

LH2 Storage
Hazards evaluation Study

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1.0 Introduction

1.1 General

23100 USG capacity of Liquid hydrogen storage tank at the bulk gas yard. The purpose of this document is evaluate the risks arise from of the new LH2 process tank and accessories and to summarize the regulatory requirements for the installation.

1.2 Location

The is located at the main gas bulk gas yard .

The currently proposed location is near the two existing LH2 tanks.

This document will challenge this location in order to comply with the regulatory requirements.

1.3 Systems general description

The proposed system consist of a new 23,100 USG liquid Hydrogen storage tank (with better than 50ppb impurities). The Pressure is about 8 barg at environment temperature.

The tank will be installed outdoors above ground at the existing bulk gas yard at campus.

The tank will be uploaded by from a LHY container shipped by sea load.

H2 from storage tank will be vaporized through the vaporizer and flow to the domestic H2 to system.

1.4 Background for evaluations.

The requirement for the hazard evaluation arises from various authorities which needs somehow different approach for the hazards evaluation and protection measures.

1. Fire Brigade.

Fire brigade requirement for risk evaluation and assessment need to fulfill the following stages:

- 1.1 Comply with ILBC (Israel Building Code) for Access roads, distances from other hazards, building materials, Fire / Explosion prevention measures, Fire protection system, and emergency response procedures.
- 1.2 Provide deterministic risk evaluation for the most probable worst case that could give as much as possible a realistic picture of an emergency event.

2. Environment Protection Office.

EPO requirement for risk evaluation and assessment need to fulfill the following stages:

- 1.1 Provide separation distances evaluations to public receptors according to the office guidelines.
- 1.2 This evaluation should be carried out using 'ALOHA' software with restricted inputs as described in the EPO executive directive.

2. IDF Civil Defense Corp.

The IDF CDC requires for physical protection of the storage tank's area against external hazards such as bombs or rockets. The requirements arise from the ' Civil protection ordinance – Hazardous Materials storage (2014) ' directive.

The directive require for storage of flammable gas a physical protection (bunker) or to bury the tank. Neither of these requirements are possible for the current system and should be addressed separately.

2. Risk evaluation.

2.1. General.

The risk evaluation will compile between the various methods of risk analysis in order to provide comprehensive recommendations for the location and safety measures required for the project.

The various methods to be evaluated –

HAZOP analysis report that was done by Air Product on January 2015.

Hazardous area classification.

Separation distances evaluations to public receptors according to EPO guidelines.

2.3. Hazard Identification.

2.3.1 HAZARDS OF HYDROGEN

Hydrogen at room temperature and pressure is a colorless, 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.

2.3.2 PROPERTIES AND CHARACTERISTICS OF HYDROGEN

Hydrogen	Property
0.090	Density (Kg/m ³) *
0.61	Diffusion coefficient in air (cm ² /s) *
0.083	Viscosity (g/cm-s x 10 ⁻⁵) *
0.02	Ignition energy in air (mJ)
4.0 – 75.0	Ignition limits in air (vol %)
585	Auto ignition temperature (C)

14.89	Specific heat at constant pressure(J/gK)
2045	Flame temperature in air (C)
0.6	Quenching gap (mm) *
5-10	Thermal energy radiated from flame to surroundings (%)
13-65	Detonability limits (vol % in air)
2.6	Maximum burning velocity (m/s)

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2.3.3 Propensity to leak

2.3.3.1 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.

2.3.3.2 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. 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 ligent equipment design and layout, this buoyancy and hydrogen's rapid dispersion rate can become a significant safety asset.

2.3.3.3 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.

2.3.4 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.

2.4 Study of Failure Scenarios

The potential consequences of a hydrogen release are directly related to factors inherent in the environment, the rate of release, and the quantity released. The characteristics of the potential consequences dictate where and how systems are d. It should be noted that the cause of the release, while important in understanding it occurred, may or may not have a bearing on the potential consequences of the release.

2.4.1 Analysis Approach

First, three hazard zones are identified, categorized by potential consequences

- 1) within the immediate enclosed area;
- 2) within a 75-ft exclusion zone; and
- 3) outside the NFPA 75-ft exclusion zone.

Any failure scenario that produces consequences that extend beyond the NFPA exclusion zones can be considered catastrophic. The following analysis identifies three categories of likely causes of hydrogen releases for the proposed hydrogen system:

- 1) component failure.
- 2) operator error.
- 3) deliberate sabotage or attack. (This category will be ignored within the protected)

The analysis then categorizes potential consequences according to the extent of effects. The categories chosen match operational requirements and applicable codes and regulations.

2.4.2 Categorization of Hazard Zones

The potential siting locations, types of hydrogen storage components, and layout of the hydrogen system on the facility property suggest three hazard zones categorized by potential consequences.

The first is defined by small leaks, hydrogen combustion, or controlled releases of hydrogen confined within the chain-link fence isolating the system from unauthorized personnel. This area is accessed only by authorized, specially trained personnel.

The second hazard zone includes scenarios with the potential for threat beyond the fencing but within the general locale of the equipment. An exclusion zone of a 75-ft radius from storage equipment is required by NFPA 55, and the functions of the storage components in the hydrogen system are applicable.

The third category represents the greatest threats that come from events with effects that reach to the buildings and beyond. Any failure scenario that produces consequences that extend beyond the NFPA exclusion zones can be considered catastrophic.

2.4.3 Hydrogen Release Hazards Caused by Component Failures

The hydrogen dispensing system is designed to provide up to 7700 scfh (202 Nm³/h) gas derived from cryogenic LH₂ storage. No attempt is made in this report to describe the design or operation of the system, except that the system includes an approximate 23100-gal LH₂ storage tank. The proposed system components have been examined for failures that would lead to significant releases of hydrogen. The evaluation includes the most probable occurrences of concern, low probability events with severe consequences, and venting rates.

2.4.3.1 Component Analysis Methodology

The hydrogen station was analyzed for component failure and resultant hydrogen release. Major components identified in the main flow path of hydrogen are included in the analysis. Minor components and instrumentation discussed in the following paragraphs are categorized by subsystem.

2.4.3.2 Analysis of Release by Subsystem Analysis is considered by subsystem. Liquid Storage and Vaporizer

Three categories of potential release are:

- o Small leaks at connections much less than 1 ft³/min of hydrogen
- o Medium leaks at connections and valve stems around 1 to 10 ft³/min
- o Large leaks from catastrophic failure of component.

Small leaks at connections are common and may occur at any of the piping connections. Initially, the leak test required by American Society of Mechanical Engineers (ASME) B31.3 should catch any connection leakage, and regular leak checks at maintenance intervals should detect leaks early. Small connection leaks are considered the most plausible under normal conditions, and they would release very small quantities of hydrogen.

Medium-sized leaks from the fill connection, manual valve stems, and liquid vaporizer tubing are possible but are mitigated. Leaks at cryogenic liquid-fill connections are common. The estimated leak rate of less than 5 ft³/min would continue until the operator stopped the operation and fixed the leak. The extended stem on cryogenic liquid valves greatly reduces the chance of stem leakage, but it still may occur over time due to valve cycling. Initially, the leak test required by ASME B31.3 will catch any stem leakage. Regular leak checks at maintenance intervals should detect leaks early.

Large leaks from catastrophic failure of the storage vessel, the liquid isolation valve, and components such as the liquid strainer and pressure-building regulator are very unlikely without outside forces acting on the component. Piping components purchased and installed per ASME B31.3 are rated for the environment (pressure and temperature) they will experience. If any of the components in this category were to fail catastrophically, the maximum potential release would be the entire contents of the liquid storage vessel.

2.4.3.3 Implications for Release Caused by Component Failure

Since the system is per ASME standards, the most likely event under normal operating conditions is that of small leaks at connections Regulators, check valves.

The NLH2 vessel has a low probability of failure. With the exception of the nozzle, all the components in question are only approached by the vendor's maintenance personnel. Large releases caused by the failure of system components are considered unlikely but will be addressed.

2.4.3.4 Hydrogen Release Hazards Caused by Operation-Induced Failure

System operations involving personnel and the potential effects of operations unrelated to hydrogen dispensing were examined for actions that would lead to significant releases of hydrogen. These operations include maintenance activities, hydrogen loading operations, dispensing activities, trespassing, emergency procedures, and accidents involving other operations. It is well known that human error overshadows equipment failure as the predominant cause of hydrogen incidents.

2.4.3.5 Discussion

A discussion of maintenance, filling operations, emergency procedures, and potential accidents involving other operations is given in the following paragraphs.

Maintenance

Maintenance and repair operations on the hydrogen system are only conducted by vendor-trained technicians. Standard procedures for repairs involving hydrogen-wetted components require purging of the hydrogen before personnel start repairs and, if necessary, purging the air before hydrogen is again introduced to the system. Operations are performed with several personnel on hand using the "buddy system," appropriate personal protective equipment (PPE), and hydrogen detectors. Emergency shut-off switches are conveniently located. Only small hydrogen releases are expected from maintenance operations.

Filling Operations

Supply of hydrogen to the system is performed by trained vendor crews. Operations will be coordinated in advance with the facility receiving staff, and the vendor crews will use the "buddy system" during the refueling operation. Barriers protect the LH2 storage tank and system from collision by the hydrogen tanker truck or other vehicles. The hydrogen refueling truck will possess automatic shutoff equipment, in case connecting lines fail or disconnect. Hydrogen gas lost during chill-down of system components during refueling should be vented in a controlled manner. Only small hydrogen releases are expected from refueling operations.

Emergency procedures

General system shutdown switches will be provided in accessible locations, both remote from and at the hydrogen station. The vendor will control what specific responses are taken to mitigate failure modes. The. should also establish facility-wide emergency procedures in response to potentially catastrophic occurrences. Errors in judgement handling emergency situations, combined with malfunctioning instrumentation, although very rare, have led to catastrophic failures of hydrogen vessels in the past (Redskuty and Stewart 1996). Depending on the circumstances, a large hydrogen release could occur.

Accidents Involving Other Operations

Operation of heavy vehicles, tankers, and other activities that could threaten the hydrogen station should be carefully reviewed and controlled. Failure of the barricades that protect the hydrogen station from vehicles could result in a large release of hydrogen. The circumstances surrounding the release of hydrogen from a vehicle collision could be further compounded should the colliding vehicle contain fuel, oxidizing materials, or hydrogen. will consider these factors in siting, design of barriers, and in planning other operations.

2.4.3.6 Implications for Release Caused by an Error in Operations

The operation of the hydrogen dispensing station as a demonstration system is planned to last several years. For a project of this duration, it is realistic to expect that, from all the operations considered above, a small leak is likely to occur. A small release of hydrogen poses a safety hazard in the immediate area of the leak. A catastrophic leak of hydrogen resulting from operations is very unlikely with this system; however, consequences and considerations for catastrophic leaks are presented in the sections that consider catastrophic releases.

2.4.4 Hydrogen Release Hazards Caused by warlike Attack

Warlike attack differs from other scenarios in that there is a deliberate intent to make the system fail in a violent manner. Therefore, the approach is to consider several likely means as examples and group them by their potential consequences.

