and Croce (1995) have carried out pool fire tests on water and on land. They spilled LNG, Gasoline, JP-4, JP-5, Kerosene, UDMH, Ethylene and pentane leading to the formation of pools with diameters up to 80 m. From these experiments they derived experimental correlations for the flame modelling.
Raj (2007) reviewed a series of 11 tests on pool fires with LNG on Water and on Land with diameters up to 35 m. Koseki (1989) gives an overview of several large pool fire experiments with diameters up to 20 m and reported for these tests the measured flame characteristics as a function of the pool diameter. A special case of pool fires was covered by Tewarson (1972a, 1972b) who investigated the behaviour of flames in enclosures. He tested solid materials arranged in a pool fire like shape (Tewarson 1972a) as well as ethyl-alcohol and paraffin oil fires. The

main aspect investigated was the influence of ventilation on the fire and flames.
Chamberlain et al. (2008) studied the effect of confined pool fires in 7 experiments in test rigs of 135 m³ and 415 m³ equipped with varying targets. The investigated pool sizes varied from 6 to 24 m² and the derived burning rates from 0.22 kg/s up to 1.6 kg/s. The objective was to test the effect of vent size and deluge.

2.3.3 Fire ball

During the INERIS Tet’s (Duplantier 2013) which mainly aimed at boil over phenomena the formation of fire balls were observed and recorded. Whilst “classic boil-overs” didn’t lead to the formation of a fire ball, this was observed for the “thin-layer” boil over for the substances diesel and domestic fuel hydrocarbon, whereas for kerosene no fire ball was formed. The observations lead to the conclusion that only fuels with a high viscosity are able to form a fire ball.

Roberts, Gosse and Hawksworth (2000) conducted tests on 2 ton vessels filled with different amounts of LPG. In the test series the vessels were engulfed in a jet fire until they failed in a BLEVE. The scope of these tests was to investigate the formation of fireballs as a consequence of a BLEVE and to determine the hazards related to the radiation out of the fireball.

2.3.4 Flash Fire

INERIS Tests (Duplantier 2013) investigating the boil over phenomenon were conducted in ponds of 30 – 60 cm diameter with fuel masses between 1,5 kg and 6 kg. The radiation heat, flame length and burning time were recorded.
Raj (1979) investigated in the China Lake experiments in a series of 16 tests the ignition of a gas cloud resulting from the spill of LNG on water forming an evaporating pool. The spills ranged from 3 to 5 m³ in 30 to 250 s. The Gas cloud was then ignited in 70 m distance to the spill point and the flame formation and fire propagation was investigated.
Butler and Royle (2001) investigated the release of 2 – 5 kg/s LPG and the subsequent cloud formation. This cloud was then ignited and the concentrations of the gas cloud as well as the resulting heat fluxes from the fire recorded.

2.3.5 Warehouse Fire

The Flumilog Project (Flumilogxx) dealt with experimental tests aiming at feeding a new calculation method and involved 9 medium-scale set-ups (12 x 8 m² cell of 3.5 m height) and one large scale set-up (36 x 24 m² and 12 m). Temperature and radiative heat flux measurements were taken for each test. The final full-scale test was undertaken in a warehouse-like building manly composed of a steel structure and containing wooden pallets. Wall collapse, flame height and smoke plume were also observed and filmed.

2.3.6 Solid Fires

Experiments on fires with solid fuels were conducted by Thomas (1963) with spruce wood as fuel. The mass of fuel and design of the crib were varied to find a correlation with the mass rates of burning. The influence of wind speed on the fire was also investigated. From these experiments, Thomas derived experimental correlations between flame height and the mass flow rate.

Lönnermark and Ingason (2005) studied the effects of fires in tunnels. For these investigations heavy goods vehicles loaded with fuels of cellulose and plastic were burnt in 4 test series in a tunnel. The heat release rates and temperatures were measured and reached peak values of respectively 202 MW and 1365°C.

2.4 Explosion

2.4.1 Pressure vessel burst

Baum (1999, 2001) conducted test series on a pressurised cylinder filled with water. Aim of the experiments was to investigate the behaviour of a pressurised cylinder in case of failure of the end cap. One part of the tests investigated the fixed cylinder propelling the end cap. In these tests the hazard of flying debris was simulated by the end cap was investigated. The other part of the tests investigated the case, that the whole cylinder is propelled by the burst and transformed in a "missile". The burst pressures lay around 80 – 90 bar.

Johnson and Pritchard (1990) investigated BLEVE's (Boiling Liquid Expanding Vapour Cloud Explosion) of LPG in 5 tests on Vessel volumes between 5,6 and 10,8 m³. While classic BLEVE's occur when a vessel is heated to a point that it's structure will fail due to the increasing inner pressure rise caused by the heating of the substance inside, the failure in these experiments was caused by the ignition of an explosive charge at defined locations of the vessel. The vessel was heated, so that the LPG could build up a substantial vapour phase. The ignition of the released LPG was done with three lances in the vicinity of the Vessel.

Birk et al. (1997) investigated BLEVES of propane in horizontal vessel with volumes of 300 and 375 l. A total of 11 tests were carried out on vessels with design pressures from 17 to 21 bar and wall thicknesses of 5 and 6 mm engulfed in a combination of jet fire and pool fire.

In the JIVE project Roberts (1995) studied 4 catastrophic failures of Vessels filled with varying amounts of propane. These vessels engulfed by a jet fire failed causing a BLEVE. Although this experimental series mainly aimed at investigating the formation and effects of the resulting fireballs, data relevant for the assessment of BLEVE's were also collected, as there is: time to failure, pressure at failure, wall temperatures.

Melhem, Croce and Abraham (1993) investigated the effects of BLEVE in 6 tests on propane filled vessels engulfed in a jet or pool fire. The vessels were of 1,9 m³ volume and filled with varying loads of propane throughout the experiments. The projection distances of fragments as well as the overpressures due to the BLEVE were recorded besides the time to failure.

In 1999 the federal institute for materials research and testing conducted a real scale test of BLEVE on a railroad tank with 45 m³ volume (Balke 1999). The tanker was filled to 22% with liquid propane and exposed to a pool fire of fuel. The temperatures inside and outside the tank, the wall temperatures as well as all relevant pressures were recorded. The effects of the BLEVE due to the emitted heat and the generated overpressure were recorded with radiation sensors and pressure sensors in the surroundings.

Stawczyk (2003) aimed at investigating the failure process of vessels during BLEVE's. He investigated propane cylinders with 5 and 11 kg charge and recorded the inner temperatures and pressures, the wall temperature and the temperature in the ambient as well as the overpressure after the vessel failure. As the aim was mainly to investigate the failure process, different liquid levels as well as different vessel positions (lying, standing) were investigated.

2.4.2 Explosions

A number of campaigns dealing with explosions investigated the so called VCE (Vapour Cloud Explosion) resulting from igniting a gas cloud. If this cloud is in an unconfined area the phenomenon is called UVCE (unconfined vapour cloud explosion), although it is reported that it is very unprobable that after igniting an unconfined vapour cloud an acceleration of the flames will occur in such manner that an explosion will be the result. Most experimental series deal with confined VCE.
Visser and de Bruijn (1991) investigated the flame propagation in diverging channels. The channel was wedgeshaped with alength of 2 m and a height of 0,25 m. An angle of 45° was chosen to give space in the diverging channel for a full expansion process.

Van Wingerden (1988) investigated the flame propagation in a partially confined area between two plates but with the influence of turbulence inducing elements. 0.08 m diameter cylindrical objects were placed in the path of the flame to serve as obstacles.

Harrison and Eyre (1987) investigated in a pie shaped segment the ignition of a heavy gas cloud at larger scales. The confined space was 30 m long, 10 m high with an opening angle of 30° representing a total of 4000 m³. In these experiments different blockage ratios were investigated and their effect on the flame propagation of Propane and LNG.

Hjertager (1993) carried out tests of the flame propagation of Methane and Propane gas clouds in a corner shaped space of 3 x 3 x 3 m filled with different configurations of cylindrical obstacles.

Mercx (1993) investigated in the MERGE Project the influence of gas mixtures of methane and Hydrogen with air on the explosion strength in an obstructed area. The experiments covered three different scales and obstruction configurations.

