Explosions followed by fire outbreak at an oil storage depot
11 December, 2005
Buncefield – United Kingdom

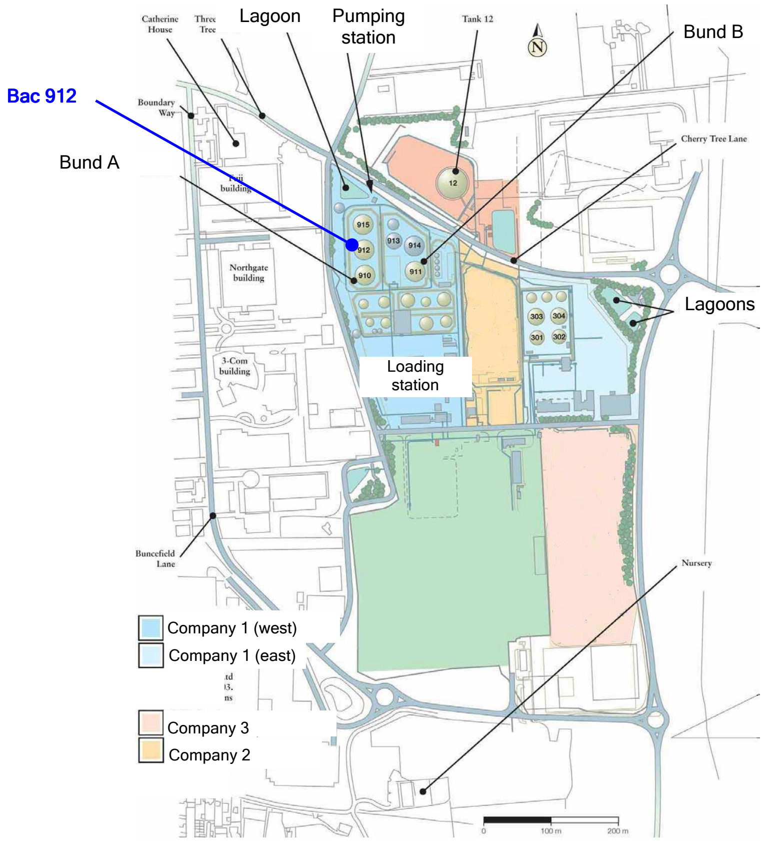
Explosion
Flammable liquids farm
Gasoline
Level detection
Automatic valve
Victims
Material damage
Transboundary effects

THE INSTALLATIONS IN QUESTION

The site:

The Buncefield oil storage depot, Great Britain's fifth largest storage site, is located 40 km north of London near the town of Hemel Hempstead, in Hertfordshire County. It typically stores 150,000 tons of fuel (gasoline, fuel oil, kerosene) for a total capacity of 273,000 m^3. This depot has the distinction of supplying kerosene via a pipeline to London's Luton and Heathrow Airports, the latter being Europe's biggest and busiest. These two sites have also implemented backup supply channels.

Diagram 1: Layout of the Buncefield Terminal



Source: Buncefield Investigation, Initial Report

The oil storage depot houses three companies (see Diagram 1) and comprises three supply pipelines and two distribution lines. The company site where the accident occurred is divided into two sections as follows:

- The eastern part contains 7 fuel oil and kerosene tanks, totalling a capacity of approximately 26,000 m^3.
- The western part covers 16 fuel oil and gasoline tanks, for a total capacity of some 58,000 m^3, along with the truck filling stations, pipeline reception installations with 3 smaller admixture tanks and the control room.

This company operates around the clock, 24 hours a day.

Located between the eastern and western sites of the company incurring the loss, lies the oil storage depot's second firm, which is authorized to store up to 70,000 tons of fuel. Towards the south-eastern portion of the site, the 3rd company's depot has been set up with a total storage capacity for 75,000 tons of gasoline.