2.4.4.1 Small Penetration

Any action that causes a small penetration into a hydrogen system and leads to the unplanned release of hydrogen is considered here. Examples would include missile shreds spear or shear the equipment. Consequences might include:

- o Loss of vacuum in the vacuum annulus of the LH2 storage tank, which could lead to a large heat leak and excessive venting of product through the relief system
- o A jet of LH2 or cryogenic gaseous hydrogen (GH2) from the LH2 storage tank
- o A jet of GH2 from connecting hardware

2.4.4.1.1 Cryogenic Vessel Subsystem

Two cases can be considered: penetration of the outer wall, or penetration of both the outer and inner walls of the LH2 storage vessel.

- Outer Wall

Breaching only the outer wall introduces air to the vacuum-jacketed region, but does not release hydrogen from the inner vessel. The loss of vacuum and introduction of air will increase the heat impinging on the inner vessel and cause an increase in the rate of GH₂ boil-off from the vessel. A larger heat leak caused by a bridge of frozen water or nitrogen is considered unlikely. The vacuum annulus is filled, to a large extent, with thermal insulating material (pearlite or Mylar). This material, given a penetration of the outer wall, would slow entry of air into the annulus and significantly reduce the amount of air that can enter by displacing the available volume. Both of these effects will limit the effect of the heat incursion to the immediate area of the penetration. The relief system is specifically designed to safely vent hydrogen should vacuum be lost.

- Penetration of Inner Wall

With both walls of the vessel breached, air and hydrogen can potentially meet at some point external to the inner vessel. However, as noted above, the vacuum-jacketed space is filled with pearlite or Mylar in sufficient quantities to displace most of the volume in which a hydrogen-air mixture could form, leaving little to combust. The hydrogen within the inner vessel is under a maximum working pressure of 150 psig and will exit in a plume or jet through the hole in the outer vessel wall. Ignition of the hydrogen outside of the outer wall might lead to further heating of the

system on the outside vessel walls. Given the low emissivity of hydrogen-air reactions, radiative heating is not a major concern. External regions with direct exposure to the hydrogen combustion will experience high temperatures, but the ASME vessel design can withstand the fire. Loss of pressure in the vacuum annulus or heating of the inner vessel if sufficiently extreme, will lead to an emergency shutdown of the system. Should a fire result in an internal pressure rise greater than the maximum allowable working pressure for the volume, the relief system will protect against over-pressure .

2.4.4.1.2 Summary

Penetration in the cryogenic sub systems will present a fire and/or pressure release hazard to personnel, ancillary equipment, or vehicles in the immediate area. The safety equipment incorporated into the hydrogen system will preclude the further escalation of hazards such that the exclusion zones specified by standards NFPA 55 are thought to be adequate. This reasoning applies to equipment/component failure noted in the component analysis and failures caused by warlike attack.

2.4.4.2 Large Penetration

This analysis examines the consequences of the release of hydrogen. Large explosive charges with yields that far exceed the hazard posed by the hydrogen are not considered here since their effects would be greater than that of the hydrogen inventory in the dispensing system. Therefore, explosive-charges of interest might include a rocket-propelled grenade. The results are distinguished from the penetrations considered above by the large size of the opening and attendant shrapnel.

2.4.4.2.1 Effect on the Liquid Hydrogen Vessel

High explosives can produce a large hole or rupture of the vessel, the worst case leading to a spill of the entire contents. Ambient surface temperatures, regardless of season, are so high relative to the temperature of liquid hydrogen that the spilled LH2 will flash to a gas on contact. Heating the LH2 to 300 K will result in an 845-times increase in the volume of the hydrogen. The process of heating the liquid to a gas is rapid, with the air supplying much of the heat during mixing. The

resultant mixture behaves as a plume, subject to weather conditions.

2.4.4.2.2 Bonfire

A bonfire may possess sufficient fuel to heat the system beyond the point where the internal hydrogen pressure trips the relief systems and vents. This could arise by an accident involving the delivery of other fuels at the facility or by deliberate action. The system design and ASME construction provide fail-safe operation under considerable heating and provide redundant relief paths to allow hydrogen to be safely vented without rupture of the vessel. Boiling liquid expanding vapor explosion (BLEVE) is theoretically possible if the contents of the LH2 tank are heated above the critical point causing a BLEVE, but this is not considered a reasonable threat.

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2.5 Analysis of Released Hydrogen

Hydrogen, with high levels of purity as found in storage systems, must mix with an oxidizer before any hazardous reaction can take place. In terrestrial hydrogen systems, air provides the greatest concern, whether hydrogen is released into the air, or air enters the hydrogen system. One line of reasoning traditionally used to establish the degree of possible hazard is to determine the greatest quantity of energetic material that can participate in an accident and determine the range of its effects. This so-called quantity-distance evaluation assumes the energetic material is premixed to provide a theoretically optimum release of energy, localized at a point, with a manner of energy release similar to solid explosives. These assumptions seldom fit hydrogen accident scenarios. Therefore, in the case of hydrogen, the key to a realistic evaluation of hazards is to determine the following:

- o How much of the released hydrogen can participate to form a combustible mixture
- o The extent of formation of the combustible mixture
- o The type of reaction (fire, deflagration, or detonation)
- o The importance of environmental factors such as temperature, wind, and the effects of confinement.

A chemical dispersion code was used to evaluate dispersion of hydrogen from liquid spills and gas jets. The code also was used to evaluate combustion of hydrogen-air clouds. A pressure code helped to evaluate the release of hydrogen and shrapnel from pressurized components.

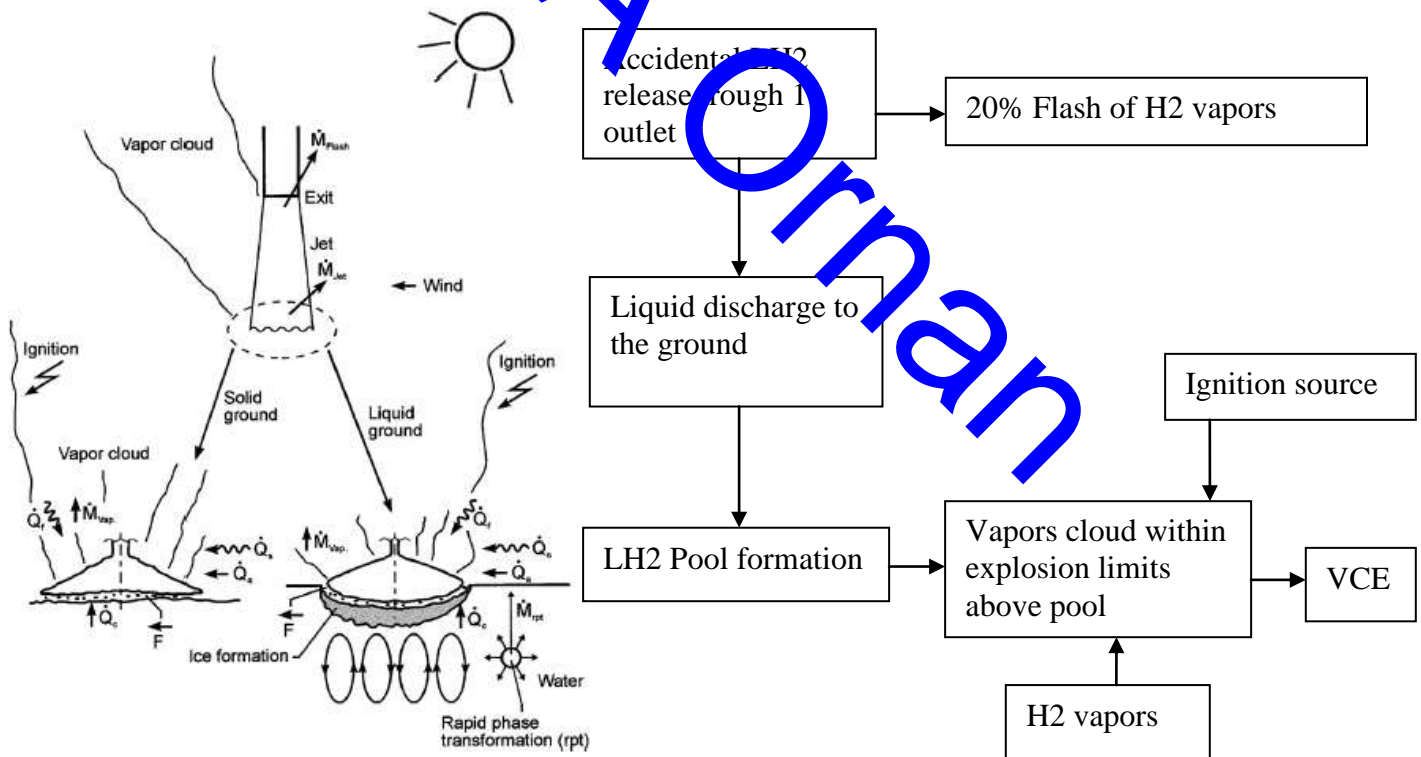
2.5.1 Computations for the Release of Hydrogen

2.5.1.1 Liquid Hydrogen Spill Characteristics

A spill could involve the entire cryogenic inventory of the LH2 vessel (up to 23,100 gal). A typical fill of the vessel would result in a saturation pressure of 60 psig. Given a large rupture, the sudden exposure of the inventory to ambient pressure or 0 psig will instantly boil or “flash” a significant portion of the liquid to cryogenic vapor. At 60 psig, 19 percent would flash, leaving approximately 18,700 gal to spill onto the ground.

Several factors influence the characteristics of cryogenic spills. Liquid hydrogen boils at 20.3 K under 1 atmosphere of pressure, so any surface at ambient temperatures will have sufficient heat to vaporize the LH2. The amount of surface to which the spilled cryogen is exposed affects the rate at

which the liquid flashes to vapor and warms. The cross-sectional area of the liquid spill determines the plume diameter or cross section. At hydrogen's boiling point, the cold hydrogen vapor is heavier than air until it warms to 23 K, where it becomes neutrally buoyant. As the cold vapors mix with air, the air is chilled below the dew point, causing condensation and forming a visible cloud. After dwelling near the ground and warming sufficiently, the visible vapor cloud forms a plume as it rises. Time-lapse photographs of LH2 spills conducted at NASA WSTF in 1980 show the general behavior of cryogenic hydrogen-air plumes (Witcofski, August 1981). For wind speeds ranging from 1.6 to 6.3 m/s, the water vapor clouds traveled 50 to 100 m near the ground, then rose at a rate of 0.5 to 1.0 m/s (Witcofski 1981). During NASA test 6, the observations reported a maximum pool of 2-3 meters.



2.5.1.2 Hydrogen-Air Cloud Flammability

The flammability limits for hydrogen-air mixtures range between 4 and 75 percent-by-volume hydrogen in air. These data are for combustion in the upward direction. It is the convention to provide this information as representative of hydrogen's flammability limits. However, flame fronts observed in hydrogen-air mixtures burn less readily when constrained to burn in a horizontal direction, and even less so in a downward direction. The lower flammability limit for downward propagation increases to 9 percent-by-volume hydrogen in air, as a direct effect of the buoyancy of hydrogen (Benz 1988). In uniform mixtures with low hydrogen concentrations (4 to 9 percent-by-volume concentration), combustion of the entire volume of a mixture in an upward direction is not complete. The combusted region tends to form a volume in the shape of a cone that expands in the upward direction, but the mixture outside of the cone is left unburned (Sherman et al. 1981). In general, the release of a large quantity of hydrogen forms a plume that possesses an increasing concentration of hydrogen towards the centerline of the plume. Initially, the central region of the plume may be above the upper flammability limit. In addition, the lower-concentration, hydrogen-air mixtures require greater initiation energy to ignite. Flow and water vapor will also result in greater initiation energy when compared to the same composition mixture, but dry and without movement. This fact has importance in the context of a hydrogen system located where it is desirable for any release of hydrogen to rise above and clear the tops of nearby structures.

