Health and Safety Executive

Hazards of liquid hydrogen

Position paper

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In the long term the key to the development of a hydrogen economy is a full infrastructure to support it, which include means for the delivery and storage of hydrogen at the point of use, eg at hydrogen refuelling stations for vehicles. In the meantime as an interim measure to allow the development of refuelling stations and rapid implementation of hydrogen distribution to them, liquid hydrogen (LH2) is considered the most efficient and cost effective means for transport and storage. This will result in increasing amounts of LH2 transported by road, and possibly by rail, and storage of moderately large quantities at refuelling stations, many of which will be in urban areas. Although cryogenic liquid storage has been used safely for many years in secure and regulated industrial sites, its use in relatively congested, highly populated urban areas presents a new set of issues in relation to security, safety and associated planning. The Health and Safety Executive commissioned the Health and Safety Laboratory to identify and address issues relating to bulk liquid hydrogen transport and storage and update/develop guidance for such facilities. This position paper, the first part of the project, assesses the features of the transport and storage aspects of the refuelling stations that are now being constructed in the UK, compares them to existing guidance, highlights gaps in the regulatory regime and identifies outstanding safety issues.

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Objectives

In the long term the key to the development of a hydrogen economy is a full infrastructure to support it, which include means for the delivery and storage of hydrogen at the point of use, eg at hydrogen refuelling stations for vehicles. As an interim measure to allow the development of refuelling stations and rapid implementation of hydrogen distribution to them, liquid hydrogen is considered the most efficient and cost effective means for transport and storage.

The Health and Safety Executive have commissioned the Health and Safety Laboratory to identify and address issues relating to bulk liquid hydrogen transport and storage and update/develop guidance for such facilities. This position paper, the first part of the project, assesses the features of the transport and storage aspects of the refuelling stations that are now being constructed in the UK, compares them to existing guidance, highlights gaps in the regulatory regime and identifies outstanding safety issues.   The findings, together with the results of experiments to improve our understanding of the behaviour of liquid hydrogen, will inform the development of the guidance for refuelling facilities

Main Findings

1. Applications involving liquid hydrogen present additional fire and explosion hazards to those arising from use in gaseous form, which need to be fully appreciated if levels of safety comparable to those from conventional fuels such as petrol and liquefied petroleum gas are to be achieved.

2. The requirements in the current regulatory framework are adequate for controlling the fire and explosion hazards from the transport and storage of liquid hydrogen. Where safety issues arise they are in the understanding of liquid hydrogen behaviour and the lack of standards and guidance to assess the hazards, ensure equipment is fit for purpose and to demonstrate compliance with the regulations.

3. The consequences of an accidental spillage or leak of liquid hydrogen are poorly understood, particularly the initial stages of pool spread and vaporisation. A better understanding of this initial phase together with more experimental data on the dispersion phase are required if reliable models for predicting the consequences are to be developed and validated.

4. The separation distances given in current standards and guidance on hydrogen applications are derived from industrial experience and if applied to hydrogen refuelling stations are likely to put severe limitations on where they could be located in urban areas. There is a need to assess the scientific basis of the recommended distances, to see if they can be safely reduced, either because they are overly conservative or by the use of appropriate mitigation measures.

5. Liquid hydrogen presents severe challenges to the materials it comes into contact with, in equipment such as pumps, vaporisers, pipework and storage vessels.   It is essential that materials used are properly assessed to ensure they are compatible with the extremely low temperature of liquid hydrogen (-253^{o}C), are resistant to hydrogen embrittlement (causing weakening of the material) and have a low permeability (passage of hydrogen through the material).

6. The risks of widespread use of road tankers to supply refuelling stations with liquid hydrogen, particularly through urban areas, needs to be comprehensively assessed and

compared to those currently incurred by the transport of petrol or diesel fuels. An issue for particular consideration is the control of the bulk transport of liquid hydrogen through tunnels.

1 INTRODUCTION

In the long term the key to the development of a hydrogen economy is a full infrastructure to support it, which include means for the delivery and storage of hydrogen at the point of use, eg at hydrogen refuelling stations for vehicles. The problem with the currently available means of transporting and storing hydrogen, either as a compressed gas or a cryogenic liquid, is the low volumetric energy density (VED). For example on a volume basis hydrogen gas compressed to a pressure of 700 bar, the current upper limit for vehicle hydrogen storage systems, contains about one seventh and liquid hydrogen about one quarter the energy of petrol. Considerable effort is being devoted to develop alternative means of storing hydrogen, for example bonding hydrogen to other materials, to increase the VED. It will be, however, some years before any of these new storage technologies will be viable alternative means to storing and transporting hydrogen. In the longer term hydrogen pipework systems are likely to be developed, possibly using the existing natural gas network, for delivering hydrogen. It is also possible to generate hydrogen at the point of use, either by the steam reformation of hydrocarbons, or the electrolysis of water. On site generation systems are currently in use at a number of demonstration refuelling stations. Small-scale ‘home energy stations’ are also being developed that are capable of generating sufficient hydrogen to power a fuel cell vehicle for daily operation as well as providing the home with electricity. The widespread adoption of onsite hydrogen generation would remove the need for much of the infrastructure that would be required for the supply and bulk storage of hydrogen at refuelling stations.

In the meantime as an interim measure to allow the development of refuelling stations and rapid implementation of hydrogen distribution to them, liquid hydrogen (referred to in industry as LH2) is considered the most efficient and cost effective means for transport and storage. This will result in increasing amounts of LH2 transported on our roads, and also possibly by rail, and storage of moderately large quantities at refuelling stations, many of which will be in urban areas. Although cryogenic liquid storage has been used safely for many years in secure and regulated industrial sites, its use in relatively congested, highly populated urban areas presents a new set of problems in relation to security, safety and associated planning.

The Health and Safety Executive have commissioned the Health and Safety Laboratory to identify and address issues relating to bulk liquid hydrogen transport and storage and update/develop guidance for such facilities. This position paper, the first part of the project, assess the features of the transport and storage aspects of the refuelling stations that are now being constructed in the UK, compares them to existing guidance, highlights gaps in the regulatory regime and identifies outstanding safety issues. The findings, together with the results of experiments to improve our understanding of the behaviour of LH2, will inform the development of the guidance for refuelling facilities.

2 HAZARDS OF HYDROGEN

Hydrogen at room temperature and pressure is a colourless, odourless flammable gas that is lighter than air. The public perceive hydrogen as a very dangerous substance due to its association with the Hindenberg airship disaster and the hydrogen bomb. It is true that hydrogen has many characteristics that are significantly different from the conventional gaseous fuels, such as natural gas and the liquefied petroleum gases propane and butane, that potentially render it more hazardous to transport and store. If, however, these differences are adequately taken into account in the design, construction and operation of facilities handling hydrogen there is no reason why hydrogen cannot be used as safely as any other fuel.

2.1 PROPERTIES AND CHARACTERISTICS OF HYDROGEN

A comparison of the characteristics of hydrogen against two other widely used fuels, natural gas (NG) and liquefied petroleum gas (LPG), is given in Table 1. The significant differences of hydrogen from the other fuels, that are used in gaseous form, and the implications for safety are discussed below.

Table 1 - Characteristics of hydrogen, dry natural gas and gaseous propane

Property	Dry natural gas (methane)	LPG (propane)	Hydrogen
Density (Kg/m^3) *	0.65	1.88	0.090
Diffusion coefficient in air (cm^2/s) *	0.16	0.12	0.61
Viscosity (g/cm-s x 10^{-5}) *	0.651	0.819	0.083
Ignition energy in air (mJ)	0.29	0.26	0.02
Ignition limits in air (vol %)	5.3 – 15.0	2.1 – 9.5	4.0 – 75.0
Auto ignition temperature (C)	540	487	585
Specific heat at constant pressure (J/gK)	2.22	1.56	14.89
Flame temperature in air (C)	1875	1925	2045
Quenching gap (mm) *	2	2	0.6
Thermal energy radiated from flame to surroundings (%)	10-33	10 - 50	5-10
Detonability limits (vol % in air)	6.3-13.5	3.1 – 7.0	13-65
Maximum burning velocity (m/s)	0.43	0.47	2.6

* at normal temperature and pressure – 1 atmosphere and 20^{o}C

2.1.1 Propensity to leak

2.1.1.1 Low viscosity

Hydrogen gas has a very low viscosity and so it is very difficult to prevent hydrogen systems from developing leaks. Pipework that was 'leak tight' when pressure-tested with nitrogen will often be found to leak profusely when used on hydrogen duty.

Hydrogen leakage through welds, flanges, seals, gaskets, etc is an important consideration and an important design and operational issue for hydrogen systems.

The use of suitable sealing interfaces and appropriate components within a hydrogen system, however, will significantly reduce the likelihood of this occurring if fitted by a competent person. For high-pressure storage systems, hydrogen would leak nearly three times faster than natural gas and over five times faster than propane. However the low VED of hydrogen means that it produces substantially lower energy leakage rates.

2.1.1.2 Extremely high diffusivity

Hydrogen is very much lighter than air and is also very diffusive. Thus, unlike heavier gaseous fuels, if a hydrogen leak occurs in an open or well-ventilated area its diffusivity and buoyancy will help to reduce the likelihood of a flammable mixture forming in the vicinity of the leak. However, as with other gases when leaks occur within poorly ventilated or enclosed areas, the concentration may rapidly reach dangerous levels. Due to its lightness, hydrogen will concentrate in elevated regions of an enclosed space, whereas other gases, dependent upon their relative mass, will concentrate at ground level (LPG) or at elevation (NG). If unprotected electrical equipment or other sources of ignition are present, the risk from explosion could be considerable.

As hydrogen diffuses more rapidly through air and through solid materials compared to other fuel gases such as methane or propane, it will usually disperse more rapidly if released, although buoyancy effects are less significant for high momentum releases from high-pressure hydrogen systems. When harnessed through intelligent equipment design and layout, this buoyancy and hydrogen's rapid dispersion rate can become a significant safety asset.

2.1.1.3 High buoyancy

The buoyancy of hydrogen can also be used to manage the risk normally associated with fuel handling by segregating the hydrogen from foreseeable sources of ignition using internal partitions and bulkheads and differential pressurisation. This can also be done by locating all potential sources of ignition well below the level of the equipment from which hydrogen may leak and accumulate, and ensuring adequate ventilation and safe discharge of the exhaust.