THE ACCIDENT, ITS BEHAVIOUR, EFFECTS AND CONSEQUENCES

The accident:

- ***Sequencing of events:***

Beginning at 7:00 pm on December 10, Tank 912 with a floating screen, located in the sector of the first company's storage area A, received a delivery of unleaded gasoline via pipeline at an inflow rate of 550 m^3/hr.

December 11:

- At midnight, the storage site was closed and inventory verification was underway.
- At 3:00 am, the Tank 912 level gauge indicated a stable volume at 2/3 capacity, while supply delivery was ongoing at the same flow rate.
- At 5:20 am, Tank 912 began to overflow and a high-concentration air/fuel mix started to form.
- At 5:50 am, the parallel supply delivery of another tank was halted and the inflow rate of Tank 912 reached 890 m^3/hr, with the tank's supply valve remaining open.
- At 6:01 am, the first and most powerful explosion occurred, followed by a fire that spread to 21 of the facility's large storage tanks, as a direct result of the primary explosion, which detonated at the level of the Fuji and Northgate parking lots (see Diagram 1) located near the corresponding buildings. The explosion was heard at a distance of up to 160 km. British geological surveying teams would classify the seismic effects of the event at a 2.4 reading on the Richter scale.
- At 6:08 am, the emergency/rescue services were notified.
- At 6:27 and 6:28 am, two subsequent explosions occurred.
- At 9:00 am, the emergency response coordination team met.

Photo : www.buncefield-oil-fire-hemel-hempstead.wingedfeet.co.uk

Photograph 1: Devastated building at the terminal site

On December 12 at noon, the fire reached its maximum intensity; the fire extinction water supply mixed with fuels overflows the retention units. On December 14, additional and sizable leaks were detected at the retention areas and products from the site flow beyond facility boundaries.

Foam liquids were brought onsite and mixed with water pumped out of the Grand Union Canal located 3 km from the disaster zone. This operation, planned to commence at midnight, had to be postponed due to concerns over a possible environmental impact, especially out of concern for potential water quality impacts. More specifically, some of the extinction foam used contained perfluorooctane sulfonate (PFOS), a water and oil repellent, known to be a persistent, bioaccumulative and toxic substance and an endocrine disruptor. Nonetheless, given the state of emergency regarding the need for extinction resources, British authorities decided to implement these foams.

Fire-fighters began combating the blaze on December 12 at 8:20 am using 6 high-pressure water pumps capable of projecting 32,000 litres of water and foam liquid per minute. Within a few hours, while half of the tanks onsite were ablaze, crews succeeded in containing the fire. By the beginning of the evening, operations were suspended due to the explosion risk.

Over 600 fire-fighters then worked together to pour a tremendous quantity of foam onto the terminal in order to suffocate the flames. They finally extinguished the fire after some 60 hours of fighting, yet on the morning of December 14, vapours emanating from one of the larger tanks that until then had been spared from the conflagration caught fire. This outbreak however could be contained by the crew until extinction due to the lack of fuel source.

Emergency services declared the fire extinguished on December 15. In all, 786 m^3 of foam liquid and 68,000 m^3 of water (53,000 m^3 from supply sources and 15,000 m^3 recycled) were used and 30 km of pipes placed into service. At the height of fire intensity, 180 emergency personnel, 20 vehicles and 26 pumps were deployed.

Photo credit: www.buncefield-oil-fire-hemel-hempstead.wingedfeet.co.uk

Photograph 2: Pipes supplying water to emergency teams

Emergency units had to cope with several difficulties during their mission. First of all, fire fighting equipment had been destroyed by the explosions. The site's water supply reserves could not be used due to destruction of the pumping station located north of retention zone A (see Diagram 1), which had enabled managing onsite water flows. The northern lagoon (fire extinction water supply) had also incurred serious damage. No onsite means of extinction could be employed by fire-fighters on this sector of the terminal. Moreover, the site was covered by a mix of extinction water and fuels flowing out from tanks, thereby hindering access to the various installations.

- ***The main explosion:***

Despite the erroneous information provided by the tank's level indicators, temperature recordings measured within the supply pipeline and inside Tank 912 subsequently enabled confirming that this tank had in effect been filled.