Therefore, as a plume of hydrogen rises, the exterior regions of the plume (the regions likely to encounter an ignition source) are less likely to ignite when compared to near-stoichiometric mixtures. Should ignition occur in an exterior region of the plume, only the gas in the immediate vicinity of the ignition source will tend to burn and the potential for flame propagation or deflagration throughout the cloud is reduced. Therefore, unless some process rapidly mixes the hydrogen plume to form a near-stoichiometric mixture with air throughout the cloud, the normal factors that typically influence mixing (diffusion, buoyancy, wind, and turbulence) in a release will not result in complete combustion of the plume.

The movement of flammable mixtures can be partially deduced by observing the movement of the vapor cloud associated with a LH2 spill. From the work performed at WSTF, it was determined that

the concentration of hydrogen within the water vapor clouds had to be greater than 6.8 percent to cool the air below the dew point (Witcofski, March 1981). It must be stated, however, that there is an invisible region outside of the vapor cloud, with concentrations between 4 and 6 percent hydrogen in air, that is flammable in the upward direction. However, for mixture compositions in this range, the ignition sources must have energies greater than 1 mJ, or approximately 100 times greater than the minimum ignition energy (MIE). The presence of wind or water vapor will further increase the amount of energy needed to ignite the mixture. The direct initiation of the detonation in hydrogen-air mixtures in free air (or unconfined by solid surfaces) requires high-energy shock waves, typically produced from high explosives. With confining surfaces present, smaller ignition sources initiate a flame that accelerates until a deflagration-to-detonation transition can initiate detonation. Ignition sources commonly found within buildings could initiate a detonation, should some portions of a hydrogen-air plume become entrained within the associated confined spaces or ducts. Under such circumstances, the lower detonability limit is 8 percent hydrogen in air.

The dispersion of LH2 pool was simulated using three gas mixing model and standard k-ε turbulence model. The study was done using PHOENIX, Computational Fluid Dynamics (CFD) software that involves a numerical solution of the conservation equations for mass, momentum and energy, which govern fluid flow. The CFD method involves subdividing the flow domain into a large number of small cells, where the gas velocity, pressure and temperature are calculated at nodes in each cell. For turbulent flows, it is not computationally feasible to directly resolve all of the fine eddy structures in the flow. Instead, the flow is time-averaged and the mean conservation equations are solved. As a consequence of this averaging, additional terms are introduced into the equations to account for the unresolved eddy motions. These terms are approximated using a turbulence model. In the present work, the industry-standard k-ε model has been applied.

The CFD code in use is PHOENIX Flair by CHAM UK is a modern CFD sets of codes uses an automatic Grid / Mesh sizing by the auto-mesher following these guidelines:

1. The maximum cell size is not allowed to exceed a set fraction (0.05 by default) of the domain size.

2. The ratios between the sizes of the first cell in the current region and the last cell in the previous region, and the last cell in the current region and the first cell in the next region, are not allowed to exceed a set limit (1.5 by default).
3. If the ratios are exceeded, the number of cells in that region is increased, and the spacing is set according to a geometrical or power-law progression using a set expansion ratio (geometrical 1.2 by default), until either the ratio criterion is satisfied at both ends of the region, or the cells at both ends are below a set minimum fraction (0.005 by default) of the domain size.

Where there is an INLET object on the edge of the domain, the auto-meshing will assume that grid is required in that direction, even if there is only one region.

After the meshing an adjustment was made before a final run was made.

The adjustment include refining cell number and the use of the power-law or geometrical expansions to reduce the change in grid-size between regions. This assists convergence of the Earth solver. With the auto-meshing turned on, this is controlled by reducing the minimum cell size and adjusting the maximum size ratio. Reducing both these values will act to reduce the rate of change of grid size across region boundaries, but also increase the number of cells.

The model settings are as follows:

COMPUTATIONAL GRID

NX – 70 cells

NY – 80 cells

NZ – 30 cells

The model settings are as follows:

BOUNDARY CONDITIONS

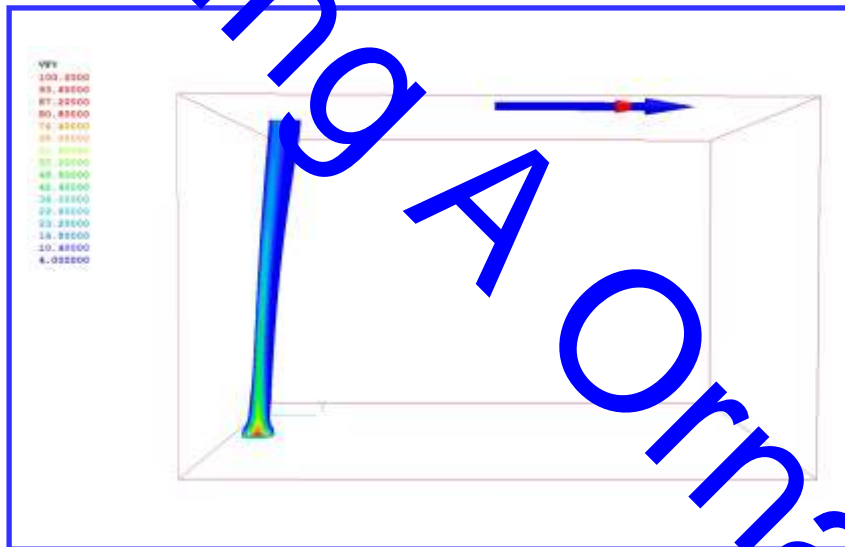
Wind inlet – fixed velocity boundary conditions – 0.5 m/s, 5 m/s , 10 m/s.

Side and top outlets from the domain: fixed pressure boundary condition with atmospheric pressure

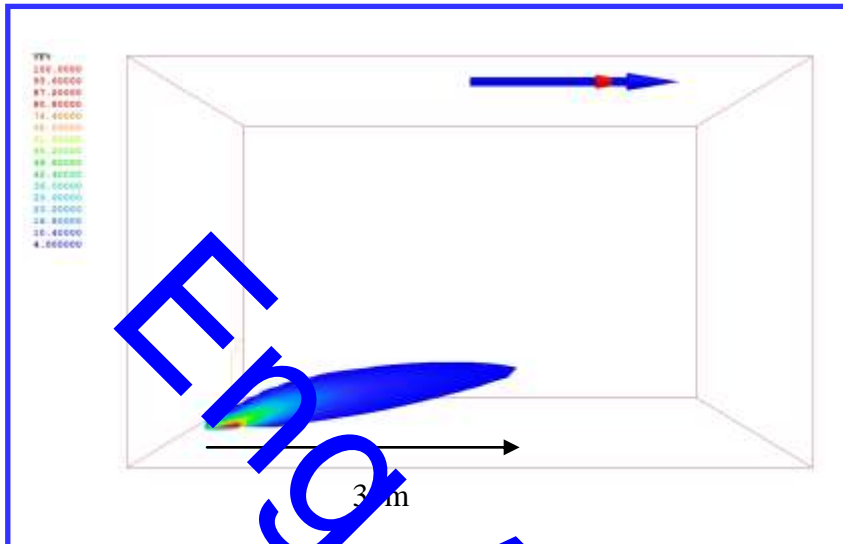
vapors inlet – fixed velocity boundary condition.

Ground plane – plate object

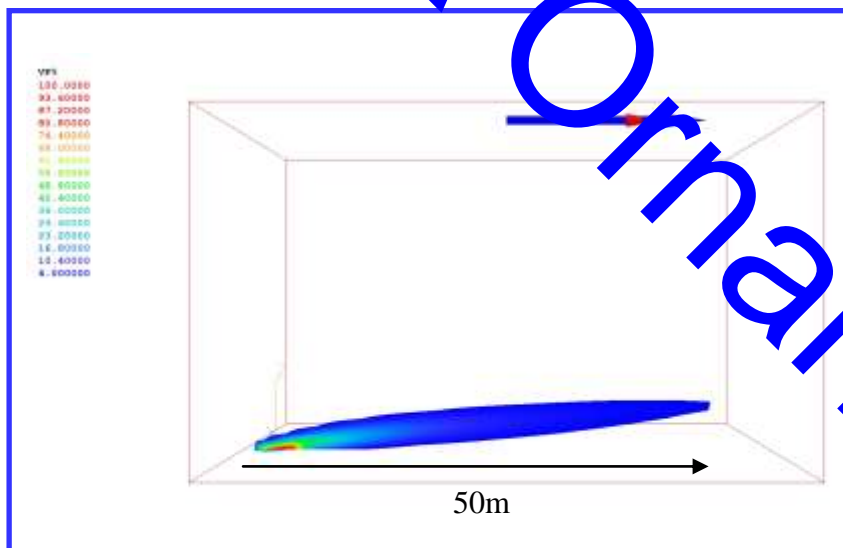
The size of the Cryogenic pool was taken as 3 m diameter following NASA Test no 6, and the evaporation rate was taken 0.5 kg/



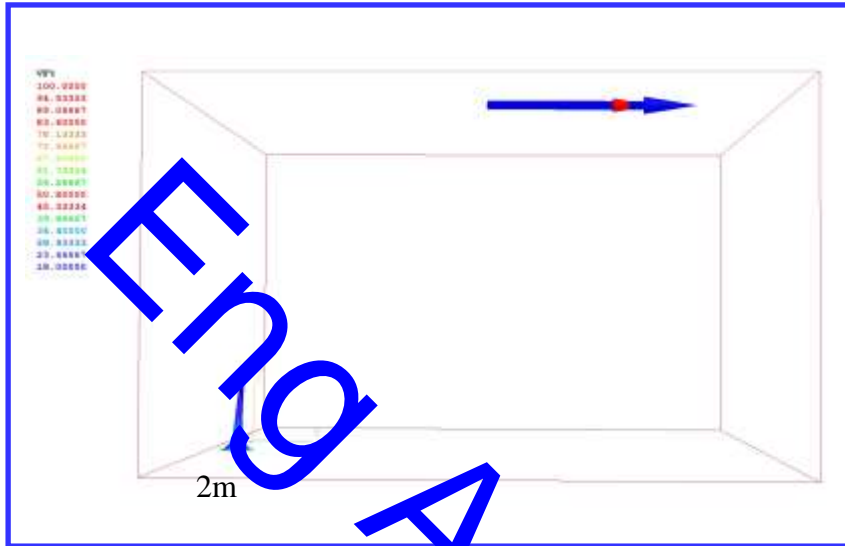
4% v/v concentration (LEL) from LH2 volatile pool (3m dia) wind velocity – 0.5 m/s