Van den Berg and Versloot (2003) used the same obstacle configurations as in the MERGE Project. The aim was to identify a Factor SD (standing for "some Distance") related to the overpressure occurring in a so called "acceptor region" when the "donor region" where the gas cloud was ignited is SD away. The Tests dealt with different blockage ratios of the obstacles as well as with different gas mixtures of air with Ethylene, Methane and Propane.

Johnson et al. (1997) (also described in the overall report of Selby, Burgan 1998) investigated in a series of twelve full scale hydrocarbon explosion experiments different obstacle densities, confinements and ignition positions for two different geometric configurations. A maximum overpressure of 4 barg was assumed for the design of the test rig with dimensions of up to 8 m height, 12 m width and 28 m length.

2.5 Atmospheric dispersion

2.5.1 Neutrally buoyant or light gas dispersion

For the dispersion of neutrally buoyant or light gases, the main experimental campaigns all deal with the release and measurement of tracer gases as SF6 and SO2. Whilst some of them adress the release near ground on flat terrain, others deal with the elevated release from as stack on flat terrain and in an urban topology. The most well-known series is certainly the Prairie Grass trials conducted in 1958 (Barad 1958). 68 releases of SF6 with mass release rates up to 0,1 kg/s were carried out on a flat terrain for a release height of 0,46 m. The concentrations were measured along arcs up to a distance of 800 m in 1,5 m height. Round Hill trials cover the release of SO2 with up to 0,11 kg/s from a source 0,3 m to 0,5 m over ground and with measuring distances up to 200 m at a height of 2 m. The Kincaid release experiments (Browne et al. 1983) cover the release of SF6 and SO2 from an elevated source at 187 m in flat terrain. Whilst most trials have sampling durations of several 10 minutes, in these experiments the measuring time was 150 h with measuring distances up to 50 km.
Disperion in an urban topology is copvered by the test series of Copenhagen (Gryning, Lyck 1984), Indianapolis (Murray, Browne 1988) and Lillestrom (Oelsen, Chang 2010). The gas released in these experiments was SF6 as tracer gas. The measuring distances were respectively 6 km, 12 km and 1 km. Whilst the release in the Copenhagen (10 experiments) and Lillestrom (170 experiments) trials

occured from an elevated source (115 m and 84 m respectively) the Lillestrom release was close to the ground.
The MUST trials (Bitloft 2001) dealt with the release of Propylene as tracer gas in 37 experiments. The topology was mocked up to resemble an urban topology by placing shipping containers as obstacles on the test site. Measuring distances were up to 150 m with a release rate of 150 – 225 l/min.

2.5.2 Heavy gas dispersion

The dispersion of heavy gases has been studied in the wind tunnel and in free field trials.

Schatzmann, Marotzke, Donat (1991) released SF6 in wind tunnel experiments with various artificial roughness configurations and derived from these experiments a guideline to calculate the heavy gas dispersion.

Havens and Spicer (2005) also carried out wind tunnel experiments with CO2 as heavy gas over artificial roughness with a release rate of 33 l/min. A model of an industrial tank in a dike at 1:150 scale was also placed in the dispersion area and its influence on the gas dispersion was investigated.

The DRI/WIR/EPA CO2 trials (Briggs 1995) dealt with the release of CO2 mixed with SF6 as tracer gas. The release took place on a field without obstacles for release rates of up to 1,6 kg/s, a maximum released mass of 172 kg and with maximum measuring distances of 100 m.

The Kit Fox Series (Coulombe et al. 1999) also investigated the release of CO2 under atmospheric conditions in a free field environment. It is a continuation of the previously mentioned DRI/WIR/EPA series. This time the release rates ranged from 1,5 kg/s to 4 kg/s and obstacles were placed in the dispersion area. A maximum of 1,7 tons was released and the measuring distance was up to 225 m.

Burro Series (Koopmann et al. 1981) aimed at measuring the heavy gas dispersion resulting from the spill of LNG on Water. The release rates varied in nine tests from 10 – 20 m³/min and a maximum released amount of 24 to 39 m³. The measuring distance was up to 1 km from the source location.

Coyote Series (Goldwire et al. 1983) had the same experimental setup than burro series and aimed not only at investigating the dense gas dispersion but also the vapour burn and RPT explosions. A maximum of 28 m³ was released in 10 experiments with a release rate of up to 19 m³/min. The maximum measuring distance was 500 m.

Desert tortoise (Goldwire et al. 1985) dealt with the release of ammonia through a nozzle close to the ground with release rates of 7 to 12 m³/min throughout 4 tests. The experiments took place in dried out lake called Frenchman flat. Although intended to be a release on land, during the experiments rain caused the test site to be partially covered with a thin water layer for the first test but the test site totally dried until the fourth test. The concentration measurements were carried out up to a distance of 800 m whilst also temperature measurements of the gas cloud were done up to a distance of 9 m from the source. The maximum amount released was 28 m³.

Eagle series (Koopman et al. 1983) investigated the release of Ni2O4 at release rates of up to 1,4 m³/min also at the location of Frenchman flat. A total maximum of 4.2 m³ were released. A total of 6 tests were carried out, but only the first four were intended for dispersion purposes. The last two tests were used to test a Foam vapour suppression system. Besides the gas dispersion the tests also investigated the evaporation rates as a function of the pool size and wind speed. The concentration measurements were carried out in a distance of 785 m from the spill point.

Falcon Series (Brown et al. 1990) is a collection of 5 large scale tests on the gas dispersion from the spill of LNG on flat terrain (Frenchman flat). The tests aimed at evaluating vapor fences as a mitigation tool for dense gas clouds. The spills were carried out on a water pond and reached a maximum amount of 63 m³ LNG with release rates up to 30 m³/min. The vapour fence was installed directly around the spill area and had a height of approximately 9 m. The measuring distance was 250 m from the spill point.

Goldfish Series (Blewitt et al. 1987) consisted of 6 test series. 3 of them were used to test the effectiveness of water sprays as mitigation measures. The substance released was Hydrogen Fluoride with mass flows ranging up to 28 kg/s and a maximum total mass released of nearly 4 tons. The maximum measuring distance was 3000 m.

Thorney Island (McQuaid, Roebuck 1985) dealt with the investigation of instantaneous and continuous gas releases of Freon and N2. The instantaneously released volume was 2000 m³. The continuous releases were carried out with release rates up to 250 m³/min. The maximum measuring distance was 600 m. The experiments took place on an airfield, which was considered as more or less flat mostly neglecting the existing buildings, as they were not positioned within the dispersion corridor.

FLADIS (Nielsen, Ott 1996) covered the release of Ammonia with release rates of 0,25 - 0,6 kg/s in a flat terrain. The concentrations were measured in the near field (20 m) and up to a distance of 235 m.

Maplin Sands (Puttock, Blackmore, Colebrander 1982) dealt with the spill of LNG and Propane with release rates of up to 5,6 m³/min. The release was over water but within a dyked area. A maximum of 20 m³ was released and the concentrations were measured up to a distance of 500 m.

2.5.2.1 Jet release

Jet release experiments were mainly carried out in wind tunnels, as the effort for real scale experiments is considerable. Birch (1984) conducted tests on jet releases of sub- and supercritical Natural Gas and Ethylene in absence of wind. The aim was to collect validation data for the pseudo-diameter theory at high release pressures (up to 70 bara). Hoehne and Luce (1970) studied the behaviour of mixtures of Methane, Ethane, Butane and Heptane in cross-wind flow in a wind tunnel. In these experiments the flow was only laminar and not similar to the atmospheric boundary layer. Schatzmann and Snyder (1991) studied the release of heavy gases, with densities from 2 – 6 kg/m^3, in a boundary layer wind tunnel. They investigated jet releases in cross wind for laminar and turbulent flows for three different roughness settings. Donat (1996) based on the work of Schatzmann and Snyder and carried out 50 jet experiments with the release of a mixture of SF6, CO2 and C2H6 to realise different densities. The aim was to investigate high density differences between the surrounding air and the jet with varying exit angles in a boundary layer flow. Moodie and Ewan (1990) investigated the small scale release of Freon 11 jets at constant pressure into the atmosphere, concentrating here on the temperature, mass fraction and velocities in the jet. Larger scale experiments are reported from the Desert Tortoise (Goldwire et al. 1985) and the Goldfish Series (Blewitt et al. 1987). Although these experimental campaigns mainly aimed at investigating the heavy gas dispersion, it is mentioned that the jet releases were also recorded. Both experiments dealt respectively with the release of ammonia up to 12 m^3/min and Hydrogen Fluoride up to 28 kg/s.