2.1.2 Propensity to cause embrittlement

Hydrogen can cause embrittlement of high strength steels, titanium alloys and aluminium alloys with cracking and catastrophic failure of the metals at stress below the yield stress. This is most commonly related to the carbon content of metallic alloys. Pure, unalloyed aluminium, however, is highly resistant to embrittlement. The industry standard for components in hydrogen service is grade 316 stainless steel. Cupro-nickel is also suitable for hydrogen service and copper can be used for low-pressure applications.

2.1.3 Propensity to ignite

2.1.3.1 Wide flammability range

Hydrogen readily forms an explosive mixture with air. The range of hydrogen/air mixtures that will explode is wide. Mixtures from 4% v/v hydrogen, which is the lower explosive limit (LEL), up to 75% v/v, which is the upper explosive limit (UEL), may propagate a flame. The wide range of flammability of hydrogen-air mixtures compared to propane and methane-air mixtures is, in principle, a disadvantage. There are, however, only minor differences between the LEL of hydrogen and that of methane or propane. The LEL of hydrogen is considered by many experts to have a greater significance in hazard ranking than the width of the fuel's flammable range. Furthermore, in the case of low momentum releases, the dispersion characteristics of hydrogen will make it less likely that a flammable mixture will form.

2.1.3.2 Very low ignition energy

The energy necessary to initiate a hydrogen/air explosion is very small. The ignition energy for a 2:1 hydrogen/oxygen mixture is only about 0.02 mJ. This is less than one tenth that of other fuels such as methane, LPG or petrol. Even very small sparks, such as those produced by wearing certain types of clothing, are capable of igniting hydrogen/air mixtures and causing an explosion.

2.1.3.3 Spontaneous ignition

Hydrogen has been demonstrated to spontaneously ignite on sudden release from pressurised containers. A number of incidents have been attributed to spontaneous ignition, but the mechanism responsible for these ignitions is not fully understood.

2.1.4 Consequences of a fire / explosion

2.1.4.1 Invisible flame

Hydrogen burns with a hot flame, but as it produces no soot the flame is pale, colourless and almost invisible in daylight, making it difficult to detect the flame. Although the heat radiated by a hydrogen flame is also relatively low compared to hydrocarbons (eg only about 10% of that radiated by an equal sized propane flame) it is important to take into account the differences in heats of combustion, burning rate and flame size. For example the radiation from a flame above a burning pool of liquid, per unit area of pool surface, is about the same for liquid hydrogen and liquid natural gas (about 20 kW per square foot of pool surface[70]). The rapid burning rate of hydrogen, however, reduces the total energy radiated for equal volumes of liquid consumed. This low emissivity of hydrogen flames (total heat flux radiated) may reduce the heat transfer by radiation to objects near the flame, thus reducing the risks of secondary ignition and burns.

2.1.4.2 Rapid burning rate

The maximum burning velocity of a hydrogen-air mixture is about eight times greater than those for natural gas and propane air mixtures. The high burning velocity of hydrogen makes it difficult to confine or arrest hydrogen flames and explosions, particularly in closed environments. In its favour, however, this rapid rate of deflagration means that hydrogen fires transfer less heat to the surroundings than other gaseous fuel fires, thereby reducing the risk of creating secondary fires in neighbouring materials. Another downside of a higher burning velocity of hydrogen is that for a given scenario hydrogen would result in higher explosion pressures and rates of pressure rise than other fuels.

2.1.5 Possibility of detonation

Hydrogen/air mixtures have a greater propensity to detonate than mixtures of air with other more common flammable fuels. Detonations cause much more damage and are far more dangerous than ordinary explosions (deflagrations). However, due to the rapid dispersal characteristics of hydrogen, this is only likely to occur in a confined or congested space.

2.2 LIQUID HYDROGEN

Though hydrogen will be usually used in gaseous form, eg in fuel cells and internal combustion engines, at present the most efficient way to transport and store hydrogen is as a liquid. The downside of using liquid hydrogen is that the liquefaction process using current technology is not energy efficient, the process consuming one-third or more of the energy in the hydrogen.

Liquid hydrogen (LH2) is transparent, odourless and not corrosive or significantly reactive. Hydrogen co-exists in two different forms, ortho-hydrogen where the spins of the protons in the two atoms of a hydrogen molecule are in the same direction and para-hydrogen with the spins in opposite directions. The ortho- and para-hydrogen molecules have slightly different physical properties, but are chemically equivalent, so the hazards associated with the use of hydrogen are the same irrespective of molecular form. At thermodynamic equilibrium and room temperatures gaseous hydrogen is made up of a mixture of 75% ortho-hydrogen and 25% para-hydrogen. Ortho-hydrogen is unstable at the low temperature required for LH2 and after liquefaction will change to the more stable para-hydrogen over time (several days). This process releases heat that increases the vaporisation rate of the liquid.

Hydrogen is produced as a gas, the main method of bulk production being the steam reformation of NG or LPG. Some hydrogen is also produced by electrolysis of water, which also produces it as a gas. Hydrogen is a permanent gas and cannot be liquefied by compression alone at normal ambient temperatures, like the liquefied petroleum gases, and then kept in liquid form in pressurised containers at ambient temperatures. Before it can be liquefied it has to be first cooled below its critical temperature (-240^{o}C) and then transported or stored in vacuum insulated containers at a temperature below its boiling point (-253^{o}C at atmospheric pressure). An ortho-para catalyst is used during the liquefaction process to convert most of the ortho to para-hydrogen during liquefaction, which helps to reduce the vaporisation rate of the stored liquid by minimising the amount of the conversion occurring after liquefaction.

Transporting and storing hydrogen as a cryogenic liquid presents additional hazards that need to be addressed. In addition for many applications the hydrogen needs to be re-gasified before use by a suitable vaporiser.

2.2.1 Low temperature

Materials for piping, vessels and fittings need not only be suitable for hydrogen service, eg resistant to hydrogen embrittlement, but also suitable for the low temperatures they will be exposed to. Consideration also needs to be given to the thermal expansion and contraction of equipment when exposed to temperature fluctuations of ambient to LH2 temperatures. For example the pipework and fittings used to transfer liquid from a delivery tanker to a storage vessel has to be able to withstand a change from ambient to LH2 temperatures, a temperature range of about 280 degrees.

Liquid hydrogen and also the cold boil-off gas, evolving from the liquid, can produce severe burns (similar to thermal burns) upon contact with the skin. Delicate tissue, such as those of the eyes can be injured by exposure to the cold gas or splashed liquid in a brief period of time, which would be normally too short to effect the skin of the hands or face. Contact between unprotected parts of the body with un-insulated piping or vessels containing liquid hydrogen can cause the flesh to stick and tear. There is also a cold burn hazard from condensed liquid air that may be dripping from cold lines, vent stacks or vaporiser fins.

The dispersion behaviour of a liquid release of hydrogen is likely, at least in the early stages, to be different from a release from gaseous storage. Though leaks of liquid hydrogen would rapidly vaporise the gaseous hydrogen would be initially very cold, especially if there was a significant leak. The gas, until it warms up, would be denser than air and behave as a dense gas and start accumulating at low level.

When a cold liquid comes into contact with hot liquid, that is at a temperature above the boiling point of the cold liquid, there is the possibility of a rapid phase transition (RPT) explosion. A RPT arises due to a physical process, the explosive vaporisation of the cold liquid, rather than a chemical reaction and the energy released is usually small compared to a chemical explosion. The mechanism for the rapid heat transfer required for this type of explosion is still not fully understood, but a spill of LH2 onto water or the spilled liquid flowing onto water could potentially create the conditions for a RPT. RPTs have been observed for spills of liquefied natural gas (LNG) on water[88], but no record of a RPT resulting from a LH2 spill has been found. This does not mean that RPTs from LH2 can be ruled out.

2.2.2 Boil-off

Storage of liquid hydrogen is particularly challenging due to its relatively low heat of vaporisation and low boiling point. Even though the liquid hydrogen is stored in highly insulated containers, no insulation is perfect and so there will be some heat transfer into the liquid and thus loss of hydrogen due to boil-off. For small storage volumes, for example the fuel tank on a car, the boil-off rate can be 1% or greater per day, but this decreases as the storage volume increases, dropping to a fraction of a per cent for volumes of the order of tens of cubic metres.

Cryogenic hydrogen containers are not designed to withstand the high pressures that would be generated if the liquid vaporises, liquid storage being typically operated at pressures no greater than 5 bar. The vaporisation of liquid hydrogen to gas at standard conditions results in an expansion of approximately 845 times. If the resulting gaseous hydrogen is completely confined in a fixed volume and taking into account the compressibility of hydrogen, this transition can result in a final pressure of 172 MPa (1720 bar) from an initial pressure of 0.101 MPa (atmospheric pressure). Hence LH2 storage tanks are equipped with a pressure relief device to prevent over-pressurisation. The gas vented off will be cold so it initially may accumulate at low level until it warms up and buoyancy causes it to rise.

2.2.3 Condensation

Another consequence of liquid hydrogen's low temperature is that, with the exception of helium, all gases will be condensed and solidified should they be exposed to it. Leaks of air past valve seals, gaskets, joints etc into systems containing liquid hydrogen can lead to several hazards. The solidified air can plug pipes and orifices and jam valves. The reduction in volume of the condensing air may create a vacuum that can draw in yet more air, in a process know as cryopumping. Should the leak persist for long periods, large amounts of solidified air can accumulate and displace the liquid hydrogen. Storage tanks and other containers should be kept under positive pressure to prevent air ingress. Nitrogen, often used as a purge gas, can also condense and solidify, and the solid particles of nitrogen cause damage to components or cause failures such as preventing a valve from fully closing. This can be avoided if the nitrogen purge is followed by a purge of gaseous hydrogen at ambient temperatures. Ideally helium should be used to purge liquid hydrogen vessels and transfer lines, as this will not condense out at liquid hydrogen temperatures, but the price of helium makes this an expensive option.

As the boiling and melting points of oxygen are higher than for nitrogen, oxygen will preferentially condense out leading to oxygen enrichment of the solidified material. Initial condensation can result in enrichments of up to 50% oxygen and subsequent evaporation of the condensate can result in even higher oxygen concentrations. Should the system be allowed to warm up, eg for maintenance, the solid material will re-gassify possible resulting in high pressures and an oxygen enriched flammable mixture. Oxygen-enriched air reduces the ignition energies, increases the combustion rate of flammable and combustible materials and increases the likelihood of a detonation. The amount of oxygen can build up during repeated refilling and pressurisation of permanent LH2 storage vessels, as result of inadequate purging or trace quantities of oxygen in the source gaseous hydrogen. As a further precaution periodic cleaning of permanent storage vessels may be necessary.