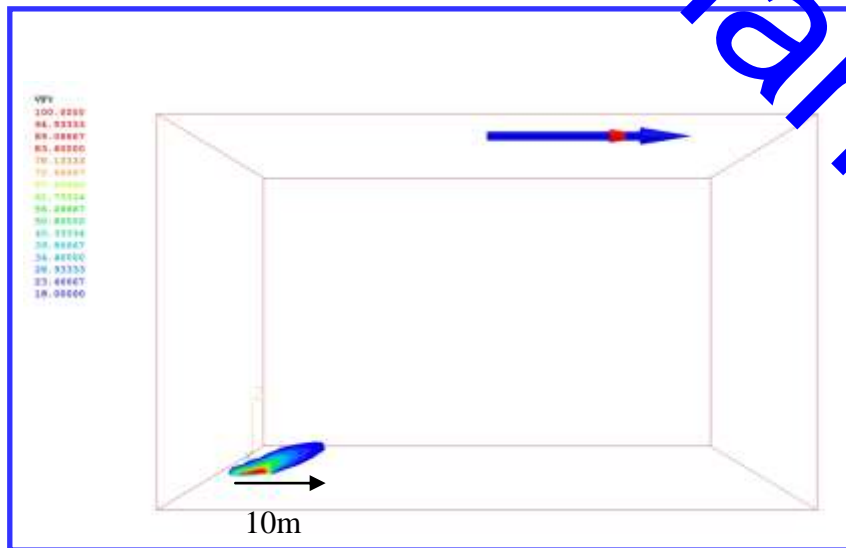
4% v/v concentration (LEL) from LH2 volatile pool (3m dia) wind velocity -5 m/s



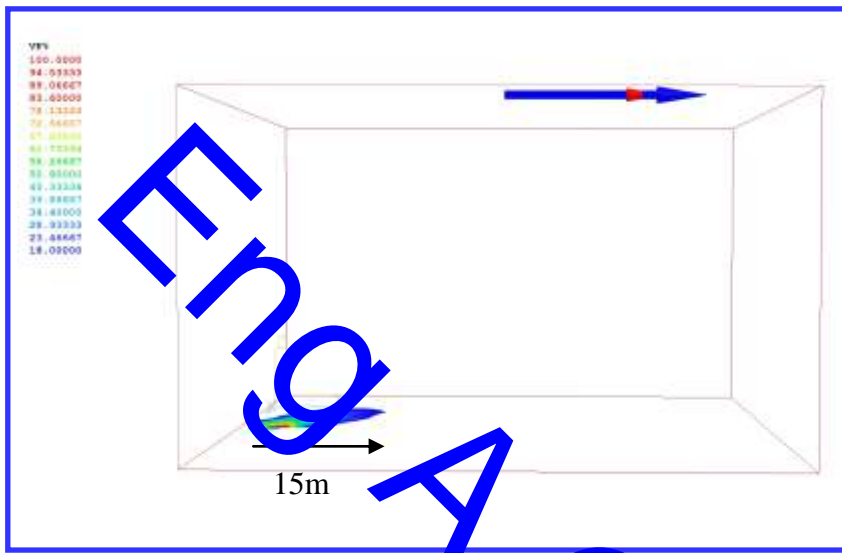
4% v/v concentration (LEL) from LH2 volatile pool (3m dia) wind velocity - 10 m/s



18% v/v concentration from LH2 volatile pool (2m dia) wind velocity – 0.5 m/s



18% v/v concentration from LH2 volatile pool (3m dia) wind velocity – 5 m/s



18% v/v concentration from LH2 volatile pool (6m dia) wind velocity – 10 m/s

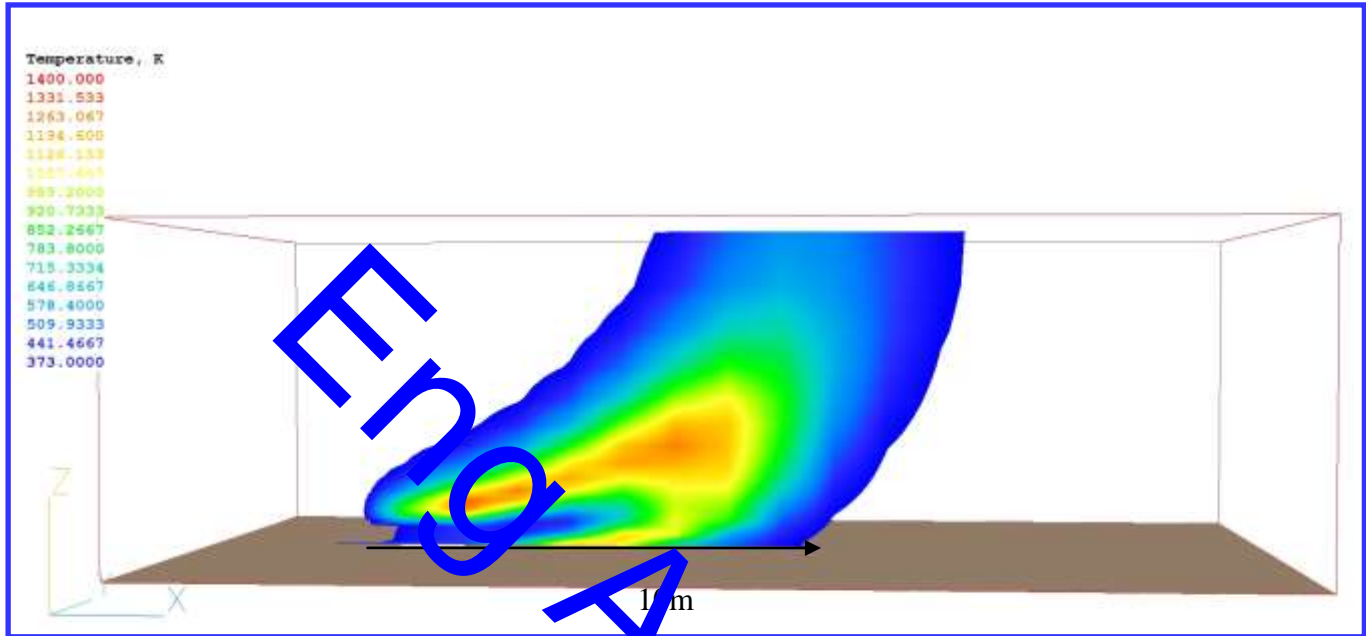
2.5.1.3 Release with Mitigation

Two worthwhile strategies are to increase the rate at which the LH₂ is vaporized and to reduce the diameter of the plume. Given the positions of facilities surrounding the hydrogen station, it is desirable to make a potential release of hydrogen rise as rapidly as possible. Several features have been discussed for incorporation into the facility design. These include a spill pond that contains crushed rock to enhance heat transfer to the spilled liquid, and slats inserted within the surrounding walls. The effects of crushed rock and slatted fence on potential spills. Little information was found in the literature on how to use crushed rock to increase the rate of LH₂ boil-off. Preliminary work (Zabetakis and Burgess 1961) suggests that the boil-off rate of LH₂ using crushed rock is double the rate for moist sand. Installing slats within the security fence that encloses the spill pond should help direct the hydrogen plume upward as it warms rather than letting it spread out over the ground. This kind of control, known as a vapor fence or barrier, has been used to reduce vapor travel of flammable cryogenic vapors such as liquid natural gas (LNG) (Moorhouse and Roberts 1988).

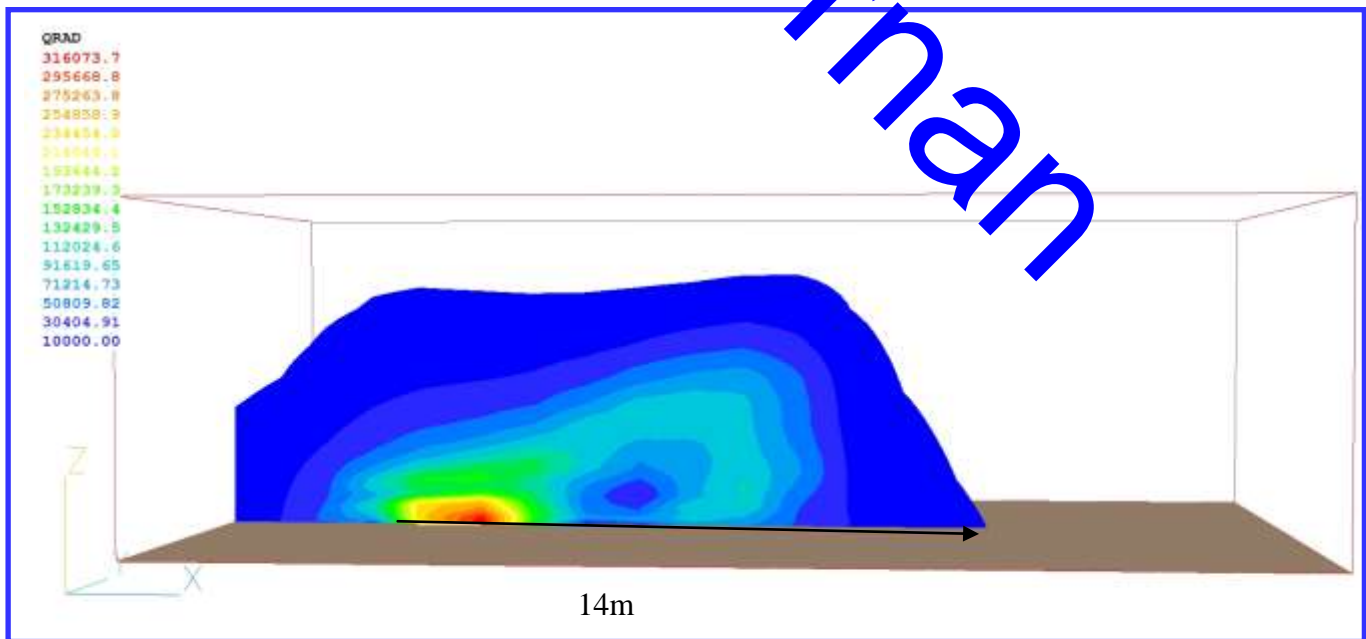
2.5.4 Flash Fire Hazards

Hydrogen fire has several characteristics of note. Hydrogen flames, unless seeded with impurities, are very hard to see in daylight. This property, combined with its low emissivity (puts out very little infrared radiation), makes hydrogen combustion hard to sense until physical contact is made with the flame. Hydrogen combustion in air also produces ultraviolet (UV) radiation capable of producing effects similar to overexposure to the sun. Direct exposure to hydrogen flames produces immediate burns. Hydrogen is so easily ignited that where it is released, one should expect or be prepared for ignition and fire. The equipment is designed to ASME standards that provide redundant protection in the case of fire. Small leaks may occur and ignite, but go unnoticed until maintenance personnel enter the secure area. A plume of hydrogen that is ignited will rapidly flash back to the source of hydrogen. From the perspective of controlling hazards, hydrogen fire localized to a source or leak is often preferable to a growing hydrogen plume.