3 Detailed Analysis of the campaigns

The detailed analysis of the campaigns will be presented in alphabetical order. The aim of this detailed analysis is to provide all informations on the experimental setup, boundary conditions and experimental data recorded and the form they are provided. From this detailed information it should then be possible to decide whether the experimental campaign is providing a sufficient degree of detail for e.g. model validation purposes.
Due to the limited time and resources in the project, the detailed descriptions only cover a fraction of the test campaigns presented earlier.

3.1 Falcon trials (Brown et al 1990)

A series of five large-scale LNG spill tests were carried out by the Lawrence Livermore National Laboratory (LLNL) at Frenchman Flat, an extremely flat playa with little vegetation. The aim of the experiments was to evaluate the effectiveness of vapor fences as a mitigation technique for accidental releases as well as providing a dataset for model validation purposes. The spills were done onto a specially designed water pond equipped with a circulating system to maximise evaporation.

Description of the test setup

LNG was supplied to the spill area (see Figures 4 and 5) from two cryogenic 100 m3 storage tanks. The LNG was driven along spill pipes by means of nitrogen gas. The main 10”diameter spill pipe terminated immediately above the centre of the pond and then divided into 6” diameter pipes as a multi-exit “spider” to provide a uniform distribution of LNG over the spill pond. The spider consisted of four arms of 11.6 m length oriented at 90 degrees to each other. Each arm was fitted with a restrictive orifice at the downstream end of the horizontal portion to prevent flashing in the pipe. The orifice diameter was 4.5”, except in the Falcon-4 trial when a 1.5” diameter orifice was used. The outlet of each arm was directed vertically downwards. A 36” diameter horizontal splash plate was located beneath each outlet, level with the pond water surface so as to direct the LNG horizontally. The height of the pipe outlet above the splash plate is not provided in Brown et al (1990), but appears to be greater than 12” and much less than 36” (estimated from schematic drawings).
The spill pond was 40 m by 60m and filled to a depth of approximately 0.76 m. An 8.7 m high vapor containment fence 44 m by 88 m surrounded the spill pond, with the spill pond located at the downwind end of this fence. The fence was a proprietary fibreglass cloth impregnated with a mixture of silicon, Teflon and graphite. Immediately upwind of the spill pond was a 13.3 m high and 17.1 m wide “billboard” structure intended to generate turbulence typical of a storage tank within the vapor fence. The billboard was made of the same fibreglass material as the fence.

Instrumentation

Gas concentration and temperature sensors were arranged in three downwind station arrays at 50 m, 150 m and 250 m. Each station had sensors disposed at 1 m, 5 m, 11 m and 17 m above the ground. The layout remained largely unchanged between tests other than between Falcon 3 and 4 when two stations were moved from the 50 m row to the 150 m row. The instrument array centreline was oriented at 225 degrees, from the southwest, to coincide with the prevailing wind direction.

Data provided

Key variables were examined, including spill rate, spill volume, and fluid velocity for LNG released onto a water pond inside a vapor barrier. Water spills were performed in order to vaporize LNG at a rate equal to the spill rate. A goal was to conduct all tests at the nominal worst-case atmospheric conditions of 3.5 m/s wind speed and a stable atmosphere.

The report provides data about the release and atmospheric conditions. The wind speeds and temperatures provided are mean values over the experiment duration, provided with an average deviation.
The five tests were conducted with spill rates varying from 8.7 m3/min to 30 m3/min, spill volumes from 20 m3 to 63 m3 and fluid velocities from 32 m/s to 146 m/s. From these five experiments only 3 provided usefull data, as for test 2 and 5 an accidental ignition of the gas cloud led to the loss of data.
The wind speeds ranged from 1,2 m/s to 7,9 m/s and the temperatures ranged from 30,5°C to 35°C.
The composition of the LNG is described as being "methane/heavy %". Entries for gas composition in the Database are taken directly from the data report, whereas the remaining physical properties (molecular weight, density, boiling point, latent heat of evaporation, specific heats) are those for pure methane.

Explicitly provided as time dependent data (although not in tabular form but to be extracted from graphical representations) are:

- wind speed
- turbulence
- spill data
- vapour cloud temperature
- concentration
- vapour cloud contours

3.2 Prairie Grass (Barad 1958)

A total of 68 gas dispersion experiments were carried out, each with a duration of 10 minutes. The release was close to the grozudn (46 cm height) and the gas released was SO2 as a tracer gas. The dispersion occurred in a flat terrain with an average roughness of 0,6 to 0,9 cm. It is to note that the terrain is climbing up slightly to form a hill 0,6 miles southeast of the release. The aim was to measure the gas dispersion with the source at the center of five concentric semicircles having radii of 50, 100, 200, 400, and 800 meters.The measurements were carried out close to the ground (measuring height 1,5 m).

Description of the test setup

Liquid sulfur dioxide from an inverted 150-lb cylinder was vaporized in a specially-constructed chamber immersed in 150 gallons of hot water contained in a large circular tank. The required heat transfer to maintain a constant level of evaporation was facilitated by continuous circulation of the heated water in the large tank. The rate of tracer emission was adjustable over a wide range and ranged from 40 g/s to 100 g/s. The maximum source strength of about 100 g/s was used during the daytime releases. The tracer was conducted from the meter outlet through a 50-m length of 2-inch plastic pipe buried just beneath the surface of the ground, and was released horizontally at a height of 46 centimeters. In six experiments (Number 63-68), the height of the release point was adjusted to 1,5 m, corresponding to the height of the samplers in the horizontal sampling network.

Instrumentation

Average gas concentrations were determined at approximately 600 individual sampling stations located within a semicircle of radius 800 m around the release point. Gas sensors were mounted at a height of 1.5 m on steel fence posts located along five semicircular arcs in a distance of 50-, 100-, 200-, 400- and 800m. The concentrations were als measured along the vertical for the 100 m arc. Whilst on all measuring posts the sensors were at a standard height of 1,5 m, on six supplementary measuring posts placed on the 100 m arc they covered nine height levels (0.5, 1.0, 1.5, 2.5, 4.5, 7.5, 10.5, 13.5, and 17.5m).

Data provided

The data recorded during the experiments and provided in the report are measurements of the concentration as a 10 min average. The meteorological conditions were measured for the same sampling period of 10 minutes. Herein are reported the wind speed, wind direction, ambient temperature and stability class. The Wind was measured along two positions, one close to the source and one at 450 m distance. In addition so called “Micrometeorological data” were recorded for all experimental runs, as there is the soil temperature, the vapour pressure, and the wind speed at 7 different heights. These measurements took place on a post placed at 800 m distance from the source.

3.3 Burro (Koopman et al 19828) and Coyote (Goldwire et al 1983) Series

The burro and coyote series are described here together, as they were not only performed on the same test ground, but they coyote series were planned in addition to the burro tests to study the vapour burn and rapid phase transition (RPT) phenomenon that could be observed on the Burro trials.
Both test series were carried out at the china lake test ground of the naval weapons center of California. The Burro series covered eight tests of LNG spills on water with volumes of 24 to 39 m³ and the aim to study the vapour dispersion. In the coyote series a total of ten experiments with volumes of 3,3 to 28 m³ were carried out with LNG on water to study the vapour dispersion and burn as well as the RPT phenomena

Description of the test setup

LNG stored in a 40 m³ tank was connected to a 5,7 m³ spill tank with valve through a 25 cm diameter spill line, which also ran from the spill tank to the release point 1 m above the water surface. Below the plate on the water surface was fitted a splash plate to redirect the vertical LNG emission into a horizontal direction. The water basin had a diameter of 58 m and a water depth of 1 m. The water surface was 1,5 m below the ground level.