At 5:30 am, tank capacity had been reached and by 5:38 the cloud that formed at the tank base was already visible on video recordings and extended 1 m in thickness, increasing to 2 m by 5:46 am. The tank had thus started to overflow and the explosive cloud that had gathered was spreading over the entire site covering a surface area of 80,000 m². At 5:50 am, the cloud had already moved beyond the company's perimeter; the ensuing explosion was much more violent than the UVCE (Unconfined Vapour Cloud Explosions) type phenomenological models would have predicted:

- **700 to 1,000 mbar at the level of the ignition zone (Fuji and Northgate car parks)**, according to the initial report issued by the British Experts' Committee assigned the Buncefield accident, **whereas calculations based on a mathematical model would have yielded 20-50 mbar;**

- 7-10 mbar at a 2-km distance from the site.

According to surveillance camera videos, the first and most powerful explosion, which occurred on the Northgate parking lot, would have been preceded by another smaller-intensity explosion 1 or 2 seconds prior.

Other lesser explosions occurred subsequently.

The consequences:

- ***Material consequences:***

The blast from the explosion caused **sizable damage within a 800-m radius:** shattered windows, doors broken, the warehouse wall completely destroyed, the roof on a neighbouring house blown off, etc. Cars parked nearby were burned.

On the site of Company No. 1, the damage inventoried consisted of:

- Western sector: All primary storage tanks were destroyed by the fire, except for 2 smaller tanks and 5 small vertical cylinders which incurred minor damage;
- Loading station (western sector), located approximately 200 m from the storage centre: the siding was damaged, but the trucks present remained by and large intact;
- Control room (western sector), also located 200 m from the storage centre: the steel-framed building with panels displayed no effects on its partition walls, yet the interior suspended ceilings revealed some damage;
- Eastern sector: tank roofs experienced structural impacts due to the blast from the explosion.

On the site of the second company, 4 tanks were destroyed by the fire and another smaller tank damaged. Company No. 3 sustained fewer losses.

The houses lying closest to the terminal were heavily affected and residents had to be temporarily housed elsewhere during repair work. A total of 300 other dwellings incurred more minor damage.

- ***Human consequences:***

Of the 43 accident victims, the majority sustained cuts due to broken glass; one was more seriously injured and suffered respiratory problems due to the effects of environmental pressurization. All 10 employees present onsite at the time of the accident were safe.

- ***Environmental consequences:***

Impact on air quality

A tremendous black cloud containing irritating substances rose more than 300 m off the ground and propagated over the southern part of England, migrated over France's Brittany and Normandy coastal regions on December 12, 2005, before moving southwest in the direction of Spain.

Local authorities advised residents living near the terminal to remain indoors; 2,000 individuals were evacuated and then authorized to return home the same evening. England's M1 motorway connecting London with the Midlands remained closed for several days out of fear of repeat explosions.

According to the Health Protection Agency (HPA), the smoke plume was primarily composed of carbon monoxide, carbon dioxide, nitrogen dioxide, volatile organic compounds and polycyclic aromatic hydrocarbons. A portion of the smoke plume generated by the fire rose in altitude and, carried by wind currents, reached France. The French monitoring networks reported that indicators in the country's metropolitan areas reached by the cloud did not reveal any significant degradation in air quality attributable to the accident. A French health and safety institute concluded that, given the smoke plume's composition and level of atmospheric dispersion, the Buncefield fire should not have any adverse health impact on the French population.

Impact on soil and water

A portion of the extinction water could not be contained onsite and flowed into the natural environment, polluting the soil and both surface and underground water resources.

Boreholes were drilled on the terminal site and around its periphery to obtain a reading of the pollution of surface soil layers as a result of the presence of hydrocarbons and fire extinction water.

Once the accident was over, a quality tracking system was implemented for surface water and groundwater within potentially-impacted zones in order to determine the effects of this accident over the short and long term as well as to discern the pollution extension mechanism. In this aim, a large number of piezometers were installed. Pollution due to hydrocarbons and residue from fire fighting foam was detected in groundwater beneath the Buncefield fuel depot and within a radius of more than 2 km to the north, east and southeast.