The worst-case scenario is a large plume that, if ignited, can burn personnel or initiate other fires in readily combustible materials. PHOENICS computations indicate the thermal flux from an ignited hydrogen-air mixture will range between 10 to 100 kW/m² for exposures at distances from tens of feet to near contact with the mixture. Combustion of a hydrogen cloud will be burned out completely within 1 to 3 seconds. There is not enough deposition of thermal energy to ignite typical materials of construction. Personnel caught in the proximity may be severely burned; and flammable liquids, if directly exposed, may be ignited.



100 C contour from LH2 volatile pool (3m dia) wind velocity – 10 m/s

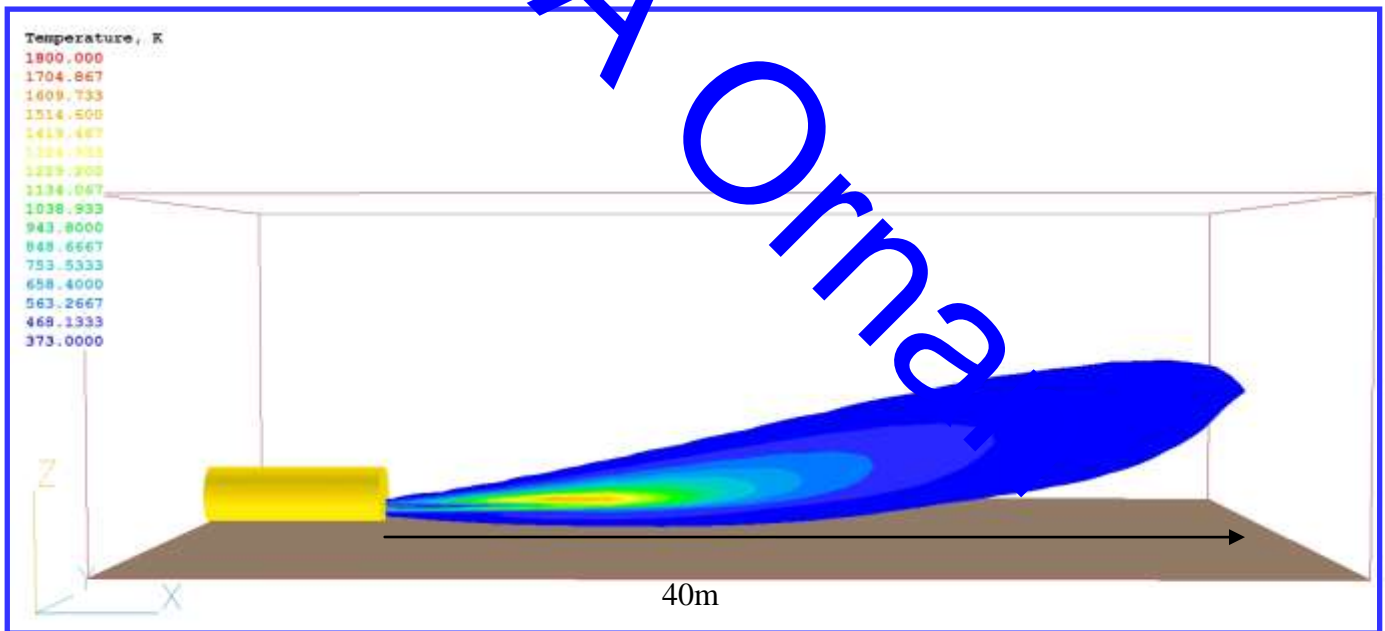


10KW/m2 heat flux contour from LH2 volatile pool (3m dia) wind velocity – 10 m/s

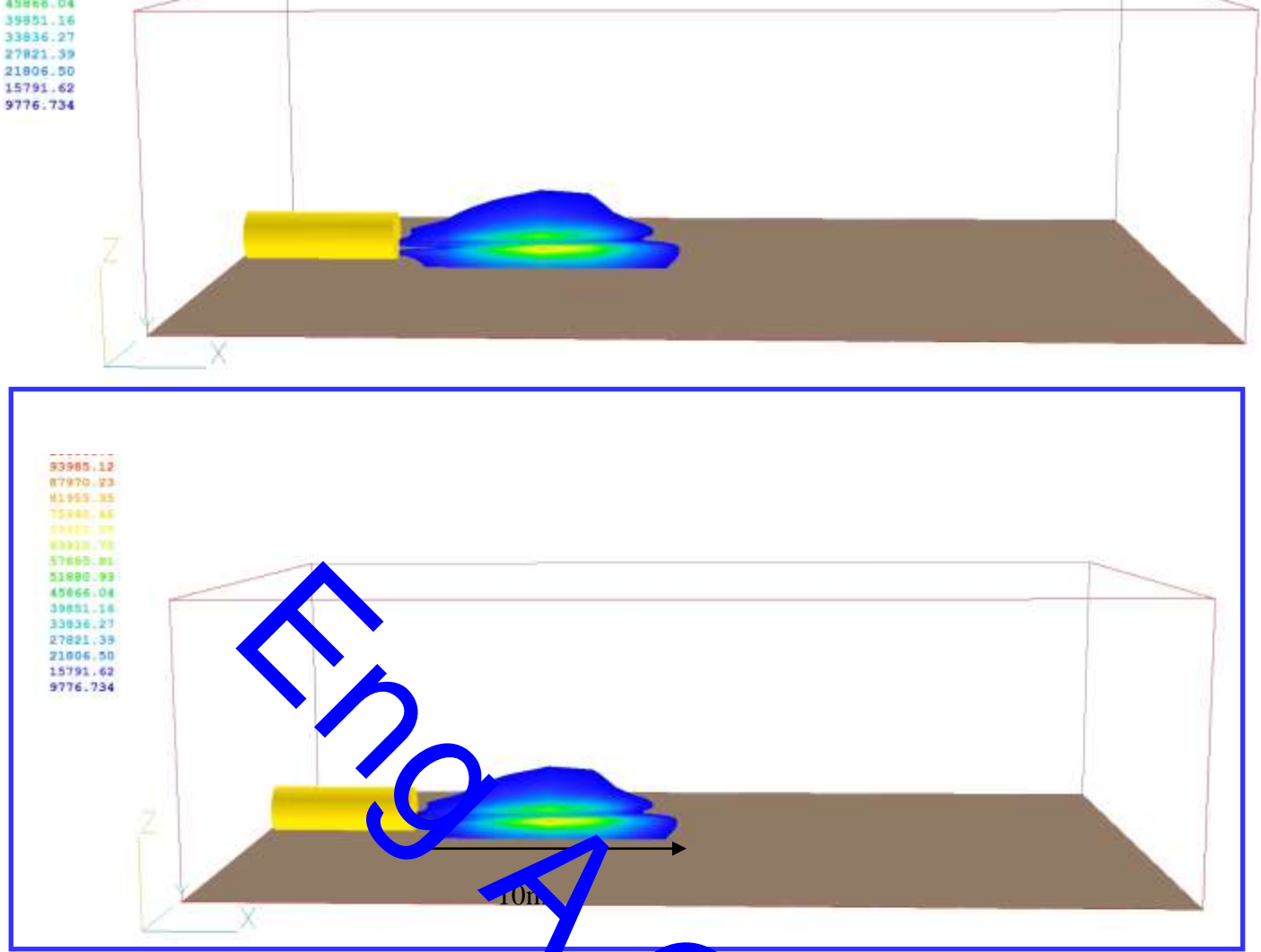
2.5.5 Jet Fire Hazards

Although the pressure in the LH2 system is considered low, is certain circumstantiate release could be injected from the PRV or RD and if ignited will be a Jet Fire.

The worst-case scenario is a large plume that, if ignited, can burn personnel or initiate other fires in readily combustible materials. PHOENICS computations indicate the thermal flux from an ignited hydrogen-air mixture will range between 10 to 100 kW/m² for exposures at distances from tens of feet to near contact with the mixture. Personnel caught in close proximity may be severely burned; and flammable liquids, if directly exposed, may be ignited.



100 C contour from LH2 jet fire 1" 0.82 kg/s, wind velocity – 10 m/s



10 KW/m² heat flux contour from LH2 jet fire 1" 0.12 kg/s, wind velocity – 10 m/s

2.5.5 Deflagration and Detonation Hazards

Deflagration and detonation are two modes of hydrogen combustion capable of producing high temperatures, shock waves, and high overpressures. Following table lists some of the characteristics of deflagrations and detonations. Both processes require confinement such as pipes, ducts, narrowly spaced walls, or large initiation energies to occur. Keeping the hydrogen dispensing system away from structures will give plumes from a large release a chance to rise. Both detonations and energetic deflagrations require the formation of mixtures of hydrogen and air that are close to stoichiometric. In the open air, powerful explosives or very large sparks are required to initiate detonation. In the case of warlike attack on the system, the explosives used in the attack are not considered initiation sources since they act before the hydrogen mixes with the air. Although data predict hydrogen-air plumes will clear nearby structures, if a plume were to brush up against intake ducts, a potentially detonable mixture could form in a confined space. A process that might mitigate the formation of a detonable mixture is the dilution of the mixture (as make-up air) with air

already in the building. Potential spaces outside include small courtyards. Hydrogen-air mixtures swirling in spaces with walls approximately 15 ft apart or less have produced significant overpressures when ignited. In summary, detonation or energetic deflagration is an unlikely outcome for a large hydrogen release if the system is located away from structures.

Eng A Ornan

2.5.6 Summary of Release Hazards

The consequences of equipment failure, operational error, accidents, or attack can be categorized as producing one of two types of releases: a leak; a penetration (or very large leak/jet); or a rupture (a rapid emptying of the containment). The division seeks to separate the consequences of the release into two increasing levels of potential hazard to the surroundings:

- o Leaks may pose a hazard to adjacent system components or attending personnel directly exposed to combustible mixtures in the immediate vicinity of the leak. Here, the concern is for direct exposure to hot hydrogen reaction products.
- o A penetration produces a larger release that can pose a hazard to the entire system and personnel or equipment near the station. The concern includes not only direct exposure to hydrogen combustion over a larger area, but exposure to thermal and UV radiation capable of producing burns, minor shrapnel, and the potential for secondary ignition of station components or nearby materials.
- o A rupture in the liquid storage system may pose a hazard to equipment and personnel in the greater vicinity of the station, and threaten adjacent structures and public spaces located outside of the exclusion zone as specified by NFPA code. The most likely outcome from the threat is flash fire.

3. Israeli Environment Protection Office (EPO) separation distance .

3.1. General

The Israel EPO issued separation distances policy guide (June 2011) in order to preform risk assessment from steady hazards sources. The policy document is based on scenarios which use the 'ALOHA' software using specific inputs for each case.

3.2 Analysis for leak from top of tank.

DATA:

Location: -----

Time: March 13, 2015 13:30 hours DST

CHEMICAL DATA:

Chemical Name: HYDROGEN Molecular Weight: 2.02 g/mol

PAC-1: 65000 ppm PAC-2: 250000 ppm PAC-3: 400000 ppm

LEL: 40000 ppm UEL: 750000 ppm

Ambient Boiling Point: -252.8° C

Vapor Pressure at Ambient Temperature: greater than 1 atm

Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)

Wind: 3 meters/second from E at 10 meters

Ground Roughness: urban or forest Cloud Cover: 5 tenths

Air Temperature: 25° C Stability Class: D

No Inversion Height Relative Humidity: 50%

SOURCE STRENGTH:

Leak from short pipe or valve in horizontal cylindrical tank

Flammable chemical escaping from tank (not burning)

Tank Diameter: 3 meters Tank Length: 12 meters

Tank Volume: 84.8 cubic meters

Tank contains liquid Internal Temperature: -250° C

Chemical Mass in Tank: 5,420 kilograms

Tank is 95% full

Circular Opening Diameter: 1 inches

Opening is 2.82 meters from tank bottom

Release Duration: ALOHA limited the duration to 1 hour

Max Average Sustained Release Rate: 49.3 kilograms/min
(averaged over a minute or more)

Total Amount Released: 2,673 kilograms

Note: The chemical escaped as a mixture of gas and aerosol (two phase flow).