The tests at Burro series with 40 m³ of released mass had a release duration varying between 175 and 80 s, leading to spill rates of 230 l/s up to 500 l/s. The Coyote series spill volumes and durations were as follows: 14,6 m³ and 65 seconds, 28,0 m³ and 98 seconds. and 22,8 m³ and 82 seconds.

Instrumentation

A large array of instruments for sensing gas concentrations and measuring temperatures and windspeeds was deployed to measure the characteristics of both the dispersing LNG vapor cloud and the ambient atmosphere. The array centerline was oriented to coincide with the prevailing southwesterly wind direction for the summer season. The array was made up of three groups of instruments:

1. cup-and vane anemometers to map the wind field
2. gas sensors at three heights to track the LNG vapor cloud
3. propeller bivane anemometers and fast gas sensors also at three heights to measure turbulence effects and to track the cloud.

The first group consisted of 20 stations with a single anemometer mounted at an elevation of 2 meters.
The second group consisted of 25 gas stations (24 in the Coyote tests) and 5 turbulence stations arranged in arcs downwind from the spill point. In the Burro tests, there were four arcs at 57, 140, 400, and 800 meters from the spill point. This array was rearranged in the Coyote series because of the special requirements of the vapor burn and RPT tests and because the Burro series demonstrated the desirability of concentrating the gas sensors in the zone from 100 to 500 meters downwind. In both

test series, one turbulence station with no gas sensors was located just upwind of the spill basin. Each turbulence station had three anemometers at heights of 1.36, 3, and 8 meters; three infrared (IR) gas sensors at 1, 3, and 8 meters; and thermocouples collocated with each gas sensor to provide temperature measurements of the gas cloud. The gas sensor stations were similar to these except they had no anemometers. Also, they took data at a slower rate than the turbulence stations (1 Hz as compared with 3.3 to 5 Hz), and they had some gas sensors other than the IR type. Seven gas stations had humidity and heatflux sensors in addition to the gas and temperature sensors normally present.

Data provided

For each test the composition and relevant physical properties of the LNG are given.
The wind-field station data consisted of 10 s averages for speed, direction, and (new on the Coyote series) standard deviations of direction. Sensors on the gas stations were sampled at 1-second intervals, and those on the turbulence stations at 0.3- and 0.2-second Intervals.
The release rate ranged between 0.22 m^3/s and 0.5 m^3/s for the Burro tests and between 0.22 m^3/s and 0.3 m^3/s for the coyote series.
Concentrations are provided in a distance of 57, 140, 400, and 800 meters for the Burro tests and in arcs between 140 m and 400 m distance for the coyote series tests.

3.4 Heavy Goods vehicle fires in tunnels (Lönnermark and Ingason 2005)

Four large scale tests with heavy goods vehicles in fire in a tunnel were carried out. In three tests mixtures of cellulose and plastics were used as burning load and in a fourth test furniture and fixture was used. The tests were performed in a decommissioned two-way road tunnel of 1600 m length. The produced fire loads varied from 66 to 202 MW resulting in maximum ceiling Temperatures of 1281 °C and 1365 °C.

Description of the test setup

The asphalted two-way tunnel used is 1600 m long, 6 m high and 9 m wide with a slope of 0.5% uphill and 1% downhill. For the burning load a fixed mass ratio of 82% cellulose to 18 % plastics for the first three tests was chosen, with total masses of 10160 kg, 6390 kg and 7530 kg. The fourth test was carried out with plastic cups in cardboard boxes on wood pallets with a total mass of 2850 kg.
The burning load was placed at 563 m from the exit of the tunnel in the flow direction of the wind. The load was on a rack storage system to simulate a heavy goods vehicle with total dimensions of 10450 mm length, 2900 mm with and a total height of 4500 mm. The platform was located at 1100 mm over above the road. Fans were installed to induce a constant flow speed of 3 m/s in the tunnel.

Instrumentation

The temperature was measured mainly with unsheathed thermocouples 0.25 mm of Type K over the length of the tunnel (approx.. 100 m before and 500 m after the fire). In the vicinitiy of the fire sheathed thermocouples 1 mm Type K were used. The Temperatures were also measured between 4.7 m and 5.7 m above the road and in two locations at 1.8 m above the road.
Plate thermometers on the ceiling near the fire were used to measure the thermal insult on the tunnel structure. Heat release rate, gas velocity and composition were also measured.

Data provided

The data recorded during the experiments and provided in the report are measurements of the maximum heat released the gas temperatures over the time of the experiment at different locations.

3.5 Natural Gas Flares – Jet Fire (Cook et al. 1987)

At the Brithis Gas Spadeadam Test site, 57 experimental series were carried out with LNG. The Test site provided a 100 x 100 m concrete platform, in the center of which the flares were installed, so that building influences on the wind field could be excluded. In these series release rates up to 89 kg/s were carried out, resulting in flame lengths of up to 90 m. In these tests subsonic and sonic releases were investigated. Data on the size, shape and radiation characteristics have been obtained.

Description of the test setup

The British Gas Spadeadam test site consisted of a flat concrete pad with 100 m x 100 m. The gas was stored in two tanks with 83 m³ and 92 m³ of volume as gaseous phase, at respectively 135 bar abs and 75 bar abs. The experimental rig was connected to the reservoirs by pipework of 150 mm or 200 mm inner diameter depending on the required mass flow. During the tests the mass flow was maintained constant for at least 30 s. The vent stacks used for the release were made from steel pipe with inner diameters of 51 to 590 mm. They were placed with vertical orientation in the centre of the concrete pad to guarantee that that the wind was unaffected by buildings or other obstacles. The composition of the gas released was sampled for each test and found to be consistently between 92 and 95 Vol. % of Methane.

In these 57 Experiments the Reynolds number was high enough to give fully developed turbulent flow. The ratio of jet velocity to wind speed ranged from 19.1 to 386.6.

In 19 of the 57 tests the release was a sonic release with exit stagnation pressure of 27 bar abs.

The stack heights varied from 2 m to 16 m and the mass release rates from 1 kg/s to 88.7 kg/s

The gas releases were ignited using a premixed natural gas-air pilot burner, which was switched off after the ignition of a release.

Instrumentation

The gas flow rates through the stacks were monitored using pitot stagnation pressure and temperature probes at the bottom and of the stack and 100 mm upstream of the exit.
Up to four Barnes GC-4 fast response, wide angle field of view radiometers were used as well as Bolex 16 mm cine cameras to measure the spatially averaged surface emissive powers.
Up to 6 Land RAD/P/W slow response thermopile type radiometers as well as a narrow angle fast response radiometer (developed in-House) were employed for measuring the incident thermal radiation.
Wind Measurements were done at a height of 9 m with a light-weight cup anemometer and wind vane. Ambient pressure and humidity were measured using a 1 bar abs pressure transducer and a sensor housed in a Stevenson's screen.
With the cine cameras at 25 frames per seconds the luminous envelope of the flame was recorded.

Data provided

The data reported in the article are the flame length in relation to the total heat release. The angle from vertical of line joining the flame tip, as well as the dimensionless height over the velocity ratio. The surface emissive power is given for all experiments as a graph over the flame locus as well as the variation of the total radiative power over the total heat release.