As an ancillary incident, 800 m^3 of previously-stored extinction water were inadvertently conveyed to a treatment plant and then discharged into the River Colne, a tributary of the Thames. An investigation was conducted following this incident.

Furthermore, some of the liquid foams used contained perfluorooctane sulfonate (PFOS), a water and oil repellent that incites the spreading of fire extinction foams. This product is persistent within the natural environment, a bioaccumulative agent and an endocrine disruptor. Its presence in surface water was investigated for the first time as a consequence of the Buncefield fire. PFOS was indeed detected in small quantities in water extracted from both the Ver and Colne Rivers a few days after the accident. No direct impact could be discerned and a monitoring program was introduced to measure all environmental impacts related to this substance. The potable water threshold of 3 µg/l was not reached in the analysis performed on water intended for human consumption.

- ***Financial consequences:***

The total cost of this accident is still not known in definitive terms yet should exceed 750 million euros; the rebuilding of terminal installations would have amounted to 37 million and the product loss value estimated at 52 million. Other companies located within the industrial zone also sustained substantial damage: some twenty businesses employing a total of 500 personnel were destroyed, while another sixty firms accounting for 3,500 jobs incurred major damage.

European scale of industrial accidents:

By applying the rating rules of the 18 parameters of the scale made official in February 1994 by the Committee of Competent Authorities of the Member States which oversees the application of the 'SEVESO' directive, the accident can be characterized by the following 4 indexes, based on the information available.

The parameters which compose these indexes and the corresponding rating method are indicated in the appendix hereto and are available at the following address: http://www.aria.ecologie.gouv.fr.

The index relative to quantities of hazardous substances equals 5 since approximately a third of the 35,000 m^3 of hydrocarbons stored onsite at the time of the accident escaped or were destroyed in the fire (parameter Q1). Parameter Q2 relative to the quantity of substances that actually contributed to the explosion in TNT equivalences has been rated at a level 3 given that major damage could be observed at distances of up to 800 m.

The index relative to human and social consequences is evaluated at 6 since 4,000 people were forced out of work as a result of damage caused by the explosion on buildings belonging to some 80 companies. The 2,000 nearby residents evacuated from their homes for a half-day yields a level 5 for the H7 parameter and the 43 injured victims reflect a level 4 for the H4 parameter.

The index relative to economic impacts also equals 6, given that the total cost incurred due to the accident should, in all likelihood, wind up topping the 750 million euros.

Since the environmental impacts were not precisely known (i.e. pollution of the water, air and soils), the corresponding index value cannot be determined.