Similarly spills of liquid hydrogen can result in air condensing out in and around the pool of liquid. This can result in the formation of zones in the pool, containing an explosive mixture of liquid hydrogen and solidified oxygen-enriched air. These mixtures are shock-sensitive and can detonate with a yield similar to an explosive. As the pool warms up and the hydrogen vaporises any deposits of solidified air will also vaporise and potentially result in an oxygen enriched flammable atmosphere.

3 REGULATIONS, CODES AND STANDARDS

Many UK regulations dealing with health and safety stem from the implementation into UK law of a series of “New Approach” Directives from the European Union (EU). These directives are intended to facilitate the creation of a single European market by establishing common safety standards, referred to as essential health and safety requirements (EHSR), for many types of product together with a system of CE marking, undertaken by accreditation organisations known as Notified Bodies, to demonstrate compliance with the directive. They are called “New Approach” as the directives set out general requirements, while the specific detail for conforming to these requirements is described in European harmonised standards. Some of the “New Approach” directives give general health and safety principles for the workplace and general requirements for the management of health and safety. Others describe, in general terms, product law applicable to the design and construction of items, such as machinery and equipment intended for specific applications, for example where there is a risk of fire and explosion. These are known as product directives. More information on EU legislative system and how it operates can be found in the BSI Published Document PD 6686[1].

In the sections below the main regulations, codes and standards relevant to the transport and storage of liquid hydrogen, that is those mainly aimed at reducing the risk of fire and explosion, the principal risk from liquid hydrogen, are summarised.

3.1 UK REGULATIONS

The primary regulations that will govern the handling of liquid hydrogen and the associated infrastructure are the DSEAR, COMAH, PER and the Carriage of Dangerous Goods Regulations (see sections 3.1.1 to 3.1.4) all of which arise from implementation of EU Directives. The other regulations described below will still need to be adhered to, but in complying with the four primary regulations most of their requirements are likely to have also been met. General health and safety law, which would apply to any workplace or public area, will also need to be met.

3.1.1 Dangerous Substances and Explosives Atmospheres Regulations (DSEAR) 2002

DSEAR[2] sets out the UK law for the management of the risks from the use or presence of dangerous substances in the workplace. These include substances with explosive properties, but not specifically used as an explosive, eg flammable gases and liquids such as hydrogen. They implement in the UK the requirements of the ATEX 137 Directive[3] (sometimes also called the ATEX 118a Directive), often just referred to as the User Directive. The Directive requires the employer to prepare an Explosion Protection Document that includes identification of the fire and explosion hazards, classification of the areas where explosive atmospheres may exist, an evaluation of the risks and specification of the measures to prevent, or where this is not possible mitigate the effects, of an ignition. Although the DSEAR regulations do not require specifically the production of an explosion protection document, as required by the User Directive, the key requirement of the Regulations is that risks from dangerous substances are assessed and controlled. DSEAR also implements in UK law those parts of the EU Chemical Agents Directive[4], that cover measures to prevent the occurrence of hazardous concentrations of flammable materials. The Health and Safety Executive (HSE) has responsibility for the DSEAR regulations and in Britiain they are the main enforcing authority.

3.1.2 Control of Major Accident Hazard (COMAH) Regulations

The Control of Major Accident Hazard Regulations 1999 (COMAH)[5] came into force on 1 April 1999 and were amended by the Control of Major Accident Hazard (Amendment) Regulations 2005[6] as of 30 June 2005. They implement the EU Directive 96/82/EC[7], known as the Seveso II Directive, as amended by Directive 2003/105/EC[8] and replace the Control of Industrial Major Accident Hazards Regulations 1984 (CIMAH). They apply mainly to the chemical industry, but also to storage facilities where threshold quantities of the dangerous substances identified by the Regulations are kept or used. There are two threshold levels given in the regulations. Sites with quantities exceeding the lower level are known as 'lower-tier' sites and those exceeding the upper value as 'top-tier' sites. The operators of all lower-tier sites must: notify the Competent Authority (CA); prepare a major accident prevention policy (MAPP); take 'all measures necessary' to prevent a major accident; and, report major accidents. Operators of top-tier sites in addition to the duties placed on lower-tier sites must prepare a safety report and make arrangements for emergency planning. The CA is HSE and the Environment Agency (EA) in England and Wales, and HSE and the Scottish Environment Protection Agency (SEPA) in Scotland. The requirements of COMAH are fully explained in a guidance document published by HSE[104].

Threshold values for hydrogen are 5 tonnes and 50 tonnes, which means that many of the larger hydrogen refuelling stations would be classed as 'lower-tier' sites.

3.1.3 Pressure Equipment Regulations (PER) 1999

These regulations were made by the DTI to implement parts of the EU Pressure Equipment Directive (PED)[9]. The Directive aims to harmonise the laws on the design, manufacture and conformity assessment of pressure equipment that is subjected to an internal pressure greater than 0.5 bar above atmospheric pressure. The application of PER[10] to the design, placing on the market and putting into service of items of pressure equipment and assemblies requires knowledge of the contents, the maximum allowable pressure and the volume of the item, or diameter in the case of a pipe. This information is then used to determine the appropriate conformity assessment procedure, which is linked to the risk presented in the event of an uncontrolled release of stored energy. The conformity assessment procedure normally requires an independent assessment of the equipment by a Notified Body.

PER will apply to vessels and associated pipework for transporting and storing liquid hydrogen as well as the vaporisers for re-gasifying the hydrogen.

3.1.4 Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations (CDG)

In 2004, 14 sets of regulations and seven approved documents were consolidated into a single set of regulations, the Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2004[11], for the carriage of dangerous goods by road and rail. The CDG or the Carriage Regulations, as they are also known as, implement in UK law the requirements of:

a) Council Directive 94/55/EC[12] on the approximation of the laws of the Member States with regard to the transport of dangerous goods by road as amended by Directives 2000/61/EC[13] and 2003/28/EC[14]. These Directives apply the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).

b) Council Directive 96/49/EC[15] on the approximation of the laws of the Member States with regard to the transport of dangerous goods by rail as amended by Directives 2000/62/EC[16] and 2003/29/EC[17]. These Directives apply the European Agreement concerning the International Carriage of Dangerous Goods by Rail (RID).

c) Council Directive 1999/36/EC[18] concerning transportable pressure equipment, the Transportable Pressure Equipment Directive (TPED).

The CDG Regulations place general duties on everyone with a role in the carriage of dangerous goods, which includes hydrogen, and specific duties on those in the transport chain, ie consignors, carriers, loaders, packers, etc. These duties cover: classification, packing and tank provisions; consignment procedures including documentation and vehicle marking; construction and testing of packaging, containers and tanks; carriage, loading, unloading and handling; vehicle crews, equipment, operation and documentation (including training); and construction and approval of vehicles.

The CDG Regulations were amended in 2005[19] to implement the 2005 updates to the ADR and RID Directives and to put in place the transfer of the policy responsibility for the Regulations from HSE to the Department of Transport (DfT). HSE retains primary responsibility for the enforcement of the Regulations. The police and DfT's Vehicle and Operator Services Agency (VOSA) traffic examiners are also empowered to enforce certain parts of the Regulations, targeted at ensuring compliance by carriers. The CDG Regulations are regularly updated to take into account the biennial updates of the ADR and RID Directives, the latest version of the Regulations, CDG 2009[20], came into force on 1 July 2009.

3.1.5 Notification of Installations Handling Hazardous Substances (NIHHS) Regulations

The Notification of Installations Handling Hazardous Substances (NIHHS) Regulations 1982[21], amended in 2002[22], prohibit the handling of certain hazardous substances in quantities equal or exceeding the threshold quantity specified in the regulations unless HSE has been notified. The threshold quantity for hydrogen is two tonnes, so all but the smallest hydrogen refuelling stations will require notification under the current regulations.

3.1.6 Provision and Use of Work Equipment Regulations (PUWER) 1998

PUWER[23] implements in UK law the Work Equipment Directive[24], that lays down the minimum health and safety requirements for the use of work equipment by workers. It requires that all work equipment be appropriate for preventing the risk of explosion of the work equipment or of substances produced, used or stored in the work equipment. HSE is responsible for PUWER and enforcing its requirements.

Flammable mixtures of hydrogen and air are much more easily ignited than other fuel/air mixtures such as natural gas and air, ie hydrogen has a lower ignition energy. As a consequence equipment for use with hydrogen needs a higher level of protection to prevent it causing an ignition than does equipment for use with other gaseous fuels.

3.1.7 Equipment and Protective Systems for Use in Potentially Explosive Atmospheres (EPS) Regulations

The legal requirements for equipment and protective systems intended for use in potentially explosive atmospheres are given in the ATEX 100A Equipment Directive[25] (sometimes also called the ATEX 95 Directive). The Directive covers both electrical and non-electrical (mechanical) equipment. The requirements also extend to controlling and regulating devices intended for use outside the explosive atmosphere, but required for, or contributing to, the safe functioning of equipment or protective systems in the explosive atmosphere. Furthermore not only has the product to comply with essential health and safety requirements, but so does the production process. Requirements for establishing and maintaining the production quality control system are also specified in the Directive. The Directive was implemented in UK law by the Department of Trade and Industry (DTI), now the Department for Business, Innovation and Skills (BIS), under the EPS 1996 Regulations[26] as amended in 2001[27]. The amendment principally covers the concept of "putting into service" of equipment. BIS are responsible for policy issues arising from the EPS Regulations, resolution of supply issues at EU level and the appointment of the UK Notified Bodies. The regulations are enforced in Britain by HSE.

Due to the lower ignition energy of hydrogen compared to other gaseous fuels a higher level of protection will be required for hydrogen systems.

3.1.8 Pressure Systems Safety Regulations (PSSR) 2000

The Pressure System Safety Regulations (PSSR)[28] were introduced to eliminate the duplication of the legal requirements between PER and the old Pressure Systems and Transportable Gas Containers Regulations (PSTGCR)[29]. The PSSR are the responsibility of HSE and came into force on 21 February 2000. They effectively re-enact all the requirements contained in PSTGCR, with only minor changes, and cover the use of all pressure systems in Great Britain which fall outside the scope of PER and which contain a relevant fluid. A relevant fluid covers amongst other substances, gases or liquids that are at a pressure greater than 0.5 bar above atmospheric. Pressure systems will also have to be subjected to a regular inspection regime.