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Appendix A. Tabular representations of resulting experimental campaigns spreadsheet

(note that the full spreadsheet also contains columns with references, tools using this, and validation references which are not listed here because of readability)

SOURCE TERM

Liquid outflow

Series name	References	Description of the experiment
Johnson and Woodward	Johnson D W and Woodward J L (1999) RELEASE A model with data to predict aerosol rainout in accidental releases	Experiments measuring rainout
Allen	Allen, J.T. (1998a): Laser-based measurements in two-phase flashing propane jets. Part one: Velocity profiles, Journal of Loss Prevention in the Process Industries, Vol. 11, pp 291-297 Allen, J.T. (1998b): Laser-based measurements in two-phase flashing propane jets. Part two: droplet size distribution, Journal of Loss Prevention in the Process Industries, Vol. 11, pp 299-306	Experiments using laser-based non-intrusive measurement technique for velocity and droplet distribution in flashing Propane jets
Fletcher	Fletcher, B, (1984), “Flashing flow through orifices and pipes,” Chemical Engineering Progress,” 80(3), pp 76-81	Superheated liquid releases
Fauske	H.K. Fauske, The discharge of saturated water through tubes, Chem. Eng. Prog. Symp. Ser. 61 (1965) 210–216.	Discharge from tubes
Sozzi, Sutherland	Sozzi GL, Sutherland WA (1975) Critical flows of saturated and subcritical water at high pressure. General Electric, San Jose, CA, NEDO-13418, July 1975	Discharge from nozzles

Boivin	Boivin JY (1979) Two-phase critical flow in long nozzles. Nucl Technol 46	Discharge from nozzles
Lee, Swinnerton	Lee DH, Swinnerton D (1983) Critical flow of subcooled water at very high pressure relevant to an ATWS. Safety and Engineering Science Division	Discharge from nozzles
Simoneau, Hendricks	Simoneau RJ, Hendricks RC (1984) Two phase flow of cryogenic fluids in converging-diverging nozzles. NASA Technical Paper	Discharge from nozzles
Veneau	Veneau T (1995) Etude expérimentale et modélisation de la décompression d'un réservoir de stockage de propane. Thèse de doctorat – Institut National Polytechnique de Grenoble	Discharge from nozzles
Dodge	Dodge, F. T., Bowlles, E. B., White, R. E., & Flessner, M. F. (1980). Release rates of hazardous chemicals from a damaged cargo vessel. In Proceedings of the 1980 National Conference on Control of Hazardous Material Spills, May 13–15, 1980 (pp. 381–385). Nashville, TN: Vanderbilt University	Release of liquid from a submerged vessel

Gas outflow

Series name	**References**	**Description**

McIntosh	McIntosh, R.D. et al. (1995): Small-scale evaluation of dump tank sizing methods, Journal of Loss Prevention in the Process Industries, Vol. 8, No. 3, pp. 185-196	Sizing of dump tanks to separate gas and liquid phase

Flash and Evaporation

Series name	References	Description
Okamoto	Okamoto K. et al. (2010): Evaporation characteristics of multi-component liquid, Journal of Loss Prevention in the Process Industries 23, 89-97, 2010	Evaporation of several mixtures of organic solvents (including n-pentane, n-hexane, n-heptane, toluene and p-xylene), with no wind and a pool surface of 0,1 m²
	Okamoto K. et al. (2012): Evaporation and diffusion behavior of fuel mixtures of gasoline and kerosene, Fire Safety Journal, Volume 49, Pages 47-61.	
Fingas	Fingas F. (1997): Studies on the evaporation of crude oil and petroleum products : I. the relationship between evaporation rate and time, Journal of Hazardous Material, Journal of Hazardous Material, 56, 227-236,	Large number of evaporation tests with hydrocarbon mixtures like AVGAS, gasoline, diesel fuel, heptane-octane, heptane-octane-nonane, etc. Evaporation from Petri dishes (of diameter 139 mm – 0,015 m²) was observed during several tens of hours, up to four days, with and without wind .
	Fingas F. (1998): Studies on the evaporation of crude oil and petroleum products: II. Boundary layer regulation, Journal of Hazardous Material, Journal of Hazardous Material, 57, 41-58.	

Mackay/Matsugu	Mackay D. & R.S. Matsugu (1973): Evaporation Rates of Liquid Hydrocarbon Spills on Land and Water, Canadian Journal of Chemical Engineering vol 51, August 1973	Evaporation of water, cumene and gasoline from pans of 1,5 m² and 3 m² in outdoor conditions.
Esso	G.F. Feldbauer, J.J. Heigl, W. McQueen, R.H. Whipp, W.G. May, Spills of LNG on water—vaporization and downwind drift of combustible mixtures, API Report EE61E-72, 1972	LNG spills (boiling pool) over water (volume 0.73–10.2 m3), pool radius 7–14 m.
Maplin Sands	J.S. Puttock, D.R. Blackmore, G.W. Colenbrander, Field experiments on dense gas dispersion, J. Hazard. Mater. 6 (1982) 13–41.	LNG and Propane spills (boiling pool)over water – Volumes of 5–20 m3 spilled in a dyked area. Pool radius ~ 10 m. Twenty-four continuous and ten instantaneous spills were performed in average wind speeds of 3.8–8.1 m/s
	D.R. Blackmore, J.A. Eyre, G.G. Summers, Dispersion and combustion behavior of gas clouds resulting from large spillages of LNG and LPG on to the sea, Trans. I. Mar. E. (TM) 94, paper 29, 1982.	
	D. Blackmore, et al., An updated view of LNG safety, in: American Gas Association Transmission Conference, Operation Section Proceedings, 1982, pp. T226–T232.	
	G.W. Colenbrander, J.S. Puttock, in: Fourth Int. Sym. on Loss Prev. and Safety, vol. 90, Dense gas dispersion behavior experimental observations and model developments (1983), pp. F66–F76.	

Pettitt	Pettitt, G.N., (1990), "Characterisation of two-phase releases," PhD thesis, South Bank, London, UK Polytechnic.	Instantaneous flashing release from shattering glass spheres
Schmidli	Schmidli, Y., Yadigaroglu, G., and Banerjee, S, (1992), "Sudden releases of superheated liquids," HTD, vo1.l97, Two-Phase Flow and Heat Transfer, ASME.	Instantaneous flashing release from shattering glass spheres
Maurer	Maurer, B., Hess, K., Giesbrecht H. and Leuckel, W., (1977), "Modelling of vapour cloud dispersion and deflagration after bursting of tanks filled with liquefied Gas," Int. Loss Prevention Symposium, Heidelberg.	Near instantaneous releases from 0.124 to 452 kg

FIRE

Jet fire

Series name	References	Description
Cook	Cook DK, Fairweather M, Hammonds J, Hughes DJ. (1987): Size and radiative characteristics of natural gas flares, Chem Eng Res Des, 1987, 65(4): 310-317	Data obtained from 57 field scale experiments is described. The flares employed were of natural gas, with both subsonic and sonic releases having been considered. Experimental data on the size, shape and radiative characteristics of the flares has been obtained, in addition to measurements of thermal radiation incident about the flares.
Bennett	Bennett, J.F, Cowley, L T., Davenport, J. N. And Rowson, J. J., 1991, Large-scale natural gas and LPG jet fire final report to the CEC, CEC research programme: Major Technological Hazards, CEC contract (Shell Research Ltd)	Large scale experiments with LPG and natural gas. Incident radiation flux at different locations and flame SEP were measured.
Acton and Ewans	Acton, M.R., Evans, J.A. and Sekulin, A.J., (1996a): Blast and Fire Engineering Project Phase 2 - Horizontal jet fires of oil and gas: Data Report for Jet Fire Test 1, GRCR 109 (1), British Gas, UK Acton, M.R., Evans, J.A. and Sekulin, A.J., (1996b): Blast and Fire Engineering Project Phase 2 - Horizontal jet fires of oil and gas: Data Report for Jet Fire Test 2, GRCR 109 (2), British Gas, UK	Unconfined jet fire tests on horizontal oil and jet fires, partially with impingment on a wall
Chamberlain	Chamberlain, G.A., Persaud, M.A., Wighus, R. and Drangsholt, G. (2008): Blast and Fire Engineering for Topside Structures. Test programme F3 - confined jet and pool fire tests. Final report, Shell Research and Sinteff	Confined jet fires with horizontal and vertical jets of condensate fuel in rigs of 135 and 415 m³ equipped with targets / obstacles

Fire ball

Series name	References	Description
INERIS' test	Duplantier. Boil-over classique et boil-over couche mince. INERIS-Omega 13	Tests for Boil-over phenomenon within which fire ball formation has been observed
LPG Fireball	Roberts,T.; Gosse, A.; Hawksworth, S.; 2000: THERMAL RADIATION FROM FIREBALLS ON FAILURE OF LIQUEFIED PETROLEUM GAS STORAGE VESSELS, IchemE, Trans IChemE, Vol 78, Part B, May 2000	LPG Vessels in Fire to investigate the vessel response, mode of failure and the consequences of failure with special interest to formation of fireballs

Flash Fire

Series name	References	Description
INERIS' test	Duplantier. Boil-over classique et boil-over couche mince. INERIS-Omega 13	Experimental observations were performed from trial tests with bund diameter up to 60 cm and different hydrocarbons
MHIDAS	MHIDAS databse discontinued???	Database of Flash fire experiments
	Villafane D., Darbra R.M., Casal J.: Flash Fire: Historical Analysis and Modeling, Chemical Engineering Transactions, Volume 24, AIDIC, 2011	
Raj	Raj, P. K., A. N. Moussa & K. Arvamudan, "Experiments involving pool and vapor fires from spills of liquefied natural gas and water," U.S. Navy Report, DOT/USCG (G-DSA), 1979	16 Tests with LNG on Water with ignition of the gas cloud (70 m long) and the pool
HSL VCF	Butler C.J., Royle M. (2001): Experimental data acquistion for validation of a new vapour cloud fire (VCF) modelling approach HSL/2001/15	Measurement of Gas Cloud Conecentrations and Heat Fluxes when igniting the cloud.