THE ORIGIN, CAUSES AND CIRCUMSTANCES OF THE ACCIDENT

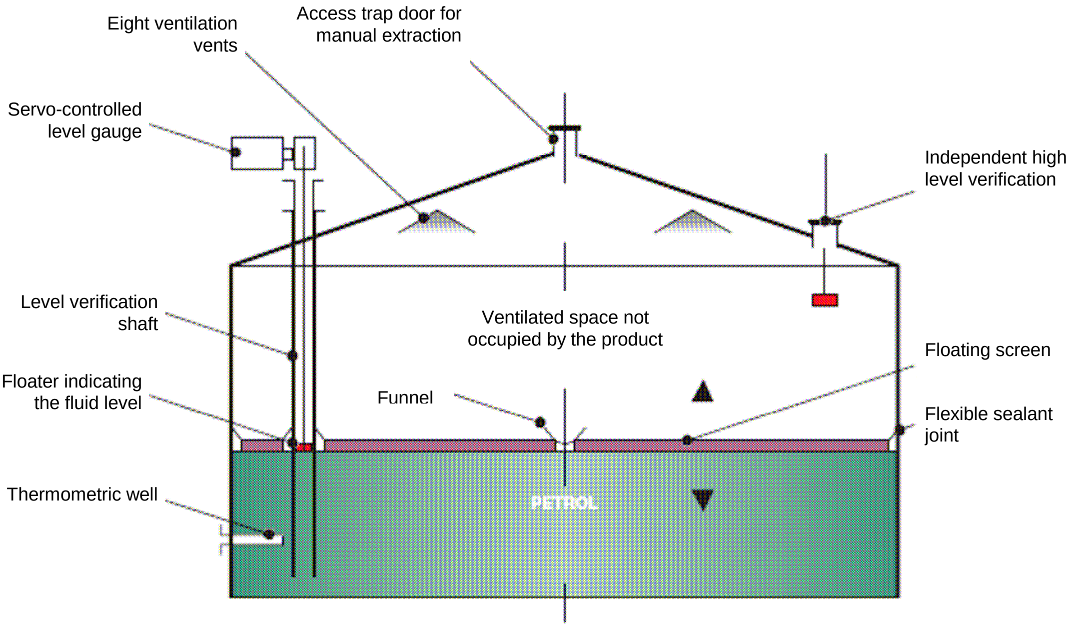
Control and measurement system installed on the tanks:

Tank 912 was equipped with a wide array of measurement instruments: fluid level, temperature, etc. This equipment was connected to an automatic tank gauging system common to all tanks located on the Company 1 site. Data recordings were transmitted and verified within a control room where a single operator is able to activate various remote-controlled valves. The **automatic tank gauging system** also makes it possible to interpret information and correlate it with critical event scenarios, which if detected by the system trigger an alarm. All measurement readings are recorded, thereby creating a system that relies upon a large amount of input data.

The tank had moreover been equipped with an **independent, "high level" control system** with both a visual and sound alarm that at the same time closes the pertinent set of valves on the piping network. An alert is sent to the instrumentation consoles and computer monitoring system of the carrier, who must then also proceed with closing the client's distribution valve.

Moreover, a control room switch allows cancelling the transmitted signal sent to the fuel supplier during the "high level" test periods. When placed in the active mode, a red indicator lights up on the control panel.

Diagram 2: Control instrumentation present on Tank 912



Source: Buncefield Investigation, Third progress report

Accident causes:

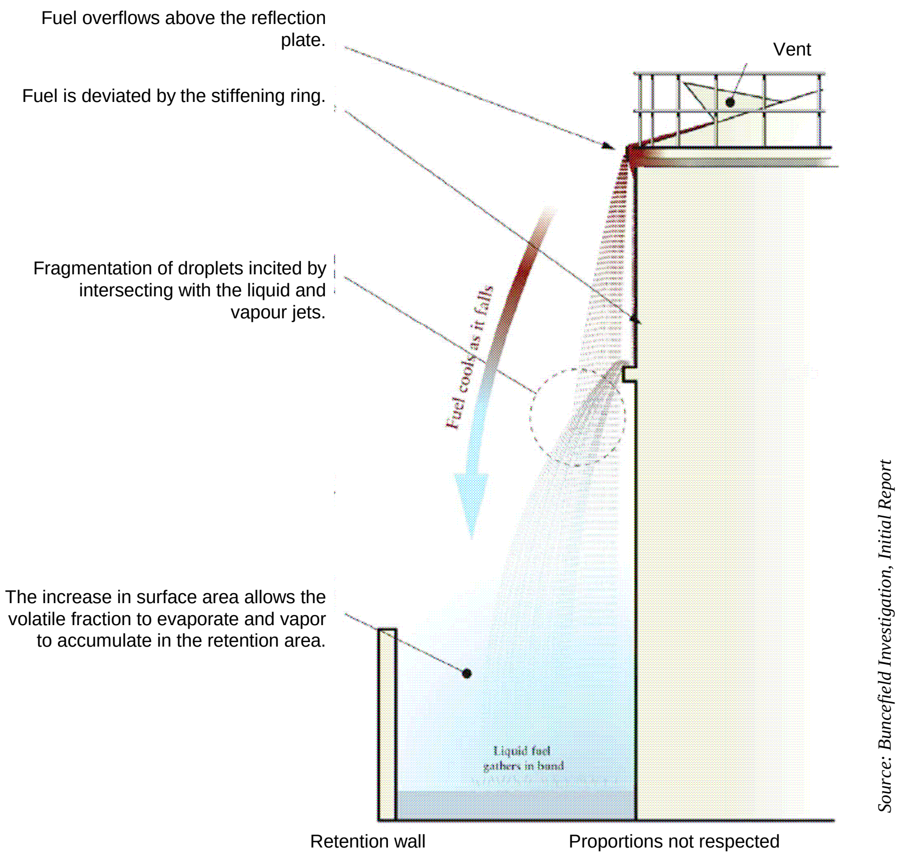
Neither of the two automatic level detection systems within the tank, as detailed above, was operable, and the gasoline supply into Tank 912 was not shut off. An expert evaluation was conducted to determine the reasons for malfunction of the automatic control and tank gauging systems. Following tank overflow, an explosive cloud formed and then spread over the site.