THREAT ZONE:

Threat Modeled: Overpressure (blast force) from vapor cloud explosion

Type of Ignition: ignited by spark or flame

Level of Congestion: congested

Model Run: Heavy Gas

Red : 135 meters --- (0.1 atmospheres)

Orange: 78 meters --- (0.28 atmosphere)

3.3 Analysis for leak from reloading pipe.

DATA:

Location: -----

Time: March 19, 2015 1130 hours

CHEMICAL DATA:

Chemical Name: HYDROGEN Molecular Weight: 2.02 g/mol

PAC-1: 65000 ppm PAC-2: 230000 ppm PAC-3: 400000 ppm

LEL: 40000 ppm UEL: 750000 ppm

Ambient Boiling Point: -252.8° C

Vapor Pressure at Ambient Temperature: greater than 1 atm

Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)

Wind: 3 meters/second from E at 10 meters

Ground Roughness: urban or forest Cloud Cover: 5 tenths

Air Temperature: 25° C Stability Class: D

No Inversion Height Relative Humidity: 50%

SOURCE STRENGTH:

Leak from short pipe or valve in horizontal cylindrical tank

Flammable chemical escaping from tank (not burning)

Tank Diameter: 3 meters Tank Length: 12 meters

Tank Volume: 84.8 cubic meters

Tank contains liquid Internal Temperature: -253° C

Chemical Mass in Tank: 5420 kilograms

Tank is 90% full

Circular Opening Diameter: 2 inches

Opening is 0.60 meters from tank bottom

Ground Type: Concrete

Ground Temperature: equal to ambient

Max Puddle Diameter: Unknown

Release Duration: ALOHA limited the duration to 1 hour

Max Average Sustained Release Rate: 28.2 kilograms/min

(averaged over a minute or more)

Total Amount Released: 1,688 kilograms

Note: The chemical escaped as a liquid and formed an evaporating puddle.

The puddle spread to a diameter of 4.1 meters.

THREAT ZONE:

Threat Modeled: Overpressure (blast force) from vapor cloud explosion

Type of Ignition: ignited by spark or flame

Level of Congestion: congested

Model Run: Gaussian

Red : 109 meters --- (0.1 atmospheres)

Orange: 77 meters --- (0.28 atmospheres)

4. Hazardous Area Classification.

4.1 General

Hazardous area classification classify the surrounding zone around the facility which has explosion hazards due to the presence of flammable vapors at an explosive concentration that could be ignited by a spark or other energy source.

4.1.1 Reference documentation

IS EN 60079-10:2012 Classification of areas —Explosive gas atmospheres
International standard 60079-10 Classification of hazardous areas.

IP – 15 : 2005 Area classification code for installations handling flammable fluids.
NFPA® 55 Compressed Gases and Cryogenic Fluids Code 2013 Edition

4.1.2 General overview of the processes involved

As a general overview, in this chapter the processes involved in an area classification will be described to understand the hazard of explosive atmospheres and the substances locations and equipment involved

4.1.3. Characteristics of the products involved in the process

The following lines summarize the flammability characteristics of the products involved in the process.

	Name	MW	Flash Point	LEL %	Vapor pressure	Melting point	Boiling point °C	Adiabatic expansion	SG water=1	Relative density gas/ air	Ignition temp °C	Class	Temp Class
1	Hydrogen	2	Not applicable	4.0	Gas @21 °C	-259.2	-252.8			0.069		Flammable gas	

Table: Summary of the physical parameters and of the available substances in the installation:

4.2 Area classification and equipment requirements

As Directive 1999/92/EC establish on Annex II, equipment and protective systems for all places in which explosive atmospheres may occur must be selected on the basis of the categories set out in Directive 94/9/EC.

In particular, the following categories of equipment must be used in the zones indicated, provided they are suitable for gases or vapors as appropriate:

In zone 0 (99/92/EC) , category 1 equipment (94/9/EC), In zone 1 , category 1 or 2 equipment. In zone 2 , category 1, 2 or 3 equipment.

4.2.1 Classification criteria

According to Directive 1999/92 EC. places where explosive atmospheres may occur is a place in which an explosive atmosphere may occur in such quantities as to require special precautions to protect the health and safety of the workers concerned is deemed to be hazardous within the meaning of this Directive.

A place in which an explosive atmosphere is not expected to occur in such quantities as to require special precautions is deemed to be non-hazardous within the meaning of this Directive.

Flammable and/or combustible substances are considered as materials which may form an explosive atmosphere unless an investigation of their properties has shown that in mixtures with air they are incapable of independently propagating an explosion.

Hazardous places are classified in terms of zones on the basis of the frequency and duration of the occurrence of an explosive atmosphere.

The extent of the measures to be taken in accordance with Annex II, Part A, is determined by this classification.

- **Zone 0**

A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor or mist is present continuously or for long periods or frequently.

- **Zone 1**

A place in which an explosive atmosphere consisting of a mixture with air or flammable substances in the form of gas, vapor or mist is likely to occur in normal operation occasionally.

- Zone 2

A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only.

IS EN 60079-10 also define source of release as a point or location from which a gas, vapor, mist or liquid may be released into the atmosphere so that an explosive gas atmosphere could be formed.

- Grades of release

There are three basic grades of release, as listed below in order of decreasing frequency and likelihood of the explosive gas atmosphere being present:

- a) Continuous grade;
- b) Primary grade;
- c) Secondary grade.

A source of release may give rise to any one of these grades of release, or to a combination of more than one.

- Continuous grade of release

Release which is continuous or is expected to occur frequently or for long periods

- Primary grade of release

Release which can be expected to occur periodically or occasionally during normal operation

- Secondary grade of release

Release which is not expected to occur in normal operation and, if it does occur, is likely to do so only infrequently and for short periods.

Also in IS 60079-10 Annex A there are examples of sources of release:

Sources giving a continuous grade of release

- a) The surface of a flammable liquid in a fixed roof tank, with a permanent vent to the atmosphere.
- b) The surface of a flammable liquid which is open to the atmosphere continuously or for long periods.

Sources giving a primary grade of release

- a) Seals of pumps, compressors or valves if release of flammable material during normal operation is expected.
- b) Water drainage points on vessels which contain flammable liquids, which may release flammable material into the atmosphere while draining off water during normal operation.
- c) Sample points which are expected to release flammable material into the atmosphere during normal operation.
- d) Relief valves, vents and other openings which are expected to release flammable material into the atmosphere during normal operation.

Sources giving a secondary grade of release

- a) Seals of pumps, compressors and valves where release of flammable material during normal operation of the equipment is not expected.
- b) Flanges, connections and pipe fittings, where release of flammable material is not expected during normal operation.
- c) Sample points which are not expected to release flammable material during normal operation.
- d) Relief valves, vents and other openings which are not expected to release flammable material into the atmosphere during normal operation.

According to these criteria we can assume these possible sources of release:

1. Sources giving a continuous grade of release:
 - o The surface of the fuel tanks
2. Sources giving a primary grade of release:
 - o Vents at the gas installation
3. Sources giving a secondary grade of release
 - o Seal in pumps and valves in the gas and fuel installation

Ventilation

Gas or vapor released into the atmosphere can be diluted by dispersion or diffusion into the air until its concentration is below the lower explosive limit.

Ventilation, i.e. air movement leading to replacement of the atmosphere in a volume around the source of release by fresh air, will promote dispersion. Suitable ventilation rates can also avoid persistence of an explosive gas atmosphere thus influencing the type of zone.

Main types of ventilation

Ventilation can be accomplished by the movement of air due to the wind and/or by temperature gradients or by artificial means such as fans. So two main types of ventilation are thus recognized: a) Natural ventilation;

b) Artificial ventilation, general or local.

Degree of ventilation

The most important factor is that the degree or amount of ventilation is directly related to the types of sources of release and their corresponding release rates. This is irrespective of the type of ventilation, whether it is wind speed or the number of air changes per time unit. Thus optimal ventilation conditions in the hazardous area can be achieved, and the higher the amount of ventilation in respect of the possible release rates, the smaller will be the extent of the zones (hazardous areas), in some cases reducing them to a negligible extent (nonhazardous area).

Ventilation								Grade of release
Degree								
Low	Medium			High				
Good, fair or poor	Availability			Availability				
	Poor	Fair	Good	Poor	Fair	Good		
Zone 0	Zone 0 + Zone 1	Zone 0 + Zone 2	Zone 0	(Zone 0 NE) Zone 1 ^a	(Zone 0 NE) Zone 2 ^a	(Zone 0 NE) Non-hazardous ^a	Continuous	
Zone 1 or zone 0c	Zone 1 + Zone 2	Zone 1 + Zone 2	Zone 1	(Zone 1 NE) Zone 2 ^a	(Zone 1 NE) Zone 2 ^a	(Zone 1 NE) Non-hazardous ^a	Primary	
Zone 1 and even zone 0c	Zone 2	Zone 2	Zone 2	Zone 2	(Zone 2 NE) Non-hazardous	(Zone 2 NE) Non-hazardous ^a	Secondary ^b	

NOTE 1 '+' signifies 'surrounded by'.

NOTE 2 Particular care should be taken to avoid situations where enclosed areas containing sources that give only secondary grades of release might be classified as zone 0. This applies also to small non-purged and non-pressurized enclosed areas, e.g. instrument panels or instrument weather protection enclosures, thermally insulated heated enclosures or enclosed spaces between pipe installations and envelope of thermal insulation.

Such enclosures should preferably be provided with at least some kind of appropriately located apertures that will enable unimpeded movement of air through the interior. Where that is not possible, practicable or desirable, effort should be made to keep major potential sources of release out of enclosures, e.g. pipe connections should normally be kept out of insulation enclosures as well as any other equipment that may be considered a potential source of release.

NOTE 3 Continuous and primary sources of release should preferably not be located in areas with a low degree of ventilation. Either sources of release should be relocated, ventilation

a 'Zone 0 NE, 1 NE or 2 NE' indicates a theoretical zone which would be of negligible extent under normal conditions.

b The zone 2 area created by a secondary grade of release may exceed that attributable to a primary or continuous grade of release; in this case, the greater distance should be taken.

c Will be zone 0 if the ventilation is so weak and the release is such that in practice an explosive

Release rate calculations:

Release rate of gas

The release rate of gas from a container, if the gas velocity is non-choked, may be estimated by means of the following approximation:

$$\frac{dG}{dt} = Sp \sqrt{\gamma \frac{M}{RT} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/2(\gamma-1)}}$$

where

dG/dt is the release rate of gas (mass per time, kg/s)

p is the pressure inside the container (Pa);

γ is the polytropic index of adiabatic expansion;

S is the cross section of the opening, through which gas is released (surface area, m²); M is the molecular mass of gas (kg/kmol);

T is the absolute temperature inside the container (K); R is the universal gas constant (8.314 J kmol⁻¹ K⁻¹).