Pool Fire

Series name	References	Description

Mudan and Croce's tests.	Mudan, K.S. and Croce, P.A. Fire hazard calculations for large open hydrocarbon pool fires", SFPE Handbook of fire protection engineering, second edition, National Fire Protection association, Quincy, MA, 1995	Experimental correlations regarding flames have been derived from trial tests with pool diameter ranges from 1m to 80m with different hydrocarbons
Raj	Raj P.K., 2007. LNG fires: A review of experimental results, models and hazard prediction challenges . J. Hazard. Mater. 140 , 444 - 464 (plus errata J. Hazard. ater. 143, 603).	Review of 11 Test series on LNG pool fires on Water and on Land
Large liquid pool fires	“Combustion properties of Large Liquid Pool Fires”, H. Koseki, Fire Technology, 1989, Vol. 25, Issue 3, Pages 241-255	A compilation of large liquid pool fire tests is summarised. Pool diameters range from 0.5m to 20m. Burning rate, flame temperature, radiative heat flux and radiative fraction were reported as functions of pool diameter for the tested products.
Chamberlain	Chamberlain, G.A., Persaud, M.A., Wighus, R. and Drangsholt, G. (2008): Blast and Fire Engineering for Topside Structures. Test programme F3 - confined jet and pool fire tests. Final report, Shell Research and Sinteff	7 tests of pool fires of condesate fuel in a confinement of 135 m^3 and 415 m^3 with pool diameters of 6 m and 24 m-

Experimental Fires in Enclosures	Some Observations on Experimental Fires in Enclosures. Part 1 : Cellulosic Materials, A. Tewarson, Combustion and Flame, Vol. 19, 1972, Pages 101-111 Some Observations on Experimental Fires in Enclosures. Part 2 : Ethyl Alcohol and Paraffin Oil, A. Tewarson, Combustion and Flame, Vol. 19, 1972, Pages 363-371	Experiments involving cellulosic products first, then ethyl alcohol and paraffin oil were conducted in box-type enclosures. The smaller enclosure was 48 cm wide, 101 cm long and 53 cm high. The larger enclosure was 105 cm wide, 203 cm long and 98 cm high (only for cellulosic products). Dual, full-width windows were symmetrically placed at the centre of opposite walls. Fire behaviour was studied with respect to 4 parameters: ventilation parameter, burning rate, gaseous product composition and temperature. For the tested products, 4 distinct regions appeared as the ventilation parameter was varied. An empirical correlation was derived to characterise critical region transition corresponding to extreme danger.

The Flumilog Project	"Flumilog – A computational method for radiative heat flux emitted by warehouse fire - Part 1: Experimental results" under internal review process.	Experimental tests aiming at feeding a new calculation method and involving 9 medium-scale set-ups (12 x 8 m² cell of 3.5 m height) and one large scale set-up (36 x 24 m² and 12 m) were carried out. The main parameters investigated were the type and layout of combustible material, type of the boundary walls, type of roof covering and scale effect. Temperature and radiative heat flux measurements were taken for each test. The final full-scale test was undertaken in a warehouse-like building manly composed of a steel structure and containing wooden pallets. Wall collapse, flame height and smoke plume were also observed and filmed.
Wood Crib Fires	"The size of Flames from Natural Fires", P.H. Thomas, Symposium (International) on Combustion, Vol.9, Issue 1, 1963, Pages 844-859	Experimental correlations relating flame height and mass flow rate have been derived for wood crib fires. The amount of wood and design of the crib have been varied to gain access to a range of mass rates of burning. The effect of wind was also studied in the experiment.

Heavy goods vehicle fires in tunnels	"Gas Temperatures in Heavy Goods Vehicle Fires in Tunnels", A. Lönnermark, H. Ingason, Fire Safety Journal, Vol.40, 2005, Pages 506-527	Four large-scale fire tests involving Heavy-Goods Vehicles were carried out in the Runehamar tunnel in Norway, which is 6m high, 9m wide and 1600 m long. Different mixtures of cellulose and plastic materials, furniture and fixtures were set on fire. Heat release rate of the tested fires ranged from 66 to 202 MW, and the maximum measured temperatures at the ceiling were from 1281°C to 1365°C. The gas temperature development was represented by a combination of classical fire curves, and a mathematical expression was derived to best fit the fire development.

EXPLOSION

Explosion

Series name	References	Description of the experiment
CEC-S	J.G. Visser and P.C.J. de Bruijn. Experimental parameter study into flame propagation in diverging and non-diverging flows .TNO Prins Maurits Laboratory reort no. PML 1991-C93.	Experimental parameter study into flame propagation in a diverging channel was carried out and to mimic a full expansion process, experiments were performed in a wedge-shaped channel of 2 m length, 0.25 height and a 45 degrees top angle.
DISCOE	van Wingerden C.J.M.; 1988, Experimental investigation into the strength of blast waves generated by vapour cloud explosions in congested areas; 6th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Oslo, Norway, Proceedings, 26:1-16	An extended experimental study on flame propagation in 0.08 m diameter vertical obstacle arrays and partially confined between parallel planes.
Harrison and Eyre experimental program.	A.J. Harrison and J.A. Eyre. The effect of obstacle arrays on the combustion of large premixed gas/air clouds. Comb. Science and Techn. Vol. 52, (1987), pp. 121-137.	An experimental rig was designed to represent a pie-shaped segment of a large pancake shaped cloud by using two walls each 30 m long and 10 m high with 30° angle to constrain 4000 m3 fuel-air-mixture. Different blockage ratios investigated
Hjertager	B.H. Hjertager. Explosion in obstructed vessels. Course on Explosion Prediction and Mitigation. University of Leeds, UK, 28-30 June, 1993.	En experimental study on gas explosions developing in a 3D corner of 3 * 3 *3 m3 was carried out. The corner was filled with configuration of cylindrical obstructions. Methane-air and propane-air were used as test mixtures.

MERGE	MERGE. W.P.M. Mercx . Modelling and experimental research iinto gas explosions. Overall final report of the MERGE project CEC contract STEP-CT-011 (SSMA).	Gas explosion developing in various flammable mixtures obstructed by regularly spaced grids were studied on three different scales.
MTH-BA Lathen (Field experiments)	A collection of data from Riso-R-845(EN) dense gas experiments. Morten Nielsen and S. Ott.	The LATHEN campaign was carried out by Riso. and TüV Nord Deutschland to study the behaviour and the dispersion of continuous liquefied propane gas release under obstacle patchiness
RIGOS research programme	A. C. van den Berg and N. H. A. Versloot, “The multi-energy critical separation distance,” Journal of Loss Prevention in the Process Industries, vol. 16, no. 2, pp. 111–120, 2003.	A series of small-scale explosion experiments have been performed with vapour clouds containing a donor and an acceptor configuration of obstacles separated by some distance.
Johnson et al	Johnson, DM, Shale, GA, Lowesmith, BJ, and Campbell, D (1997): Blast and Fire Engineering for Topside Structures, Phase 2: Final Report on the explosion test programme, Steel Construction Institute	Series of 12 full scale hydrocarbon explosions in 2 geometrically different test rigs of max 8 m height, 12 m width and 28 m length with varying obstacle density, obstruction, confinement and ignition position

Burst

Series name	References	Description of the experiment
BAUM	BAUM, 1999, Failure of a horizontal pressure vessel containing a high temperature liquid: the velocity of end-cap and rocket missiles, Elsevier, Journal of Loss Prevention in the Process Industries 12, pp.137-145.	Experiments on a model vessel with pressures up to 80 - 90 bar. One series for the burst of the end cap and one series for the Vessel as "missile"
	BAUM, 2001, The velocity of large missiles resulting from axial rupture of gas pressurized cylindrical vessels, Elsevier, Journal of Loss Prevention in the Process Industries 14, pp. 199-203.	