The information stemming from the gasoline distribution control system indicates that no high-level alarm from the first company's western site had been received. It was not possible however to test the high-level control gauge nor even verify the state of cables between Tank 912 and the substation, due to the extent of damage sustained. The high-level gauge could be located and assessed.

The first and most violent explosion occurred at the level of the Fuji and Northgate parking lots, completely devastating this part of the site. By spreading over this uncluttered zone, the necessary explosive conditions (i.e. a concentration lying between the lower explosive limit - LEL - and the upper explosive limit - UEL) were in fact attained. Gasoline vaporization was facilitated by 2 factors:

- Initially, yet to a more minor extent, product flow deviation by means of a tank stiffening ring (see Diagram 3).
- But more importantly, the high concentration of non-stabilized butane (10%) in this type of "winter" fuel incited both a high amount of gas evaporation even at relatively low temperatures (high vapour pressure: 70 - 100 kPa) and the formation of a butane cloud (estimated at several tons, given the quantity of gasoline that poured out).

Diagram 3: Tank 912 overflow phenomenon



An estimation of effects from excess pressure at the level of the Fuji and Northgate parking lots (700 to 1,000 mbar) is not consistent with current understanding of the UVCE phenomenon (modelled level: 20 to 50 mbar).

In its report entitled "*Buncefield Explosion Mechanism - Advisory Group Report*" released on August 16, 2007, the MIIB (Major Incident Investigation Board) group of experts forwarded the hypothesis of an acceleration in the flame front caused by turbulence created when moving past the alignment of landscaped alleyways.

Two hypotheses have been adopted for the actual cloud ignition locations: either the backup generator booth or, more likely, the emergency pump utility room upon start-up of the site emergency backup system.

ACTIONS TAKEN

Subsequent to this accident, an independent commission was set up in order to pursue investigations on the causes and consequences of the terminal explosion: "Buncefield Major Incident Investigation Board" (MIIB). One of the key emphases consisted of understanding the phenomenon that occurred and the set of circumstances that led to such unexpected over-pressurization effects.

From a more technical standpoint, various operations were performed onsite in order to limit secondary pollution and facilitate site access, particularly for the purpose of conducting the necessary research:

- Fire extinction water and other polluted water that could have been contained onsite was discharged during the three-week period following the accident and then stored on various sites. The 12,000 m³ of the most polluted extinction water were treated by the reverse osmosis process. The less polluted water (4,000 m³) was stored while awaiting an adapted form of treatment.
- The site was cleared to facilitate access. In February 2006, retention zone A, which includes Tank 912, was made accessible for the first time. The presence of inflammable vapour was subjected to monitoring.
- The southern part of the terminal, which sustained less damage, was renovated during the month of August to enable discharging stored fuel supplies. The third company based onsite undertook, in September 2006, transfer operations necessary for continuing with the tank investigations. It is anticipated that site installations will be fully dismantled by the end of 2007.