Release rate of gas with non-choked gas velocity

Non choked gas velocity is a discharge velocity below the speed of sound for the particular gas. The release rate of gas from a container, if the gas velocity is non-choked, may be estimated by means of the following approximation:

$$\frac{dG}{dt} = Sp \sqrt{\frac{M}{RT} \frac{2\gamma}{\gamma-1} \left[1 - \left(\frac{p_o}{p} \right)^{(\gamma-1)/\gamma} \right] \left(\frac{p_o}{p} \right)^{1/\gamma}}$$

where

dG/dt is the release rate of gas (mass per time, kg/s)

p is the pressure inside the container (Pa);

p_0 is the pressure outside the gas container (Pa);

S is the cross section of the opening, through which gas is released (surface area, m^2), M is the molecular mass of gas (kg/kmol);
T is the absolute temperature inside the container (K);
 γ is the polytropic index of adiabatic expansion;
R is the universal gas constant ($8314 \text{ J kmol}^{-1} \text{ K}^{-1}$).

Release rate of liquid from a pipe

$$Q_L = C_D A \sqrt{2\rho_L [(P_o - P_a) + \rho_L gh]}$$

Where:

Q_L = initial liquid release rate (kg/s)

C_D = discharge coefficient

A = hole area (m^2)

ρ_L = liquid density (kg/m^3)

P_o = initial pressure of liquid (N/m^2) (absolute)

Release rate of vapors from a volatile pool.

Estimation of hypothetical volume V_Z

The hypothetical volume V_Z represents the volume over which the mean concentration of flammable gas or vapor will typically be either 0,25 or 0,5 times the LEL, depending on the value of a safety factor, k. This means that, at the extremities of the hypothetical volume estimated, the concentration of gas or vapor would be significantly below the LEL, i.e. the volume where the concentration is above the LEL would be less than V_Z .

To ascertain the hypothetical volume, it is necessary to first establish the theoretical minimum ventilation flow rate of fresh air to dilute a given release of flammable material to the required concentration below the lower explosive limit.

This can be calculated by means of the equation:

$$(dV/dt)_{min} = \frac{(dG/dt)_{max} \cdot T}{k \cdot LEL_m \cdot 293}$$

Were:

$(dV/dt)_{min}$ is the minimum volumetric flow rate of fresh air (volume per time, m³/s);

$(dG/dt)_{max}$ is the maximum rate of release at source (mass per time, kg/s);

LEL_m is the lower explosive limit (mass per volume, kg/m³);

k is a safety factor applied to the LEL_m ; typically:

$k = 0,25$ (continuous and primary grades of release)

$k = 0,5$ (secondary grades of release);

T is the ambient temperature (in Kelvin, K).

The relationship between the calculated value $(dV/dt)_{min}$ and the actual ventilation rate within the volume under consideration (V_0) in the vicinity of the release can then be expressed as a volume (V_k).

$$V_k = \frac{(dV/dt)_{min}}{C}$$

C is the number of fresh air changes per unit time (s⁻¹) and is derived from

$$V_z = f \times V_k \frac{f \times (dV/dt)_{min}}{C}$$

Where

f is the efficiency of the ventilation in terms of its effectiveness in diluting the explosive gas atmosphere, with f ranging from $f = 1$ (ideal situation) to, typically $f = 5$ (impeded air flow)

Outside areas classified there is no risk of explosion because the concentration of flammable substance is below LEL.

It must be ensured that there is no source of ignition within classified areas for workers who will access these areas have to check the equipment to be used are suitable.

4.2.3 HAC Calculations

4.2.3.1 Zone 1 around emergency vent.

EHS-EX Tool by Eng. A. Ornan

Electrical apparatus for explosive gas atmospheres -
 Classification of hazardous area according to IS 60079-10.1

Description of process and equipment: Emergency vent from LH2 tank.

Description of Scenario;

leak from outdoor 1.5" vent piping

Characteristics of source

Type of equipment		leak from outdoor 1.5" vent piping	Total volume of liquid (m3)	
Number of sources	1		Pressure (bar abs)	12.54
			Temperature (K)	313
Location	Outdoor			

Characteristics of flammable

Flammable material:	hydrogen	Liquid density (kg/m3)	
Molecular weight of liquid (gr/mol)	2	Heat capacity ratio of gas	1.4

Heat of vaporization of liquid (kJ/mol)

Vapor pressure of liquid at ambient (bar abs)

Kinematic viscosity of liquid in air m**2/s) 6.60E-07

LEL (kg/m3)	0.003271984	LEL %	4
Initial concentration (kg/m3)	0.08	Initial concentration (%)	100

Characteristics of release

Type of source	gas leak		
Grade of release	Secondary		
Zone	Zone 1	hole diameter (mm)	38.1
Release rate (kg/s)	0.866796		
Safety factor k	0.5		

Results

No of Sources		1
Vz enclosed (m3)	Vz(m3)=	28.30
Volume m3	V (m3)=	Outdoor
For similar to air (spherical shape)	R(m)=	1.87
For lighter than air (cylindrical shape)	Ra(m)=	1.50
	h above(m)=	2.81
	h below(m)=	0.94
Vz/V ratio	Vz/V	Outdoor

4.2.3.2 Zone 2 around emergency vent.

EHS-EX Tool by Eng. A. Ornan
Electrical apparatus for explosive gas atmospheres -

Classification of hazardous area according to IS 60079-10.1

Description of process and equipment: Emergency vent from LH2 tank.

Description of Scenario:

leak from outdoor 1.5" vent pipe

Characteristics of source

Type of equipment		pipng	Total volume of liquid (m3)	
Number of sources	1		Pressure (bar abs)	12.54
			Temperature (K)	313
Location	Outdoor			

Characteristics of flammable

Flammable material:	hydrogen	Liquid density (kg/m3)	
Molecular weight of liquid (gr/mol)	2	Heat capacity ratio of gas	1.4
Heat of vaporization of liquid (kJ/mol)			
Vapor pressure of liquid at ambient (bar abs)			
Kinematic viscosity of liquid in air m**2/s)	6.60E-07		

LEL (kg/m3)	0.003271984	LEL %	4
Initial concentration (kg/m3)	0.08	Initial concentration (%)	100

Characteristics of release

Type of source	gas leak	Liquid level above hole (m)	
Grade of release	Secondary		
Zone	Zone 2	Hole diameter (mm)	38.1
Release rate (kg/s)	0.866796		
Safety factor k	25		

Results

No of Sources								
Vz enclosed (m3)	Vz(m3)=	56.60						
Volume m3	V (m3)=	Outdoor						
For lighter than air (cylindrical shape)	<table border="0"> <tr> <td>Ra(m)=</td> <td>1.89</td> </tr> <tr> <td>h above(m)=</td> <td>3.54</td> </tr> <tr> <td>h below(m)=</td> <td>1.18</td> </tr> </table>	Ra(m)=	1.89	h above(m)=	3.54	h below(m)=	1.18	
		Ra(m)=	1.89					
		h above(m)=	3.54					
h below(m)=	1.18							
Vz/V ratio	Vz/V	Outdoor						

4.2.3.4 Area classification zoning according to NFPA 55

Table 11.2.6 Electrical Area Classification

Location	Zone	Extent of Classified Area
The bulk liquefied hydrogen system fill connection, pressure relief vent outlets, or other points on the system where hydrogen is vented to the atmosphere under the designed operating conditions	1	Within 3 ft (1 m) of the system fill connection, system pressure relief vent outlets or, other points of release when the system is operating as designed
	2	Between 3 ft (1 m) and 25 ft (7.6 m) from the system fill connection, system pressure relief vent outlets, or other points of release when the system is operating as designed

Eng. A. Ornan

3.2.4 Area classification zoning according to design.

Reference & Remarks	Extent of Hazardous Area			Ventilation			Flammable Material				Source of Release			Item No.	
	Zone 2	Zone 1	Zone 0	Avail-ability	Degree	Type	Phase	Operating Temperature + Pressure		Material	Grade of Release	Description	Location		Equipment
								[bar (g)]	[°C]						
In accordance with Air Products Global EH&S Manual, Volume 3, 03.09.23 "Evaluation Procedure for Liquid Hydrogen Installations" (from NFPA 55 Table 11.2.6). A zone 1 hazard area is NOT applied to the PBU trim heater 14C-E65 as there are no mechanical connections	8m	1m		Good	Adequate	Natural	Variable	Variable	Variable	Hydrogen	Secondary	LHy Tank Installation Components (up to and including the product vaporisers)	In Open Air	H2 Tank 28-T981C	1
IP15 Section 5.4.4.5 defines a nominal hazard radius to cover any small leakages that may occur on pressure relief valves. The same radius has been applied to cover small leakages on the bursting disc's mechanical connection. Encompassed by the 8m Zone 2 radius imposed around all LHy tank components in item 1	R ₁ =1m	-	-	Good	Adequate	Natural	Gas	Atm.	Variable	Hydrogen	Secondary	Secondary Vent Stack; Release from PZE1003C	In Open Air	H2 Tank 28-T981C	2
As per item 2 comments	R ₁ =1m	-	-	Good	Adequate	Natural	Gas	Atm.	Variable	Hydrogen	Secondary	Primary Vent Stack; Release from PSVs	In Open Air	H2 Tank 28-T981C	3
IP15 Table C9(a) for G(ii) releases (0.08kg/s dump flow)	-	R ₁ =4m	-	Good	Adequate	Natural	Gas	Atm.	Variable	Hydrogen	Primary	Primary Vent Stack; Release from Dump Vaporiser E301C	In Open Air	H2 Tank 28-T981C	4
IP15 Section 5.4.5.1, Tables C6, C9(a) and C9(b) for a Level 3 G(ii) release with release hole diameter 5mm. All control valves have bellows and therefore do not need to be considered as primary grade release sources. Encompassed by the 8m Zone 2 radius imposed around all LHy tank components in item 1	R ₁ =2m R ₂ =2.5m	-	-	Good	Adequate	Natural	Variable	8	Variable	Hydrogen	Secondary	Valves, Flanges, Face Seals and Instrument Connections	In Open Air	H2 Tank 28-T981C	5
IP15 Section 5.4.5.1, Tables C6, C9(a) and C9(b) for a Level 3 G(ii) release with release hole diameter 5mm	R ₁ =2m R ₂ =2.5m	-	-	Good	Adequate	Natural	Gas	8	Variable	Hydrogen	Secondary	Pressure Control Manifolds U986 (Valves, Face Seals and Instrument Connections)	In Open Air	H2 Tank 28-T981C	6
As per item 5 comments	R ₁ =2m R ₂ =2.5m	-	-	Good	Adequate	Natural	Variable	8	Variable	Hydrogen	Secondary	Product and PBU Vaporisers (Valves, Face Seals and Instrument Connections)	In Open Air	H2 Tank 28-T981C	7