BRITISH GAS	Johnson, Pritchard, 1990, Large-scale experimental study of boiling liquid expanding vapour explosions (BLEVE), Commission of the European Communities Report EV4T.0014.UK (H).	5 experimental BLEVEs of LPG (propane or butane) horizontal vessels(5.659 and 10.796 m3), with thermal insulation, were carried out :Heating by internal electric resistances. Rupture of vessels performed by an explosive charge set up at the top and at the middle of the vessel, Inflammation of the released LPG set up by three lances. Data were used for the development of TRC Model (Shield model)
Birk	Birk, Cunningham, Kielec, Maillette, Miller, Ye, Ostic, 1997, First Tests of Propane Tanks to study BLEVEs and other Thermal Ruptures : Detailed Analysis of Medium Scale Test Results, Report for Transport Canada, Dpt of Mechanical Engineering, Queen's University, Kingston, Ontario	11 experimental BLEVEs of propane horizontal vessels (300 and 375 liters), with a design pressure of 17 or 21.5 bars and a wall thickness of 5 or 6mm, were carried out : Heat flux from combinations of jet fire and pool fire
JIVE	Roberts,T.; Gosse, A.; Hawksworth, S.; 2000: THERMAL RADIATION FROM FIREBALLS ON FAILURE OF LIQUEFIED PETROLEUM GAS STORAGE VESSELS, IchemE, Trans IChemE, Vol 78, Part B, May 2000	Aims of the tests : study of rupture pressure and temperature, failure mode and properties of fire ball; Propane vessels were exposed to heat flux from liquid propane jet fire (around 1.5 kg/s) ; Properties of vessels : horizontal, 4,546 litres, design pressure of 18.7bar, test hydraulic pressure of 23.4bar, with a safety relief valve set on 17.2bar, several liquid levels were tested

NFPA	Melhem, Croce, Abraham, 1993, Data summary of the National Fire Proctection Association's BLEVE tests, Process Safety Progress, vol. 12, n° 2, April 1993.	6 experimental trials of propane BLEVE with horizontal vessels of 1.9m3 exposed to pool fire or propane (liquid or gaseous) jet fire, several filling liquid levels were carried out
BAM	Ludwig, Balke, 1999, Untersuchung der Versagensgrenzen eines mit Flüssiggas gefüllen Eisenbahnkesselwagens bei Unterfeuerung, Rapport B.A.M. 3215, Berlin, Septembre 1999	An experimental BLEVE of a propane road tank of 45m3 (fill liquid level 22 %) was performed by exposure to a fuel fire : Thermocouples for internal temperature (in gaseous and liquid parts), wall temperature and external temperature; Pressure sensors for internal pressure and overpressure; Radiation sensors for heat flux produced by the fireball
Stawczyk	Stawczyk, 2003, experimental evaluation of LPG tank explosion hazards, Journal of Hazardous Material B96 pp.189-200	Bleve of LPG vessels (5 and 11 kg) were carried out by heating the bottom (liquid phase) of the vessel; Measurements: internal temperature (gaseous and liquid phase), outside wall temperature, internal pressure, overpressure; Several liquid levels and container positions (vertically, horizontally) were tested

Gas Dispersion

Jet release

Series name	References	Description of the experiment
Birch - Jet Release	Birch, A.D.; Brown, D.R.; Dodson, M.G.; Swaffield, F.: The structure of concentration Decay of High Pressure Jets of Natural Gas. In: Combustion Science and Technology 36 (1984) p. 249-262	Experimental validation of the pseudo diameter theory with high pressure (max. 70 bar) Jets of sub- and supercritical releases
Hoehne Luce - Jet Release	V.O. Hoehne, R.C. Luce: The Effects of Velocity, Temperature and Molecular Weight on Flammability Limits in Wind-Blown Jets of Hydrocarbon gases. 1970	Vertical Jet in Cross wind in Wind Tunnel
Donat - Jet Release	Donat, J.: Windkanalexperimente zur Ausbreitung von Schwergasstrahlen. Dissertation, University of Hamburg (1996).	50 Heavy Gas jet releases in a wind tunnel experiment to study the dispersion behaviour in crosswind situation within the atmospheric boundary layer
Schatzmann Snyder - Jet release	Schatzmann, M.; Snyder, W.H.; Lawson Jr, R.E.: Experiments with heavy gas jets in laminar and turbulent cross-flows. Atmospheric Environment Vol. 27A, No. 7, p. 1105-1116. (1991)	14 jets in laminar and turbulent cross flow with densities from 2 - 6 kg/m³; wind tunnel
Desert Tortoise	H.C. Goldwire, T.G. McRae, G.W. Johnson, D.L. Hipple, R.P. Koopman, J.W. McClure, L.K. Morris and R.T. Cederwall, Desert Tortoise series data report: 1983 pressurized ammonia spills, UCID-20562, Lawrence Livermore National Laboratory, Livermore, CA, 1985.	Jet Release experiments with subsequent gas cloud dispersion
Goldfish Series	Blewitt, D.N., J.F. Yohn, R.P. Koopman, and Brown, T.C., 1987, “Conduct of Anhydrous Hydrofluoric Acid Spill Experiments,” American Institute of Chemical Engineers, Proceedings, International Conference on Vapor Cloud Modeling, Boston, MA, Nov. 2-4.	HF Release; max: 3770 kg; Measuring distance: 3000 m

Moodie and Ewan	Moodie, K and Ewan, B C R, (1990) Jets discharging to atmosphere, J Loss Pre Process Ind, Vol 3.	Small scale flashing discharges of Freon 11 with measurements in the jet

Light or neutrally bouyant dispersion

Series name	References	Description of the experiment
Prairie Grass	Barad, M.L. (Editor) (1958): Project Prairie Grass, A Field Program In Diffusion. Geophysical Research Paper, No. 59, Vol I , Report AFCRC-TR-58-235(I), Air Force Cambridge Research Center, 299 pp.	68 experiments; 10 min duration; release height 0,46 m; flat terrain (roughness 0.,006 - 0,009 m);Measuring Distance up to 800 m in 1,5 m height
	Barad, M.L. (Editor) (1958): Project Prairie Grass, A Field Program In Diffusion. Geophysical Research Paper, No. 59, Vol I I, Report AFCRC-TR-58-235(II), Air Force Cambridge Research Center, 218 pp.	
	Haugen, D.A. (Editor) (1959): Project Prairie Grass, A Field Program In Diffusion, Geophysical Research Papers, No. 59, Vol III, AFCRC-TR-58-235(III), Air Force Cambridge Research Center, 686 pp.	
Kincaid	Bowne, N.E., Londergan, R.J., Murray, D.R., and Borenstein, H.S., (1983) Overview, Results, and Conclusions for the EPRI Plume Model Validation and Development Project: Plains Site, EPRI EA-3074, Project 1616-1, Electric Power Research Institute, Palo Alto, CA. 234 pp	3 SF6 releases from a 187 m stack with a buoyant plume rise on the order of 200 m; releases on 50 days for a total of 372 hours; near surface hourly concentrations and hourly meteorology; measurement on arcs ranging from 0.5 km to 50 km from the release.
Round Hill	Cramer, H.E., Record, F.A., and Vaughan, H.C., (1958): The Study of the Diffusion of Bases or Aerosols in the Lower Atmosphere. ARCRL-TR-58-239, The MIT Press, 133 pages.	10 minute samples along three arcs (50, 100, and 200 m); release height 30 cm and 50 cm; Sensor height 2 m; roughness >0,1m