3.1.9 Regulatory Reform (Fire Safety) Order 2005

General fire precautions are set out in the EU Workplace Directive[30], which lays down the minimum requirements for health and safety at the workplace. These requirements are implemented in England and Wales by the Regulatory Reform (Fire Safety) Order 2005[31], in Scotland by Fire (Scotland) Act 2005[32] and came into force on 1 October 2006. Under the new legislation fire certificates are no longer required and instead a risk-based approach becomes the primary method to manage fire risk in the workplace. Responsibility for compliance will rest with the Responsible Person. In the workplace, this is the employer and any other person who may have control of any part of the premises, eg the occupier or owner. The duty of the Responsible Person is to ensure that a suitable and sufficient fire risk assessment has been carried out for the site. This amongst other things covers: means of detecting and giving warning of a fire at the site; measures to reduce the risk of fire and its spread; means of escape from the site, provision of fire fighting measures; and the safety fire of fighters. In general the local Fire Authorities are now responsible for enforcing the requirements, but HSE retains enforcement responsibilities for the construction, nuclear and shipbuilding industries.

3.1.10 Building regulations

The Building Regulations 2000[33], as amended, lay down for England and Wales minimum requirements to secure the health, safety and welfare of people in and around buildings. The Regulations are supplemented by Approved Documents[34], which give more information on the requirements and ways of satisfying the requirements. Approved Document B covers the fire safety of buildings. Scotland has its own building regulations, the Building (Scotland) Regulations 2004[35], which are broadly in line with the English and Welsh regulations. Guidance on achieving the requirements of the Regulations are given in a series of Technical Handbooks[36]. The Department of Communities and Local Government are responsible for the Building Regulations in England and Wales and the Scottish Executive for those in Scotland. The enforcing authorities for the Regulations are the Local Authorities.

These regulations would apply to the buildings on the refuelling station site where liquid hydrogen is stored, eg housing the station paypoint and shop. Some buildings may be exempt such as temporary buildings and buildings not frequented by people, unless it is close to a building that is.

3.2 CODES AND STANDARDS

In the UK to assist compliance with the legislation and regulations guidance notes and Approved Codes of Practice (ACOP) have been published. The ACOPs give what is considered as 'best practice' for complying with the requirements of the law. There is no legal requirement for the recommended practice to be followed, alternative ways of meeting the requirements of the law being allowed. In this case it would be necessary to demonstrate that the alternative practice provides at least a similar level of compliance. Details of the guidance and ACOPs available for a particular set of regulations can be found on the website of the government department responsible for the regulations. For example six ACOPs[37-42] have been issued by HSE to supplement DSEAR, one of the main set of regulations applicable to hydrogen refuelling stations, and the risk assessment process required under the regulations. These cover amongst other things control and mitigation measures, storage of dangerous substances, design of plant and equipment, and maintenance and repair. None of these ACOPs are specific to hydrogen, but apply to any dangerous substance.

The detailed technical and organisational means of ensuring compliance with the essential health and safety requirements (EHSR) of the EU Directives are not published in the Directives themselves. There are several ways of demonstrating compliance, the easiest being by proving compliance with the relevant European harmonised standard. Some harmonised standards put forward mandatory requirements, especially those that support the product Directives, while others describe 'relevant good practice'. The technical content of a harmonised standard has been agreed throughout the EU and there is a presumption that if the requirements of the standard are met so are the EHSRs of the Directive. In the absence of relevant European harmonised standards then national standards or other ad hoc methods have to be used to prove compliance with the directive.

European harmonised standards are identified by EN numbers and are issued by the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENLEC). CENLEC and the International Electrotechnical Commission (IEC) have reached an agreement on parallel voting that means that a standard produced by the IEC is voted as both an IEC and CENLEC standard and can also become a European harmonised standard as well. European harmonised standards must be issued as national standards and supersede any existing national standard - in the UK the British Standards Institution (BSI) publishes these standards under BS EN and BS IEC numbers.

None of the European harmonised standards deal specifically with hydrogen, but applicable to any substance that can produce an explosive atmosphere. There are a number of other standards bodies and trade associations, both national and international, which have produced or are developing codes of practice and standards on hydrogen. It should be noted that in North America a "code" has a different meaning to what is understood by the term in the UK. In the UK, and Europe, a code is a set of guidelines and is not legally binding, while in North America it is a standard or set of rules made legally binding by local or national government. A summary of the standard organisations and their codes and standards particularly relevant to the safety of liquid hydrogen is given in the following sections (3.2.1 to 3.2.8).

3.2.1 International Standardisation Organization (ISO)

ISO's Technical Committee (TC) 197 is responsible for developing standards on systems and devices for the production, storage, transport, measurement and use of hydrogen. There are 20 countries participating in the work of TC 197 and a further 11 countries with observer status. At present TC 197 has 9 working groups actively working on standards and an ad hoc group on hydrogen components (eg dispensers, break-away devices, compressors, pressure relief devices). Standards that have already been published by TC 197 or are under development that are relevant to liquid hydrogen are described below. A fuller description can be found on the ISO website[43].

ISO/TR 15916:2004[44] provides guidelines for the use of hydrogen in gaseous and liquid forms. It identifies the basic safety concerns and risks and describes the basic properties of hydrogen that are relevant to safety.

Facilities for dispensing liquid hydrogen to vehicles are covered by ISO 13984:1999[45] and the requirements for liquid hydrogen fuel tanks for vehicles are given in ISO 13985:2006[46.]

3.2.2 CEN/CENLEC

DSEAR requires areas in a workplace where flammable gases or liquids may be present be identified and classified according to the likelihood of an explosive atmosphere being present. The following classifications should be used where appropriate:

- Zone 0 – An area in which an explosive atmosphere is present continuously or for long periods. Only category 1 equipment should be used in these areas;

- Zone 1 – An area where an explosive atmosphere is likely to occur during normal operation. Only category 1 or 2 equipment should be used in these areas;

- Zone 2 – An area where an explosive atmosphere is not likely to occur during normal operation and, if it does occur, is likely to do so infrequently and will only last for a short period. Only category 1, 2 or 3 equipment should be used in these areas.

Guidance on identifying and classifying the hazardous areas is given in BS EN 60079-10-1:2009[48] and BS EN 1127-1:2007[49].

Electrical and non-electrical equipment appropriate for use in the different areas of the workplace should be determined once the hazardous areas have been identified and classified. The EN 60079 series of standards specifies the requirements and testing of electrical equipment for use in the different zones. Part 0[50] specifies the general requirements for the construction, testing and marking of electrical apparatus and components intended for use in hazardous areas where explosive gas/air mixtures exist under normal atmospheric conditions. Part 14[51] gives the specific requirements for the design, selection and erection of electrical installations in explosive gas atmospheres. These requirements are in addition to those for installations in non-hazardous areas. Part 17[52] covers the maintenance of electrical installations in hazardous areas and Part 19[53], the repair and overhaul for apparatus used in explosive atmospheres. Non-electrical equipment is covered by the BS EN 13463 series of standards, with Part 1[54] specifying the basic method and requirements for the design, construction, testing and marking of equipment. Methodology for the risk assessment of non-electrical equipment for use in potentially explosive atmospheres is given in BS EN 15198:2007[55].

Due to the low ignition energy of hydrogen particular care should be taken to prevent the build-up of static charges that may lead to an incendive discharge. Guidance on the avoidance of hazards due to electrostatics can be found in the code of practice PD CLC/TR 50404:2003[56].

3.2.3 European Industrial Gases Association (EIGA)

EIGA[57] is a safety and technically orientated organisation representing the vast majority of European and a number of non-European companies producing and distributing industrial, medical and food gases. It fully co-operates with all the national industrial gases associations in Europe and a number of gas associations around the world are associated members, for example the Compressed Gases Association (CGA) in the USA and the Japanese Industrial Gases Association (JIGA). EIGA has published a number of codes of practice specifically on hydrogen.

DOC 06/02/E[58] gives guidance on the safe storage, handling and distribution of liquid hydrogen. It covers: layout and design; safety distances; selection of suitable electrical and mechanical equipment; testing, operation and maintenance of equipment; and training and protection of personnel.

Though not specifically for hydrogen, guidance has recently been published on the determination of safety distances (IGC Doc 75/07/E)[59]. The document establishes for the first time the basic principals to calculate appropriate safety distances for the industrial gas industry. It is intended that future EIGA working groups use this document as an aid to writing or revising any codes of practice that involve specifying separation distances for equipment and to ensure a consistent and technically sound approach.

3.2.4 National Fire Protection Association (NFPA)

The NFPA[60] is a United States organisation that produces codes and standards on fire, electrical and building safety. It has produced a number of standards that would be relevant to the handling of liquid hydrogen. The requirements of NFPA 50A[61], which dealt with gaseous hydrogen systems at consumer sites, and its companion standard NFPA 50B[62], that covered liquefied hydrogen systems, have now been incorporated in NFPA 55[63]. NFPA 55 gives requirements for designing hydrogen systems, including container locations, safety devices, marking piping, venting and other components. NFPA currently have a programme of work to consolidate all the requirements for hydrogen safety into one document, NFPA 2[64]. This code, however, is not due to be published until 2010. It being a deliberate decision by NFPA to have a long timetable for the development and publishing in order to allow sufficient time for supporting R&D, modelling and analysis to be performed.

3.2.5 Compressed Gas Association (CGA)

The American Compressed Gas Association (CGA)[65] produces technical information, standards and recommendations for safe and environmentally responsible practices in the manufacture, storage, transportation, distribution and use of industrial gases, including hydrogen. The CGA standards on hydrogen piping systems at consumer sites (CGA G 5.4[66]) and hydrogen vent systems (CGA G 5.5[67]), would be applicable to the hydrogen storage and pipework installations. CGA G 5.5 covers both gaseous and liquid hydrogen installations.

3.2.6 National Aeronautics and Space Administration (NASA)

NASA produced a very comprehensive safety standard, NSS 1740.16[68], for hydrogen and hydrogen systems. It covers the full range of hydrogen safety issues, including system design, materials selection, operation, storage and transportation. This standard was cancelled in July

2005 and is now superseded by a joint American National Standards Institute (ANSI)/American Institute of Aeronautics and Astronautics (AIAA) guide[69].

3.2.7 US National Bureau of Standards

The US National Bureau of Standards published in 1962 guidance on the use of liquid hydrogen[70]. Though this is now somewhat dated it still contains useful advice. It reviews the physical and chemical properties of hydrogen and makes recommendations on the measures to be adopted for the safe handling of liquid hydrogen. It covers both the laboratory and large-scale use of liquid hydrogen and makes comparisons with LPG and natural gas to assist in establishing the relative hazard of the three fuels.