Reference & Remarks	Extent of Hazardous Area			Ventilation		Flammable Material				Source of Release			Item No.		
	Zone 2	Zone 1	Zone 0	Avail-ability	Degree	Type	Phase	Operating Temperature + Pressure		Material	Grade of Release	Description		Location	Equipment
								[bar (g)]	[°C]						
IP15 Section 5.4.5.1, Tables C6, C9(a) and C9(b) for a Level 3 G(ii) release with release hole diameter 5mm. Encompassed by the 8m Zone 2 radius imposed around all LHy tank components in item 1	R ₁ =2m R =2.5m	-	-	Good	Adequate	Natural	Variable	Variable	Variable	Hydrogen	Secondary	Hose Post U815	In Open Air	H2 Tank 28-T981C	8
IP15 Section 5.4.5.1, Tables C6, C9(a) and C9(b) for a Level 3 G(ii) release with release hole diameter 5mm. Radius to be applied around full extent of hose reach outside of LHy enclosure (i.e. where it can be connected to the LHy container). Zone 1 to a height of 4m above grade; assumes hose shall not be lifted more than 2m above grade	-	R ₁ =2m R =2.5m	-	Good	Adequate	Natural	Variable	Variable	Variable	Hydrogen	Primary	LHy Tanker Fill Hose Corridor	In Open Air	H2 Tank 28-T981C	9
IP15 Section 5.4.5.1, Tables C6, C9(a) and C9(b) for a Level 3 G(ii) release with release hole diameter 5mm. Encompassed by hazard radii around fill hose corridor from item 9	-	R ₁ =2m R =2.5m	-	Good	Adequate	Natural	Variable	Variable	Variable	Hydrogen	Primary	Tanker Fill Connection	In Open Air	H2 Tank 28-T981C	10
Zone 1 and 2 radii from IP15 Section 5.4.5.1, Tables C6, C9(a) and C9(b) for a Level 3 G(ii) release with release hole diameter 5mm. Zone 2 shall be encompassed by the 8m Zone 2 radius imposed around all LHy tank components in item 1	R ₁ =2m R =2.5m	R ₁ =0.3m	-	Good	Adequate	Natural	Variable	Variable	Variable	Hydrogen	Primary & Secondary	Tanker Valves, Face Seals and Instrument Connections	In Open Air	H2 Tank 28-T981C	11

NOTES:

1. This classification uses the methods in IEC 60079-10-1:2009 "Electrical apparatus for explosive gas atmospheres; Part 10: Classification of hazardous areas" to determine the zone type for potential explosive gas atmospheres.
2. IEC60079-10-1 (section 7.1) allows the use of an appropriate code or cautions to determine the zone extents.
3. This classification uses Air Products Global EH&S Manual, Volume 3, 03.09.23 "Evaluation Procedure for Liquid Hydrogen Installations" and Institute of Petroleum "Area Classification Code for Installations Handling Flammable Fluids" 3rd edition of July 2005 (known as IP15) to determine zone extents. The zone extents in the Air Products EH&S Manual are based on NFPA 55 "Standard for the Storage, Use and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinder and Tanks" edition of 2005.
4. The Individual Point Source method in IP15 Chapter 5 is used to determine zone extents.
5. IP15 methodology includes a risk assessment to determine a Release Frequency Level. For this project Release Frequency level 3 is considered as this gives the most conservative hazard radii, thus avoiding uncertainty around the probabilities selected for determination of individual risk (IP15 Annex C – Part 2).
6. IP15 also allows the use of dispersion modelling to determine zone size as an alternative to itself or when the code does not cover the scenario.
7. For releases where the source is at a height above grade less than the hazard radii, $R_1 + 1m$ as specified in IP15, ground effects must be considered as per IP15 Section 5.5 with the introduction of a ground effect radius, R_2 .

4.2.5 Area classification due LH2 spillage.

Neither IS-EN 60079-10.1 nor IP15 deal with cryogenic spillage HAC.

To provide For this purpose the use of a CFD model is required. See 2.5.3

5. Summary

5.1 General.

5.1.1 LH2 storage facility embraces significant hazards that should be mitigated during design, installation and operation. Among the main hazards we can find –

5.1.1.2 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.

5.1.1.3 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.

5.1.1.4 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 surface⁷⁰). 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.

5.1.1.6 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 favor, 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 in a given scenario hydrogen would result in higher explosion pressures and rates of pressure rise than other fuels.

5.2 Recommendations.

5.2.1 Location.

5.2.1.1 It is recommended that the location of the new system will be at least 15 m away from the existing LH2 systems in order to apply for a separate permit that will not engage both system for new requirements.

5.2.1.2 The system should be at least 135 m from the public road (side walk) in order to comply with the EPO separation distances requirements.

5.2.1.2 It should be considered that there will be no combustibles / Oxidizers storage 30 m from area that LH2 could leak and create a volatile pool (filling station for example).

5.2.1.3 All other distances should comply with the following table from NFPA 55 2015 –

Table 11.3.2.2 Minimum Distance from Bulk Liquefied Hydrogen Systems to Exposures

Type of Exposure	Total Bulk Liquefied Hydrogen storage					
	39.7 gal to 3500 gal	150 L to 13,250 L	3501 gal to 15,000 gal	13,251 L to 56,781 L	15,001 gal to 75,000 gal	56,782 L to 283,906 L
	ft	m	ft	m	ft	m
Group 1						
1. Lot lines	25	7.6	50	15	75	23
2. Air intakes [heating, ventilating, or air-conditioning equipment (HVAC), compressors, other]	75	23	75	23	75	23
3. Wall openings						
Operable openings in buildings and structures	75	23	75	23	75	23
4. Ignition sources such as open flames and welding	50	15	50	15	50	15
Group 2						
5. Places of public assembly	75	23	75	23	75	23

Type of Exposure	Total Bulk Liquefied Hydrogen Storage					
	39.7 gal to 3500 gal	150 L to 13,250 L	3501 gal to 15,000 gal	13,251 L to 56,781 L	15,001 gal to 75,000 gal	56,782 L to 283,906 L
	ft	m	ft	m	ft	m
Group 3						
6. Building or structure						
(a) Buildings constructed of noncombustible or limited-combustible materials						
(1) Sprinklered building or structure or unsprinklered building or structure having noncombustible contents	5 ^a	1.5	5 ^a	1.5	5 ^a	1.5
(2) Unsprinklered building or structure with combustible contents						
(i) Adjacent wall(s) with fire resistance rating less than 3 hours	5	7.6	50	15	75	23
(ii) Adjacent wall(s) with fire resistance rating of 3 hours or greater ^b	5	1.5	5	1.5	5	1.5
(b) Buildings of combustible construction						
(1) Sprinklered building or structure	50	15	50	15	50	15
(2) Unsprinklered building or structure	50	15	75	23	100	30.5
7. Flammable gas storage or systems (other than hydrogen) above or below ground	50	15	75	23	75	23
8. Between stationary liquefied hydrogen containers	5	1.5	5	1.5	5	1.5
9. All classes of flammable and combustible liquids (above ground and vent or fill openings if below ground) ^c	50	15	75	23	100	30.5
10. Hazardous materials storage or systems including liquid oxygen storage and other oxidizers, above or below ground	75	23	75	23	75	23
11. Heavy timber, coal, or other slow-burning combustible solids	50	15	75	23	100	30.5
12. Wall openings						
Unopenable openings in buildings and structures	25	7.6	50	15	50	15
13. Inlet to underground sewers	5	1.5	5	1.5	5	1.5
14. Utilities overhead, including electric power, building services, or hazardous materials piping systems						
(a) Horizontal distance from the vertical plane below the nearest overhead wire of an electric trolley, train, or bus line	50	15	50	15	50	15
(b) Horizontal distance from the vertical plane below the nearest overhead electrical wire	25	7.5	25	7.5	25	7.5
(c) Piping containing other hazardous materials	15	4.6	15	4.6	15	4.6

^a Portions of wall less than 10 ft (3.1 m) (measured horizontally) from any part of a system must have a fire resistance rating of not less than 1 hour.

^b Exclusive of windows and doors.

^c The separation distance for Class III combustible liquids shall be permitted to be reduced to 15 ft (4.6 m).

5.2.2 Hazardous area classification.

5.2.2.1 For the gaseous phase realizes the hazardous area study which was preformed by Air product is acceptable.

5.2.2.2 For the LH2 Liquid phase there was no study made by Air product.

5.2.2.2 The distances for Zone 2 classification from areas subject to liquid release in case of an equipment or operation failure will be 15 meters. During tank filling operation a safety zone with no vehicles / construction work etc, of 50 meters should be kept.

5.2.2.3 Grounding and bonding of components should comply wit the requirements of NFPA 77 and IS-EN 60079-32.

5.2.3 Construction.

5.2.3.1 Roadways and yard surfaces located below liquefied hydrogen piping as well as areas located under the fill connections and delivery vehicles' insulated hydrogen piping from which LH2 is able to drip shall be constructed of noncombustible materials. (Asphalt and bitumastic paving shall be assumed to be combustible).

5.2.3.2 Stationary storage tanks for liquid hydrogen shall be designed and constructed in accordance with *ASME Boiler and Pressure Vessel Code* (Section VIII, Division 1).

5.2.3.3 The vacuum jacket used as an outer vessel for storage tanks in liquid hydrogen service shall be of welded steel construction designed to withstand the maximum internal and external pressures to which it will be subjected under operating conditions to include conditions of emergency pressure relief of the annular space between the inner and outer vessel. The jacket shall be designed to withstand a minimum collapsing pressure differential of 30 psi (207 kPa).

5.2.3.4 It is recommended to include a spill pond that contains crushed rock to enhance heat transfer to the spilled liquid, and slats inserted within the surrounding walls . the boil-off rate of LH2 using crushed rock is double the rate for moist sand. Installing slats within the security fence that encloses the spill pond should help direct the hydrogen plume upward as it warms rather than letting it spread out over the ground. This kind of control, known as a vapor fence or barrier, has

been used to reduce vapor travel of flammable cryogenic vapors such as liquid natural gas (LNG) (Moorhouse and Roberts 1988).

5.2.4 Protection.

5.2.4.1 Israel Ministry of Defence requires LH2 storage tank to be buried or to be protected within a bunker against warlike attacks.

5.2.4.2 For the permitting process it is recommended to approach this issue by the following concept –

- a) Try to convince that the tanks are 'process' and not 'storage' so the MOD regulation do not address the facility.
- b) To allow protection walls so they will be at least 5 m away from the system - detonation or energetic deflagration is an unlikely outcome for a large hydrogen release if the system is located away from structures.

5.2.5 Fire Protection.

5.2.5.1 Surrounding fire protection system should be available which include –
3" Fire hydrants system located 60 m apart.

Water spray monitor to allow cooling the tank or other components in case of fire.

Flame detectors (suitable for H2 flames) which cover the entire system without 'dead spots'.

Clear access road 4m wide, 4.5 m height clearance and at least 15m turning radius for fire engine truck.

6. Reference.

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- 6.3 Pool spreading and vaporization of liquid hydrogen K. Verfonderna,* , B. Dienhartb A Research Center Juelich (FZJ), Juelich, 52425, Germany bJohannes-Prassel-Strasse 20, 50765 Koeln, Germany Available online 29 May 2007
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6.8 AHE Guidelines for chemical process quantitative risk analysis 2nd ed.

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