Lillestrom	Helge Rordam Olesen, Joseph C. Chang; Consolidating tools for model evaluation ;Int. J. of Environment and Pollution, 2010 Vol.40, No.1/2/3, pp.175 - 183	Urban topology; Measuring Distance up to 1 km
Copenhagen	Gryning, S.E., and Lyck, E., (1984): Atmospheric dispersion from elevated sources in an urban area: comparison between tracer experiments and model calculations. Journal of Climate and Applied Meteorology, Vol. 23:651-660 Gryning, S.E., and Lyck, E., (2002): The Copenhagen Tracer Experiments: Reporting of Measurements. Risø-R-1054(rev.1)(EN), Riso National Laboratory, Roskilde, Denmark, 75 pages. http://www.risoe.dk/rispubl/VEA/veapdf/ris-r-1054_rev1.pdf	Urban topology (roughness 0,6 m); Measuring Distance 2 - 6 km from Source; Release Height 115 m
Indianapolis	Murray, D.R., and Bowne, N.E., (1988) Urban Power Plant Plume Studies, EPRI Report No. EA-5468, Research Project 2736-1, Electric Power Research Institute, Palo Alto, CA.	Complex urban topology (Indianapolis). Release from 84 m height with buoyant plume. 170 experiments. Near surface concentrations with hourly concentrations and meteorology. Measuring Distance from 0,2 to 12 km.
The mock urban setting test field experiment : MUST	Biltoft, C.A., 2001. Customer Report for Mock Urban Setting Test (MUST). DPG Doc. No. WDTC-FR-01-121, West Desert Test Center, U.S. Army Dugway Proving Ground, Dugway, UT 84022-5000.	The MUST field experiment consisted of 37 releases of propylene tracer gas in an array of 120 obstacles at the Dugway Proving Ground desert site. The obstacles were shipping containers, which are about the size of the trailer in a tractor-trailer rig (12.2m long by 2.42m wide by 2.54m high)

Heavy gas dispersion

Series name	References	Description of the experiment

Burro Series	R.P. Koopman, L.M. Kamppinen, W.J. Hogan and C.D. Lind, Burro series data report: LLNL/NWC 1980 LNG spill tests, Lawrence Livermore Nat. Lab., Livermore, CA, UCID-19075, 1981	LNG Release on Water; max: 40 m^3; Measuring Distance up to 1 km
Coyote Series	Goldwire et al., LNG Spill Tests: dispersion, vapor burn, and rapid phase transition, UCID - 199953, Lawrence Livermore National Laboratory, Livermore, California (1983)	LNG release through 0.25 m orifice; max 28 m^3; Measuring Distance 500 m
Desert Tortoise	Goldwire, H. C., T. G. McRae, G. W. Johnson, D. L. Hipple, R. P. Koopman, J. W. McClure, L. K. Morris, and R. T. Cederwall, 1985: Desert Tortoise series data report—1983 pressurized ammonia spills. Lawrence Livermore National Laboratory.	Release of ammonia through a 6 inch diameter nozzle 1 m over ground; max: 28 m^3; Temperature measured up to 9 m distance, concentrations measured up to 800 m
Eagle series	Koopman, R.P., T.G. McRae, H.C. Goldwire Jr., D.L. Ermak, and S.T. Chan, 1985, "Results of Recent 1983 NH3 and N2O4 Spill Tests," Proc. - Inst. Environ. Sci., Vol. 31.	Nitrogen Tetraoxide relase; max: 4.2 m^3; max distance 785 m
Falcon series	Brown, T.C., R.T. Cederwall, D.L. Ermak, R.P. Koopman, J.W. McClure, and L.K. Morris, 1990, "Falcon Series Data Report, 1987 LNG Vapor Barrier Verification Field Trails," Gas Research Institute, 8600 West Bryn Mawr Avenue, Chicago, IL 60631, GRI-89/0138.	LNG on Water; Max: 66 m^3; measuring distance: 250 m; Aimed at testing the effectiveness of Vapour fences against dispersion
Goldfish Series	Blewitt, D.N., J.F. Yohn, R.P. Koopman, and Brown, T.C., 1987, "Conduct of Anhydrous Hydrofluoric Acid Spill Experiments," American Institute of Chemical Engineers, Proceedings, International Conference on Vapor Cloud Modeling, Boston, MA, Nov. 2-4.	HF Release; max: 3770 kg; Measuring distance: 3000 m; 6 tests and 3 of them to test water fences

DRI/WRI/EPA CO2	Briggs, G.A., September 1995. “Field-measured dense gas plume characteristics and some parameterizations.” International Conference and Workshop on Modeling and Mitigating the Consequences of Accidental Releases of Hazardous Materials. New Orleans, LA, 26-29 September 1995, AIChE.	CO2 Release with SF6 as tracer Gas; max: 172 kg; measuring distance: 100 m
Kit Fox Series	Coulombe, W., J. Bowen, R. Egami, D. Freeman, D. Sheesley, J. Nordin, T. Routh, and B. King, 13 May 1999, “Characterization of Carbon Dioxide Releases−Experiment Two.” DRI Doc. No. 97-7240.F, DRI, P.O. Box 60220, Reno, NV 89506-0220.	Continuation of DRI/WIR/EPA CO2 this time with obstacles; max: 1.775 kg; measuring distance: 225 m
Thorney Island	McQuaid, J., and Roebuck, B. (1985) and DG Wilde. Large-scale field trials on dense vapour dispersion. Safety Engineering Laboratory - Health and Safety Executive.	Release of Freon and Nitrogen was released at ground level. Measuring distance 600m. 3 Phases of experiments: varying roughness and release rate from instantaneous (2000m³) to continuous max 250 m³/min
FLADIS	Morten Nielsen, Sören Ott. Field experiments with dispersion of pressure liquified ammonia: Fladis Field Experiments. Risø–R–898(EN). July 1996.	The experiment was designed to investigate the downwind dispersion of an ammonia aerosol. Liquefied ammonia was released under pressure through a nozzle situated at a height of 1.5m. These experiments differed from the Desert Tortoise experiments because the release rates were much lower, allowing for the investigation of far field passive effects. In addition, no liquid pool was observed as in the case of the Desert Tortoise experiments

Maplin Sands	J.S. Puttock, D.R. Blackmore, G.W. Colenbrander, Field experiments on dense gas dispersion, J. Hazard. Mater. 6 (1982) 13–41.	LNG and Propane spills (boiling pool)over water – Volumes of 5–20 m3 spilled in a dyked area. Measuring distance: approx. 500 m; Contiuous and instantaneous releases
	D.R. Blackmore, J.A. Eyre, G.G. Summers, Dispersion and combustion behavior of gas clouds resulting from large spillages of LNG and LPG on to the sea, Trans. I. Mar. E. (TM) 94, paper 29, 1982.	
	D. Blackmore, et al., An updated view of LNG safety, in: American Gas Association Transmission Conference, Operation Section Proceedings, 1982, pp. T226–T232.	
	G.W. Colenbrander, J.S. Puttock, in: Fourth Int. Sym. on Loss Prev. and Safety, vol. 90, Dense gas dispersion behavior experimental observations and model developments (1983), pp. F66–F76.	
CHRC Wind tunnel trials	Havens J and Spicer T, 2005, LNG vapor cloud exclusion zones for spills into impoundments, Process Safety Progress, Vol 24, Iss 3, pp 181 – 186. Havens J and Spicer T, 2006, Vapor dispersion and thermal hazard modelling, Final topical report to Gas Technology Institute under sub-contract K100029184, October 2006. Havens J, Spicer T and Sheppard W, 2007, Wind tunnel studies of LNG vapor dispersion from impoundments, AIChE National Spring Meeting, Houston.	Isothermal continuous release of CO2 over artificial roughness. 1:150 Model of an industrial tank in a dike.
Holt et al	Discharge and dispersion for CO2 releases from a long pipe: Experimental data and data review, IChemE symposium series No 160, Hazards 25	Various release and dispersion experiments

Schatzmann Windtunnel	Schatzmann M, Marotzke K and Donat J, 1991, Research on continuous and instantaneous heavy gas clouds, Contribution of sub-project EV 4T-0021-D to the final report of the joint CEC-project, University of Hamburg, February 1991.	Heavy gas release in Widntunnel with various artificial roughness/obstacle configurations