3.2.8 International Code Council (ICC)

The ICC Ad Hoc Committee for Hydrogen Gas (AHCHG) have developed new hydrogen safety requirements and modified existing requirements for incorporation in the latest editions of the International Building Code[71], International Fire Code[72] and International Fuel Gas Code[73]. Additions since the previous 2003 editions have included requirements for underground storage of liquid hydrogen. Chapter 7 of the Fuel Gas Code deals specifically with hydrogen. Though the ICC is supposedly an international organisation its codes and standards appear to be just used in North America. During information gathering undertaken for producing this position paper no evidence of them being used in the UK or Europe was found.

3.3 LAND USE PLANNING

Land use planning for hazardous installations is covered by planning legislation in Great Britain, in particular, the Town and Country Planning The Planning (Hazardous Substances) Act 1990[74] and the Planning (Hazardous Substances) Regulations 1992[75] as amended by The Planning (Control of Major Accident Hazards) Regulations 1999[76]. These latter regulations implement the land use planning requirements of the Seveso II Directive[7,8]. The planning legislation controls both the location of new hazardous installations and new developments around existing hazardous installations. The planning regulations define a hazardous installation by the presence of a substance above the threshold quantities listed in Schedule 1 of The Planning (Control of Major Accident Hazards) Regulations 1999. For hydrogen the threshold quantity is 2 tonnes, which means that most hydrogen refuelling stations will be classed as hazardous installations.

For new hazardous installations the operators are required to submit a pre-construction safety report to HSE before construction can begin. Operators must also apply for hazardous substances consent from the Hazardous Substances Authority (HSA), usually the local planning authority (LPA). This requirement would also apply for existing sites where it is proposed to increase the quantities of hazardous substances on site so that they exceed the threshold quantities, or introduce quantities of new substances above the threshold values. For example to convert an existing petrol station, which did not require consent, to a hydrogen refuelling station, or add a hydrogen refuelling facility, would now require consent from the HSA if the amount of hydrogen stored at the site exceeded 2 tonnes.

On application the HSA is required to consult HSE as to the advisability or otherwise of the location of the installation. HSE will then advise on the residual risk that still remains when all reasonable practicable steps have been taken to ensure safety. In advising on consent, HSE may specify conditions that should be imposed by the HSA, over and above compliance with the statutory health and safety requirements, to limit risks to the public. These could be, for example, limiting the amount of hazardous substance stored on the site or how the substances are delivered to the site. It is important to note that HSE's role is purely advisory. It is then up to the HSA to take into account other economic or social factors that should be considered in granting or refusing consent.

Greater control is possible when planning the location of new hazardous activities, but even here the options may be limited. There are few locations in the UK where new hazardous installations can be located without creating some risk to an existing community. The UK is a small, densely populated island and such undeveloped areas as do exist are often so remote or of such environmental value as to be unsuitable for industrial use. It also remains the case that to be economically viable, industries need to be sited where they are accessible to main transport routes and to sources of labour. For hydrogen refuelling stations it would also be important that they are located close to their customers, which would inevitably meaning locating them in or close to densely populated areas. This means that in making planning decisions about hazardous installations safety, though very important, is only one of the elements to be considered. A balance has to be struck between the necessity of the installation, the needs of the community and the interests of safety. At the end of the day it comes down to a political decision on whether the increased risk of the installation is acceptable, the price society has to pay to enjoy the benefits of the installation.

If consent is granted for a new hazardous installation, HSE notifies to the LPA a consultation distance (CD) around the installation within which HSE must be consulted on any further developments beyond a certain size (essentially those that would result in an increase in the population). HSE then advises LPA, based on the residual risk that remains after all reasonable practicable steps have been taken to ensure safety, whether to grant consent for further development around the installation. Again, HSE's role is purely advisory and it is for the LPA to take into account other economic or social factors that should be considered.

If a LPA grants consent against HSE's advice HSE usually does not pursue the matter further as long as the LPA understands and has considered the reasons for HSE's advice. However, HSE does have the option, if it believes the risks are sufficiently high, to request the decision is 'called in' for consideration by the Secretary of State in England and Wales. In Scotland, if the LPA is minded to grant permission they have to notify the Scottish Ministers who can decide to call in the application.

HSE is currently revising its assessment procedures for land use planning advice. It is proposed that information about societal risk as well as individual risk around hazardous installations should be taken into consideration in the management of such sites and in decisions on land use around them.

4 HYDROGEN REFUELLING FACILITIES

4.1 REFUELLING STATIONS

It is believed there is currently only one refuelling station in the UK where LH2 is delivered and stored, a facility at Wembley owned by BMW and used for refuelling a small fleet of experimental BMW 7-series cars with liquid hydrogen. No further information on this facility is available. There was a station at Hornchurch in London that was built by BP to refuel three hydrogen-powered London buses. The buses were taking part in the CUTE (Clean Urban Transport for Europe)[47] trials, a European funded project, aimed at demonstrating the feasibility of an innovative, high-energy efficient, clean urban public transport system. The liquid hydrogen was stored in an underground tank, of capacity 3.5 tonnes. The hydrogen had to be imported from Europe, as there are no hydrogen liquefaction facilities in the UK and transported to the station by road tanker. The station was closed in 2007, as once the CUTE trials were completed there were no other customers for the station. A further three stations were planned for the London area to provide refuelling facilities for demonstration trials of buses and light vehicles[98], but at present only one at Waltham Forest is going ahead. A planning application has been submitted for this station, which will be located at a bus garage, and used for refuelling a fleet of up to ten hydrogen hybrid buses[99]. Air Products will deliver the liquid hydrogen to the station using a new delivery method that vaporises the hydrogen into high-pressure storage on site. Each delivery will provide enough hydrogen for approximately 15 days of expected bus operation. Details of the other stations and their locations are not yet known.

Comprehensive databases of current and planned hydrogen refuelling stations worldwide can be found on a website maintained by Ludwig-Bolkow-Systemtecknik[100] and Fuel Cell 2000[101]. Of the 260 current and planned refuelling stations on the Fuel Cell 2000 website 27 of them are listed as being supplied with and storing liquid hydrogen. The supply capacity of all these stations is small compared to retail petrol stations, as they are intended for refuelling only a limited number of demonstration buses and/or cars and the public has no access to the majority of them. Details of the amounts of LH2 stored and the type of storage are not available for each station, but for those stations for which information is available the maximum quantity that could be stored ranged from 200 to 2400 kg in either above ground or underground tanks.

Most hydrogen vehicles are being developed with compressed gas onboard storage, although there are some exceptions to this, for example the BMW series-7 cars that have LH2 fuel tanks. The infrastructure required at the refuelling station to convert the LH2 supply to a compressed gas for dispensing to the vehicle is complex, involving controlled vaporisation of the liquid and compression into a compressed gas buffer storage facility.

4.2 DELIVERY AND STORAGE

Currently in the UK the only suppliers of bulk quantities of liquid hydrogen are Air Products and BOC. Air Products uses road tankers, with a vacuum insulated tank of 3.5 tonne capacity, for transporting LH2 to consumer sites and BOC insulated ISO-containers with a 2.5 tonne capacity. In comparison bulk supplies of compressed gaseous hydrogen are transported in tube trailers, which typical hold between 300 and 400 kg of hydrogen at pressures between 200 and 250 bar.

There are no commercial hydrogen liquefaction plants in the UK, so at present all bulk supplies of LH2 have to be imported from Europe. This extends the journey times and consequently the loss of hydrogen during transport. Boil-off from LH2 tankers is typically about 0.3 to 0.6% per day[102,103]. Further loss of liquid hydrogen due to vaporisation can occur during the transfer of hydrogen from the delivery tanker to the storage vessel. Flash losses (rapid vaporisation) when transferring liquid from a higher pressure vessel to a lower pressure one can be very high, between 10-20% and possibly up to 50%[102]. This can be reduced if the LH2 is transported at atmospheric pressure, but at the cost of some loss in tanker capacity. There can also be considerable vaporisation of liquid during the early stages of the transfer between the tanker and storage vessel, due to the initial temperature differences between the liquid and the transfer pipework and storage vessel. On commencement of filling the transfer pipework, and the storage vessel if it contains no LH2, will be at ambient temperature, resulting in liquid vaporisation until sufficient liquid has been transferred to cool the pipework and vessel to liquid hydrogen temperatures. Pre-cooling of vessels and pipework with liquid nitrogen, to minimise these losses, is not recommended due to the hazards that can arise from nitrogen solidifying in the pipework and valves (see section 2.2.3). Provision needs to be made to safely vent and disperse the gaseous hydrogen generated during vessel filling operations.

To reduce evaporative losses due to boil-off cryo-compressed hydrogen storage tanks have been developed for vehicles[105]. Unlike conventional storage tanks for liquid hydrogen that store the liquid at low pressure (typically less than 5 bar), cryo-compressed tanks store the liquid at high pressure. Typical storage pressures are 230 bar, but tanks have been developed with a pressure rating of 345 bar[106]. These tanks can also be used for storing cryogenic compressed hydrogen or compressed hydrogen at ambient temperature. For vehicles this expands the number of potential refuelling locations, as refuelling can be with either liquid or gaseous hydrogen. The other advantages of cyro-compressed storage is it gives a slightly higher VED than conventional storage of liquid hydrogen, losses on refilling storage tanks will be less and a lower energy requirement for liquefaction. In the future cryo-compressed tanks may be developed for the bulk delivery and storage of liquid hydrogen.

5 OUTSTANDING ISSUES

Large quantities of hydrogen, both in gaseous and liquid forms, have been used safely for many decades as a feedstock for the chemical industry, in industrial processes and as a rocket fuel. Standards, codes and regulations governing its storage and distribution for these uses are well established and the hydrogen is used in a controlled environment, remote from the public and by trained personnel. This is a very different situation to the transport to and storage of LH2 at public refuelling stations. The stations will needed to be located near their customers, which means that many will be located in urban areas and require LH2 deliveries to be transported through urban areas. The density of building in urban means that it would be difficult and very expensive to achieve the size of exclusion zones around LH2 facilities that are employed at industrial sites. At least initially the hydrogen refuelling stations may be co-located with petrol stations that would further add to the potential fire and explosion hazards. Finally members of the public would have access to areas close to where LH2 is unloaded and stored, and in the case of vehicles with liquid storage tanks actually dispensing LH2 to their vehicles. For these reasons a much higher level of "foolproofness" and reliability of the equipment and procedures than are currently employed in industrial applications are likely to be demanded of public facilities.