The British Ministry of the Environment launched, as a first time initiative, a national campaign of PFOS analysis in groundwater, with 150 measurement points already selected. The Ministry is also working on producing a modelling software to predict the evolution of pollutant flows in aquifers.

British authorities started disseminating, as of February 2006, to all operators of English installations similar to the Buncefield fuel terminal a list of safety actions to be performed immediately (operational safety, personnel training, management system robustness, effective introduction of best practices regarding precautions, emergency intervention and accident response actions, etc.). Inspections were thereafter scheduled in order to verify installation compliance and the adequate implementation of intended safety measures, along with publication of an analysis report. Other recommendations were subsequently disseminated, focusing on proper operating techniques for safety equipment and barriers (pipelines, tank overflow prevention, valves, retention basins, etc.).

Once this set of tasks had been accomplished, MIIB published several documents offering feedback on this accident:

- 3 progress reports on the investigation into the Buncefield accident: *Progress report Buncefield*, (February 21, 2006); *Second progress report* (April 11, 2006); *Third progress report* (May 9, 2006).
- *"Recommendations on the design and operations of fuel storage sites",* March 29, 2007.
- *"Recommendations on emergency preparedness for, response to and recovery from major incidents*", July 17, 2007.
- *"Safety and environmental standards for fuel storage sites - Buncefield Standards Task Group (BSTG) - Final report",* July 24, 2007.
- *"Buncefield explosion mechanism - Advisory Group Report"*, August 16, 2007.

Following this accident, inspections were also conducted inside fuel storage terminals in France and other European countries.

LESSONS LEARNT

Although the survey and investigation reports have not all been issued, a number of lessons can already be drawn from this accident.

First of all, the potential of a very extensive explosive cloud forming must not be overlooked when predicting hazardous phenomena, and precautions relative to possible offsite ignition sources must be anticipated. This approach can be justified even more vigorously given that the products involved are highly inflammable. Moreover, understanding the explosion phenomenon of an inflammable cloud needs to be sharpened in order to better predict the over-pressurization effects being generated.

This accident raises various organizational aspects as well, i.e.:

- ✓ Contractually speaking, fuel storage sites are given limited manoeuvring room regarding the quantities of product they receive; they are not in a position to refuse delivery and are thus faced with tight logistics constraints and very narrow safety margins.
- ✓ Buncefield terminal installations and associated infrastructure were not recent. Had they been sufficiently well maintained?
- ✓ Were operator qualifications and knowledge of hazards adequate?
- ✓ Would the involvement of several entities (terminal operator, pipe carrier) have exerted an influence over general safety management functions?
- ✓ The good working order and potential to perform periodic inspections (by both operators and competent authorities) with respect to monitoring data recordings, detection and alarm systems, both in terms of prevention and in the event of an accident.
- ✓ Heightened vigilance during transfer of the non-stabilized "winter" type products and products with high butane concentrations (specific to Great Britain).
- ✓ Gap between the evolution of the sinister visible on the CCTV and the personnel's response.

From a technical point of view, many aspects need to be pursued and improved on sites such as Buncefield, namely:

- ✓ Electronic monitoring/verification and associated alarms on the tanks and pipes to provide appropriate alerts in the event of malfunction;
- ✓ Detection of inflammable vapours immediately adjacent to tanks and pipes;
- ✓ Reactions upon detection of abnormal conditions, such as the automatic closing of supply valves and pipeline inflow valves;
- ✓ The extent to which auxiliary tank components serves to avoid or contribute to formation of an inflammable vapour cloud (e.g. stiffening ring);
- ✓ The place and/or means for protecting backup installations;
- ✓ The structural integrity of confinement facilities and the proper design of retention basins.

The human consequences could have taken dramatic proportions, yet the time and day of the accident kept the number of people located near or on the specific site, which is typically extremely busy, quite low. Furthermore, the issue of urbanized areas located around high-risk sites such as fuel terminals once again gets raised.

This version is not yet finalized and includes information available through 8 October, 2007.