It is considered that the requirements in the current UK regulatory framework are adequate for controlling the fire and explosion hazards arising from the transport and storage of liquid hydrogen. Most of the key regulations are relatively new and have resulted from EU Directives. They are also in the main risk based rather than prescriptive, ie they require an assessment of the hazards and if necessary appropriate prevention or mitigation measures to be put in place in order to reduce the risk to an acceptable level rather than detailing what the hazards are and the measures to be taken. Where there are gaps is in the understanding of liquid hydrogen behaviour and the standards and guidance required to assess the hazards, ensure equipment is fit for purpose and to demonstrate compliance with the regulations. This review has identified leaks or spills of liquid hydrogen, separation distances, material compatibility and transport of liquid hydrogen as the main areas were further work is required to fill in gaps in knowledge and where further development of codes, guidance and standards is required.

5.1 LEAKS AND SPILLS OF LIQUID HYDROGEN

The consequences of the accidental spillage or leak of LH2 during transport or from storage vessels are still poorly understood. It is important to be able to reliably predict how far the released hydrogen would spread, the thermal radiation levels if the hydrogen ignites to form a flame jet or the explosion pressures generated if there is a delayed ignition of the released hydrogen in order to assess the consequences of the leak, ie damage to equipment and injuries to people.

There have been relatively few experimental studies of LH2 spills. Large scale liquefied hydrogen dispersion experiments were first performed in the late 50's[77], with spills ranging from 5 litres to 19 m^3. These tests confirmed the decelerated buoyant behaviour of vaporised, but still cold gas and its tendency of horizontal spreading with strong concentration fluctuations. Some twenty years later NASA[78,79] undertook large-scale releases of LH2, with the aim of investigating the generation and dispersion of flammable clouds of hydrogen formed as a result of large, rapid spills of hydrogen. Such releases might occur as a result of the rupture of a large storage vessel. The experimental programme consisted of seven trials, with ground spills of up to 5.7 m^3 (about 400 kg) of liquid and spill durations of 35 to 85 s. Results indicated that for rapid spills thermal and momentum-induced turbulence caused the cloud to disperse to safe concentration levels and become positively buoyant long before mixing due to normal atmospheric turbulence becomes a major factor. Ground level cloud travel extended between about 50 to 100 m from the point of spillage and the pulsation-like behaviour of the hydrogen concentrations noted in the earlier trials was also observed. It is also of note that the spillage trials show that the flammable cloud extends beyond the visible cloud (formed by water in the atmosphere condensing out).

More recently smaller scale tests[80,86] have been conducted in Germany with the aim of investigating the cryogenic pool spread and vaporisation. Six tests were undertaken with releases, on average about 47 kg per test, onto a water or a solid surface. Small-scale LH2 leakage and dispersion experiments have also been performed as part of the WE-NET project[81,82]. Early phase and steady phase pool spreading and evaporation as well as cloud evolution were measured during these tests. INERIS have performed large-scale cryogenic helium spill tests[83] aimed at simulating the rupture of a connecting pipe in a LH2 system. Ten tests were undertaken with maximum flow rates, lasting for tens of seconds, of between 1.5 and 2.1 kg s^{-1} of liquid helium. Concentrations were calculated from the temperature data, measured with an array of thermocouples located down the wind of the point of release, assuming adiabatic mixing of helium with the air (ie ground heat transfer neglected).

A number of models for predicting the hydrogen dispersion from LH2 spills have been developed with various degrees of success in predicting the experimental results[80,82,84-90]. The lack of experimental data for validating models is, however, holding back the development of improved models. In particular a better understanding of the initial phase of cryogenic pool spreading and vaporisation is required, as this knowledge is essential to the subsequent step of accurately prediction the dispersion of the hydrogen.

Winters and Houf[91] have developed turbulent entrainment models to predict the characteristics of leaking jets of hydrogen, vapour or liquid, that result from unintended slow releases from liquid hydrogen storage systems. Simple expressions have been produced to describe the dilution distances for momentum dominated leaks. The predictions show that vapour leaks are positively buoyant and tend to flow upward in still air, while leaks of liquid are negatively buoyant and tend to flow downward toward the ground. Leaks from liquid hydrogen systems have relatively high densities when compared to ambient temperature hydrogen leaks and as a result predicted dilution distances for LH2 leaks tend to be several times greater than distances for ambient temperature leaks. No validations of the predictions against experimental were reported.

5.2 SEPARATION DISTANCES

Separation distances, or alternatively referred to as safety distances, are the minimum separation between a hazard source and an object (human, equipment or environment), which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident. Table 2 gives the EIGA recommended minimum safety distances[58] for liquid hydrogen storage.

The separation distances given in Table 2 and those in other standards and guidance have been developed for industrial applications. Applying them to LH2 storage at refuelling stations is likely to put severe limitations on where such stations could be located in urban areas and require the equipment to be spread over large areas to achieve the required separation distances. There is a need to re-assess the scientific basis of the separation distances to see if they are overly conservative and so could be reduced without increasing the consequences of a fire or explosion. Alternatively separation distances may be able to be reduced by the use of mitigation measures, for example water sprays to reduce thermal radiation effects or walls to protect from blast and missiles. In introducing measures to mitigate one hazard it is important to check that it may not be increasing the consequence of another hazard. For example walls to project against blast and missiles may inhibit the dispersion of hydrogen increasing the time flammable concentrations are present and the probability of an ignition. The partial confinement introduced by the wall may also increase the likelihood that the flammable cloud detonates (see 2.1.5)

Table 2 - Recommended minimum separation distances for liquid hydrogen storage [58]

ITEMS	DISTANCE (m)
90 min fire resistive walls	2.5
Technical and unoccupied buildings	10
Occupied buildings	20
Air compressor intakes, air conditioning	20
Any combustible liquids	10
Any combustible solids	10
Other LH_2fixed storage	1.5
Other LH_2 tanker	3
Liquid oxygen storage	6
Flammable gas storage	8
Open flame, smoking, welding	10
Place of public assembly	20
Public establishments	60
Railroads, roads, property boundaries	10
Overhead power lines	10

One of the problems in establishing separation distances is they depend on the hazard being considered. For example to avoid the effects of thermal radiation, from a jet flame from an ignited hydrogen leak, the distance would be based on an acceptable level of thermal radiation. This in turn would depend on what was being subjected to the radiation, equipment being able to withstand a much higher level than people. On the other hand the separation distances to avoid the risk of entry of leaking hydrogen into the air conditioning intake of a nearby building would be based on the distance at which the hydrogen concentration falls below the lower explosive limit.

Furthermore separation distances cannot be solely based on the consequences of a failure event, it is also necessary to consider the likelihood of it occurring. For example in assessing the safety distances for a jet flame event, the likelihood of a leak occurring and then the leaking hydrogen igniting need to be taken into account. A quantified risk assessment (QRA) would provide a more complete picture of the relationship between safety and separation distances. This approach then raises the question of what is an acceptable risk at the specified safety distances. Ideally the building of a hydrogen facility should not substantially increase the risk of injury or death of an individual above that which already exists for an equivalent (in terms of energy of the stored fuel) facility for a conventional fuel such as LPG or petrol. Several options for setting an acceptable level of risk are currently under consideration, but it will need to be based on sound science and reflect the consensus of all stakeholders.

5.3 MATERIAL COMPATIBILTY

A review of the materials issues relating to hydrogen applications has been undertaken by Hobbs[92]. It concluded that the main material considerations relating to the use of hydrogen are hydrogen embrittlement (weakens the material), permeability (passage of hydrogen through the material) and additionally for LH2 the material properties at cryogenic temperatures. A number of new materials are also likely to come to prominence. High performance composites are likely to be used extensively for hydrogen cylinders and new materials, or combinations of materials, may be used for hydrogen pipelines. Due to the effect of hydrogen and extremely low temperatures on materials, it is important to test any materials in the environment in which they would be used. Depending on the type of test, this could require the use of very specialist and expensive equipment. Such equipment is not widely available and test procedures and performance standards have yet to be developed in many cases.

5.4 TRANSPORTATION

To supply the size of refuelling station currently planned in the UK, intended for refuelling a small fleet of demonstration vehicles, is likely to require at most one delivery every few weeks. A recent Dutch study[93] estimated the supply requirements for a hydrogen refuelling station supplying an equivalent amount of energy to a typical large petrol station (annual sale of 10 million litres of petrol and diesel) as on average two tanker deliveries per day of liquid hydrogen. For comparison if the same amount of hydrogen were delivered in gaseous form it would require on average 23 deliveries per day. If petrol stations in the Netherlands were replaced by hydrogen refuelling stations and the hydrogen supplied in gaseous form by tube trailer the study estimated that one in five trucks on the Dutch roads would be carrying hydrogen at any one time. Using a ratio of one delivery of liquid hydrogen to about ten deliveries of gaseous hydrogen to supply the same amount of energy and assuming all the hydrogen was delivered in liquid form would translate to approximately one in fifty trucks on the Dutch roads carrying hydrogen at any one time.

Figures are not available for the UK but it is probable that similar estimates would be arrived at for the UK. Clearly supplying a substantial network of hydrogen refuelling stations by road tanker, even if delivered in liquid form, is not a viable long-term solution. Even as an interim measure, as the hydrogen refuelling infrastructure develops, means that the number of road tankers carrying liquid hydrogen and the number of tanker movements would have to increase significantly from the current near zero levels. A further problem is that there is currently no hydrogen liquefaction facility in the UK, which means that at least in the short term all LH2 has to be imported. This means increased journey times and thus increased loss of hydrogen through boil-off. One option to reduce the quantities carried by road is to transport by rail tanker, which is currently not undertaken in the UK. In the longer term, if no viable option to delivering hydrogen in liquid form becomes available, development of a piped distribution system may be necessary.

A comprehensive assessment needs to be made of the risks involved in the bulk transport of hydrogen on the UK roads compared to those currently incurred by the transport of equivalent amounts, in terms of energy content, of petrol and diesel. An accident involving a liquid hydrogen tanker in an urban area, resulting in the rupture of the tank and spillage of up to 3.5 tonnes of liquid, could potentially result in catastrophic consequences. An accident involving a petrol tanker and spillage of petrol also has far from trivial consequences. The question is are the risks from transporting liquid hydrogen higher and if so are the increased risks acceptable in view of the benefits gained from switching to hydrogen fuelled vehicles. Rigas and Sklavounos[94] and Kikukawa, Mitsuhashi and Miyake[95] have undertaken assessments of the accident scenarios that can result from the delivery and storage of liquid hydrogen. A study[96] undertaken by HSL for the Department for Transport (DfT) to assess the safety of the delivery and storage of hydrogen concluded that there are several gaps in knowledge that need to be filled before a comprehensive risk assessment methodology for hydrogen can be developed. These include:

- The current lack of clarity about the main components of the hydrogen delivery and storage infrastructure and their detailed design/geometry that will influence the combustion behaviour, for example as a result of turbulence effects on the burning rate.

- The modelling of hydrogen flames, including flame length and surface radiation.

- The modelling of hydrogen fires and explosions in confined or semi-confined spaces such as tunnels or underpasses or involving clouds of "cold" hydrogen generated from liquid spills.

- Failure rate data for the components of the hydrogen infrastructure, including hydrogen tankers involved in transport accidents.

- Ignition probabilities for hydrogen releases, including an understanding of the conditions under which spontaneous ignition could occur and the influence of cloud temperature.

- The probability of a hydrogen release giving a flash fire or a vapour cloud explosion (VCE) and for a transition to detonation to occur in a VCE.

An issue for further consideration is should the road transport of hydrogen be restricted to certain designated routes. Of particular concern is whether the bulk transport of hydrogen through tunnels should be allowed. Current restrictions[97] for the three privately operated toll tunnels in the UK (Dartford, Mersey and Tyne crossings) prevent quantities of hydrogen in excess of 50 kg being transported through the tunnels. This would allow most hydrogen fuelled vehicles to use the tunnels, typically a hydrogen fuelled car would have a tank capacity of 5 to 10 kg of hydrogen. It would exclude bulk transport of hydrogen, either in gaseous or liquid form, through these tunnels. Consideration needs to be given whether this restriction needs to be maintained, and perhaps extended to other tunnels, or whether it can be relaxed. In assessing whether a relaxation is possible it will be necessary to balance the reduced risk in prohibiting bulk transport through tunnels against the increased risk arising from the extended journey times required to avoid using tunnels.

6 CONCLUSIONS

Liquid hydrogen presents additional fire and explosion hazards to those arising from use in gaseous form. These need to be fully appreciated if comparable levels of safety to those arising from the use of conventional fuels such as petrol and liquefied petroleum gas (LPG) are to be achieved.

It is considered that the requirements in the current UK regulatory framework are adequate for controlling the fire and explosion hazards arising from the transport and storage of liquid hydrogen. Where safety issues arise are in the understanding of liquid hydrogen behaviour and the lack of standards and guidance required to assess the hazards, ensure equipment is fit for purpose and to demonstrate compliance with the regulations. Leaks or spills of liquid hydrogen, separation distances, material compatibility and transport of liquid hydrogen have been identified as the main areas were further work is required to fill in gaps in knowledge and where further development of codes, guidance and standards is required.

The consequences of the accidental spillage or leak of LH2 during transport or from storage vessels are still poorly understood. Such knowledge is required in order to reliably assess the consequences of a spill or leak, ie damage to equipment and injuries to people. Development of models for predicting the hydrogen dispersion from liquid hydrogen spills is also holding back model development. In particular a better understanding of the initial phase of the spreading of the pool of spill liquid and its vaporisation is essential to being able to reliable predict the dispersion of the hydrogen and the combustion behaviour of the resulting cloud.

The separation distances given in current standards and guidance on hydrogen applications have been derived from industrial experience. To apply them to liquid hydrogen storage at refuelling stations is likely to put severe limitations on the locations of stations in urban areas. There is a need to re-assess the scientific basis of currently recommended separation distances to see if there is any scope for reducing them, either because they are overly conservative or by the use of appropriate mitigation measures.

The extremely low temperatures of liquid hydrogen (-253^{o}C) together with the other material issues arising from hydrogen use of hydrogen embrittlement (weakens the material) and permeability (passage of hydrogen through the material) present a severe challenge. It is important that materials used for equipment (eg pumps), pipework and vessels handling liquid hydrogen are properly assesses for compatibility. The specialist equipment required to undertake a compatibility assessment is not widely available and test procedures and performance standards have yet to be developed in may cases.

To start supplying refuelling stations by means of liquid hydrogen would mean the number of road tankers carrying liquid hydrogen and the number of tanker movements would have to increase significantly from the current near zero levels. The risks involved, especially in transporting through urban areas, need to be fully assessed and compared to those arising from the transport of equivalent amounts, in terms of energy content of petrol or diesel. An issue for particular consideration is the control of the bulk transport of liquid hydrogen through tunnels.

7 REFERENCES

1. PD 6686:2006. Guidance on directives, regulations and standards related to prevention of fire and explosion in the process industries. British Standards Institute.

2. The Dangerous Substances and Explosives Atmospheres Regulations 2002, SI 2002, No 2776, London: The Stationery Office.

3. Directive 1999/92/EC of the European Parliament and Council of 16 December 1999 on the minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres (15th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC), Luxembourg 1999. (OJ No L023, 28/01/2000).

4. Council Directive 98/25/EC of 7 April 1998 on the protection of the health and safety of workers from the risks related to chemical agent at work (14th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC), Luxembourg 1998. (OJ No L131, 05/05/1998).

5. The Control of Major Accident Hazards 1999, SI 1999, No 743, London: The Stationery Office.

6. The Control of Major Accident Hazards (Amendment) Regulations 2005, SI 2005, No 1088), London: The Stationery Office.

7. Council Directive 96/82/EC of 9 December 1996 on the control of major accidents involving dangerous substances, Luxembourg 1996. (OJ L010, 14/01/1997).

8. Directive 2003/105/EC of the European Parliament and of the Council of 16 December 2003 amending Council Directive 96/82/EC on the control of major-accident hazards involving dangerous substances, Luxembourg 2003. (OJ L345, 31/12/2003).

9. Directive 97/23/EC of the European Parliament and of the Council of 29 May 1997 on the approximation of laws of the Member States concerning pressure equipment, Luxembourg 1997. (OJ L181, 09/07/1997).

10. The Pressure Equipment Regulations 1999, SI 1999, No 2001, London: The Stationery Office.

11. Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2004, SI 2004, No 568, London: The Stationery Office.

12. Council Directive 94/55/EC of 21 November 1994 on the approximation of the laws of the Member States with regard to the transport of dangerous goods by road, Luxembourg 1994. (OJ L319, 12/12/1994).

13. Directive 2000/61/EC of the European Parliament and of the Council of 10 October 2000 amending Council Directive 94/55/EC on the approximation of the laws of the Member States with regard to the transport of dangerous goods by road, Luxembourg 2000. (OJ L279, 1/11/2000).

14. Commission Directive 2003/28/EC adapting for the fourth time to technical progress Council Directive 94/55/EC on the approximation of the laws of the Member States with

regard to the transport of dangerous goods by road, Luxembourg 2003. (OJ L90/45, 8/4/2003).

15. Council Directive 96/49/EC of 23 July 1996 on the approximation of the laws of Member States with regard to the transport of dangerous goods by rail, Luxembourg 1996. (OJ L235, 31/10/1998).

16. Council Directive 2000/62/EC of the European Parliament and of the Council of 10 October 2000 amending Council Directive 96/49/EC on the approximation of the laws of Member States with regard to the transport of dangerous goods by rail, Luxembourg 2000. (OJ L279, 1/11/2000).

17. Commission Directive 2003/29/EC of 7 April 2003 adapting for the fourth time to technical progress Council Directive 96/49/EC on the approximation of the laws of Member States with regard to the transport of dangerous goods by rail, Luxembourg 2003. (OJ L90/47, 8/4/2003).

18. Council Directive 1999/36/EC of 29 April 1999 on transportable pressure equipment, Luxembourg 1999. (OJ L138, 01/06/1999)

19. Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations (Amendment) Regulations 2005, SI 2005, No 1732, London: The Stationery Office.

20. Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009, SI 2009, No 1348, London: The Stationery Office.

21. Notification of Installations Handling Hazardous Substances Regulations 1982, SI 1982, No 1357, London: The Stationery Office.

22. Notification of Installations Handling Hazardous Substances (Amendment) Regulations 2002, SI 2002, No 2979, London: The Stationery Office

23. The Provision and Use of Work Equipment Regulations 1998, SI 1998, No 2306, London: The Stationery office.

24. Council Directive 89/655/EEC of 30 November 1989 concerning the minimum requirements safety and health requirements for the use of work equipment by workers at work (second individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC), Luxembourg 1989. (OJ No L393, 30/12/1989).

25. Directive 94/9/EC of the European Parliament and of the Council of 23 march 1994 on the approximation of the laws of Member States concerning equipment and protective systems intended for use in potentially explosive atmospheres, Luxembourg 1994. (OJ L100, 19/04/1994).

26. The Equipment and Protective System Regulations 1996, SI 1996, No 192, London: The Stationery Office.

27. The Equipment and Protective System (Amendment) Regulations 2001, SI 2001, No 3766, London: The Stationery Office.

28. Pressure Systems Safety Regulations 2000, SI 2000, No 128, London: The Stationery Office.

29. Pressure Systems and Transportable Gas Containers Regulations 1989, SI 1989, No 2169, London: The Stationery Office.

30. Council Directive 89/654/EEC of 30 November 1989 concerning the minimum safety and health requirements for the workplace (first individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC), Luxembourg 1989. (OJ L393, 30/12/1989).

31. Regulatory Reform (Fire Safety) Order 2005, SI 2005, No 1541, London: The Stationery Office.

32. Fire (Scotland) Act 2005. Scottish Statutory Instrument 2005 No 1541, The Stationery Office.

33. Building Regulations 2000, SI 2000, No 2531, as amended, London: The Stationery Office.

34. Build Regulations, Approved Documents A to P. www.planningportal.gov.uk.

35. Building (Scotland) Regulations 2004, Scottish Statutory Instrument 2004, No 406, The Stationery Office.

36. Building (Scotland) Regulations. Technical Handbooks. www.sbsa.gov.uk/tech_handbooks.

37. Dangerous Substances and Explosive Atmospheres – Dangerous Substances and Explosive Atmospheres Regulations 2002, Approved Code of Practice and Guidance L138, HSE Books, 2003

38. Unloading Petrol from Fuel Tankers – Dangerous Substances and Explosive Atmospheres Regulations 2002, Approved Code of Practice and Guidance L133, HSE Books, 2003

39. Control and Mitigation Methods – Dangerous Substances and Explosive Atmospheres Regulations 2002, Approved Code of Practice and Guidance L136, HSE Books, 2003

40. Storage of Dangerous Substances – Dangerous Substances and Explosive Atmospheres Regulations 2002, Approved Code of Practice and Guidance L135, HSE Books, 2003

41. Design of Plant, Equipment and Workplaces – Dangerous Substances and Explosive Atmospheres Regulations 2002, Approved Code of Practice and Guidance L134, HSE Books, 2003

42. Safe Maintenance, Repair and Cleaning Procedures – Dangerous Substances and Explosive Atmospheres Regulations 2002, Approved Code of Practice and Guidance L137, HSE Books, 2003

43. International Standards Organisation, www.iso.org

44. ISO/TR 15916:2004. Basic considerations for the safety of hydrogen systems.

45. ISO 13984:1999. Liquid hydrogen – Land vehicle fuelling system interface.

46. ISO 13985:2006. Liquid hydrogen – Land vehicle fuel tanks.

47. CUTE (Clean Urban Transport for Europe) Project, www.fuel-cell-bus-club.com.

48. BS EN 60079-10-1:2009. Explosive atmospheres. Classification of areas. Explosive gas atmospheres.

49. BS EN 1127-1:2007. Explosive atmospheres – Explosion prevention and protection – Part 1: Basic concepts and methodology.

50. BS EN 60079-0:2004. Electrical apparatus for explosive gas atmospheres - Part 0: General requirements.

51. BS EN 60079-14:2008. Explosive atmospheres - Part 14: Electrical installations design, selection and erection.

52. BS EN 60079-17:2007. Explosive atmospheres - Part 17: Electrical installations inspection and maintenance.

53. BS EN 60079-19:2007. Explosive atmospheres – Part 19: Equipment repair, overhaul and reclamation.

54. BS EN 13463-1:2009. Non-electrical equipment for potentially explosive atmospheres – Part 1; Basic method and requirements.

55. BS EN 15198:2007. Methodology for the risk assessment of non-electrical equipment and components for intended use in potentially explosive atmospheres.

56. PD CLC/TR 50404:2003. Electrostatics. Code of practice for the avoidance of hazards due to static electricity.

57. European Industrial Gases Association (EIGA), www.eiga.org

58. DOC 06/02/E. Safety in storage, handling and distribution of liquid hydrogen. European Industrial Gases Association (EIGA).

59. ICG Doc 75/07/E. Determination of safety distances. European Industrial Gases Association (EIGA).

60. National Fire Protection Association (NFPA), www.nfpa.org

61. NFPA 50A. Gaseous hydrogen systems at consumer sites. National Fire Protection Association (NFPA).

62. NFPA 50B. Liquefied hydrogen systems at consumer sites. National Fire Protection Association (NFPA).

63. NFPA 55. Standard for the storage, use and handling of compressed gases and cryogenic fluids in portable and stationary containers, cylinders and tanks (2005 edition). National Fire Protection Association (NFPA).

64. NFPA 2. Hydrogen technologies code. National Fire Protection Association (NFPA). (code under development).

65. Compressed Gas Association (CGA), www.cganet.com.

66. CGA G 5.4. Standard for hydrogen piping systems at consumer sites. Compressed Gas Association (CGA).

67. CGA G 5.5. Hydrogen vent systems. Compressed Gas Association (CGA).

68. NASA NSS 1740.16 Safety Standard for Hydrogen and Hydrogen Systems. National Aeronautics and Space Administration (NASA).

69. ANSI/AIAA G-095-2004. Guide to Safety of Hydrogen and Hydrogen Systems. American National Standards Institute (ANSI).

70. D B Chelton. Safety in the use of liquid hydrogen. US Department of Commerce, National Bureau of Standards Report 7253, 22 May 1962.

71. International Building Code (2006 edition). International Code Council (www.iccsafe.org)

72. International Fire Code (2006 edition). International Code Council (www.iccsafe.org)

73. International Fuel Gas Code (2006 edition). International Code Council (www.iccsafe.org)

74. Town and Country Planning The Planning (Hazardous Substances) Act 1990, 1990, c.10, London: The Stationery Office.

75. Planning (Hazardous Substances) Regulations 1992, SI 1992, No 656, London: The Stationery Office.

76. The Planning (Control of Major Accident Hazards) Regulations 1999, SI 1999, No 981, London: The Stationery Office.

77. A D Little Inc. An investigation of hazards associated with the storage and handling of liquid hydrogen. Final report, Contract No AF-18 (600)-1687 (AD-324/94), 1960.

78. R D Witcofski and J E Chirivella. Experimental and analytical analysis of the mechanisms governing the dispersion of flammable clouds formed by liquid hydrogen spills. Int J Hydrogen Energy 9(5), 425-435 (1984).

79. J E Chirivella and R D Witcofski. Experimental results from fast 1500 gallon LH2 spills. Am Inst Chem Eng Symp Ser 1986; 82(25).

80. U Schmidtchen and L Marinescu-Pasoi. Dispersion of hydrogen and propane gas clouds in residential areas. Proceedings of World Hydrogen Energy Conference WHEC-10, Cocoa Beach, USA, 1994.

81. T Hijikata. Research and development of international clean energy network using hydrogen energy (WE-NET). Int J Hydrogen Energy 27, 115-29 (2002).

82. K Chitose et al. Activities on hydrogen safety for the WE-NET project – experiment and simulation of the hydrogen dispersion. Proceedings of World Hydrogen Energy Conference WHEC-14, Toronto, Canada, 2002.

83. C Proust et al. Processes of the formation of large unconfined clouds following a massive spillage of liquid hydrogen on the ground. Proceedings of 2nd International Conference of Hydrogen Safety, San Sebastian, Spain, 11-13 September 2007.

84. K Chitose, Y Ogawa and T Morii. Analysis of a large scale liquid hydrogen spill experiment using the multi-phase hydrodynamics code CHAMPAGNE. Proceedings of World Hydrogen Energy Conference WHEC-11, Stuttgart, Germany, 1996.

85. D Schmidt, U Krause and U Schmidtchen. Numerical simulation of hydrogen gas releases between buildings. Int J Hydrogen Energy 24, 479-488 (1999).

86. J C Statharas et al. Analysis of data from spilling experiments performed with liquid hydrogen. J Hazardous Materials A 77(1-3), 57-75 (2000).

87. A G Venetsanos and J G Bartzis. CFD modelling of large-scale LH2 spills in open environment. Int J Hydrogen Energy 32, 2171-2177 (2007).

88. K Verfondern and B Dienhart. Experimental and theoretical investigation of liquid hydrogen pool spreading and vaporisation. Int J Hydrogen Energy 22(7), 649-660 (1997).

89. K Verfondern and B Dienhart. Pool spreading and vaporisation of liquid hydrogen. Int J Hydrogen Energy 32, 2106-2117 (2007).

90. P Miiha, M Ichard and B J Arntzen. Validation of CFD modelling of LH_2 spread and evaporation against large-scale spill experiments. 3rd International Conference on Hydrogen Safety, Ajaccio, France, 16-18 September 2009.

91. W S Winters and W G Houf. Simulation of small-scale releases from liquid hydrogen storage systems. 3rd International Conference on Hydrogen Safety, Ajaccio, France, 16-18 September 2009.

92. J Hobbs. The Hydrogen Economy – Evaluation of the materials science and engineering issues, Health and Safety Laboratory Report HSL/2006/59.

93. R Smit and M Weeda. Infrastructure considerations for large hydrogen refuelling stations. Paper presented at 16th World Hydrogen Energy Conference, 13-16 June 2006, Lyon.

94. F Rigas and Sklavounos. Evaluation of hazards associated with hydrogen storage facilities. Int J Hydrogen Energy 30, 1501-1510 (2005).

95. S Kikukawa, H Misuhashi and A Miyake. Risk assessment for liquid hydrogen fuelling stations. Int J Hydrogen Energy 34, 1135-1141 (2009).

96. M Moonis, J Wilday, M Wardman and H Balmforth. Assessing the safety of delivery and storage of hydrogen. Health & Safety Laboratory Report PS/08/01, 14 February 2008.

97. British Toll Tunnels, Dangerous Traffic, List of Restrictions – 13th Edition. ISBN0 9545669 12.

98. London Hydrogen Partnership, www.lph.org.uk.

99. Transport for London. www.tfl.gov.uk/corporate/projectsandschemes/environment.

100. Database of planned and current hydrogen refuelling stations, www.h2stations.org.

101. Fuel Cell 2000. www.fuelcells.org/info/charts/h2fuelingstations.pdf.

102. W A Amos. Costs of storing and transporting hydrogen. National Renewable Energy Laboratory, 1998.

103. P Costello et al. Techno-economic assessment of hydrogen transmission and distribution systems in Europe in the medium and long term. The Institute of Energy, the Netherlands.

104. A guide to the Control of Major Accident Hazards Regulations 1999 (as amended), L111 (2nd edition), ISBN 0 7176 6175 X, HSE Books, 2006.

105. T Brunner. Cryo-compressed hydrogen storage – motivation and infrastructure implications. StorHy Final Event, 3 July 2008, Paris [http://www.storhy.net/finalevent/workshop3.php]

106. Storage of hydrogen in cryo-compressed vessels. Section VI.A.6, DOE Hydrogen Programme Annual Progress Report, 2007.

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Hazards of liquid hydrogen

Position paper

In the long term the key to the development of a hydrogen economy is a full infrastructure to support it, which include means for the delivery and storage of hydrogen at the point of use, eg at hydrogen refuelling stations for vehicles. In the meantime as an interim measure to allow the development of refuelling stations and rapid implementation of hydrogen distribution to them, liquid hydrogen (LH2) is considered the most efficient and cost effective means for transport and storage. This will result in increasing amounts of LH2 transported by road, and possibly by rail, and storage of moderately large quantities at refuelling stations, many of which will be in urban areas. Although cryogenic liquid storage has been used safely for many years in secure and regulated industrial sites, its use in relatively congested, highly populated urban areas presents a new set of issues in relation to security, safety and associated planning. The Health and Safety Executive commissioned the Health and Safety Laboratory to identify and address issues relating to bulk liquid hydrogen transport and storage and update/develop guidance for such facilities. This position paper, the first part of the project, assesses the features of the transport and storage aspects of the refuelling stations that are now being constructed in the UK, compares them to existing guidance, highlights gaps in the regulatory regime and identifies outstanding safety issues.

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