# POOL SPREADING AND VAPORIZATION OF LIQUID HYDROGEN

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### ABSTRACT

An essential part of a safety analysis to evaluate the risks of a liquid hydrogen (LH<sub>2</sub>) containing system is the understanding of cryogenic pool spreading and its vaporization. It represents the initial step in an accident sequence with the inadvertent spillage of LH<sub>2</sub>, e.g., after failure of a transport container tank or the rupture of a pipeline. This stage of an accident scenario provides pertinent information as a source term for the subsequent analysis steps of atmospheric dispersion and, at presence of an ignition source, the combustion of the hydrogen-air vapor cloud. A computer model LAUV has been developed at the Research Center Juelich, which is able to simulate the spreading and vaporization of a cryogenic liquid under various conditions such as different grounds (solid, water). It is based on the so-called shallow-layer differential equations taking into account physical phenomena such as ice formation, if the cryogen is spilled on a water surface. The presentation will give a description of the computer model and its validation against existing experimental data. Furthermore calculational results will be analyzed describing the prediction and quantification of the consequences of an LH<sub>2</sub> spill for different cases. They also include the comparison of an LH<sub>2</sub> spillage versus the corresponding release of other cryogens such as liquid natural gas, liquid oxygen, and liquid nitrogen.

# **1.0 INTRODUCTION**

Liquefied gaseous fuels as energy sources play an important role in the world energy economy. Since the 1970s, liquid natural gas (LNG) and liquid petroleum gas (LPG) are being transported in large amounts around the world. Still on a much smaller scale is the use of liquid hydrogen (LH<sub>2</sub>) at present, but this may change in future with the increasing application of hydrogen as a clean fuel in the energy market. With the wide use of cryogenic liquids, however, questions arise concerning their safe storage, transportation, and application. Probabilistic safety and risk analyses help to identify and classify conceivable accident scenarios covering the whole path from the release of the hydrogen via propagation of the evolving gas cloud and its potential explosion, to an assessment of the consequences for the environment.

The Research Center Juelich (FZJ) started activities to look particularly at the safety aspects of hydrogen as a significant factor in a future hydrogen economy. One of these aspects was the accidental release of cryogenic hydrogen during transportation on a water surface as was considered, e.g., in the Euro Quebec Hydro-Hydrogen Pilot Project at the end of the 1980s. Scenarios with cryogenic spills are strongly influenced by the initial accident phase. The knowledge of the spreading and vaporization of a pool of cryogen on the ground and understanding of the basic physical phenomena is essential to the subsequent step of accurate simulation of the dispersion of the vapor cloud. Both pool geometry and vaporization time determine decisively the dispersion of the cloud and in particular the size and lifetime of the flammable fraction of the cloud. The development of a computer model to simulate the vaporization and the transient spreading of a cryogenic liquid on a solid or liquid ground under given conditions as well as experimental work for code validation will be described in the following chapters.

# 2.0 PHENOMENOLOGY OF CRYOGEN RELEASE

Liquefied gases are characterized by a boiling point well below the ambient temperature. If released from a pressure vessel, the pressure relief from system to atmospheric pressure results in spontaneous (flash) vaporization of a certain fraction of the liquid. Depending on leak location and thermodynamic state of the cryogen (pressure expelling the cryogen through the leak is equal to the saturation vapor pressure), a two-

phase flow will develop, significantly reducing the mass released. It is connected with the formation of aerosols, which vaporize in the air without touching the ground. Conditions and configuration of the source determine the features of the evolving vapor cloud such as cloud composition, release height, initial plume distribution, time-dependent dimensions, or energy balance. The phenomena that may occur after a cryogen release into the environment are shown in Fig. 1.



Figure 1. Physical phenomena occurring upon the release of a cryogenic liquid

## 2.1 Vaporization of Cryogenic Liquids

The release as a liquefied gas usually results in the accumulation and formation of a liquid pool on the ground, which expands, depending on the volume spilled and the release rate, radially away from the releasing point, and which also immediately starts to vaporize. The equilibrium state of the pool is determined by the heat input from the outside like from the ground, the ambient atmosphere (wind, insolation from the sun), and in case of a burning pool, radiation heat from the flame. The respective shares of heat input from outside into the pool are depending on the cryogen considered. Table 1 compares the data for the cryogens  $LH_2$ ,  $LN_2$ , and LNG [1].

Table 1. Sources of heat input into a vaporizing cryogenic liquid pool (1 m<sup>2</sup>, 5 m/s wind speed).

Heat input by	Heat source [kW/m <sup>2</sup> ]		
	LH <sub>2</sub>	LN <sub>2</sub>	LNG
Atmospheric convection	0.8	1.8	1.1
Radiation from flame	12	-	100 - 200
Radiation from ambient	1.6	1.6	1.6
Conduction from ground	100	25	9.2

As can be seen from the table, the most dominant heat source is heat transport from the ground. This is particularly true for  $LH_2$ , where a neglection of all other heat sources would result in an estimated error of 10-20%. For a burning pool, also the radiation heat from the flame provides a significant contribution. This is particularly true for a burning LNG pool due to its much larger emissivity resulting from soot formation.

Upon contact with the ground, the cryogen will in a short initial phase slide on a vapor cushion (film boiling) due to the large temperature difference between liquid and ground. The vaporization rate is comparatively low and if the ground is initially water, no ice will be formed. With increasing coverage of the surface, the difference in temperatures is decreasing until – at the Leidenfrost point – the vapor film collapses resulting in enhanced heat transfer via direct contact (nucleate boiling). On water, there is the chance of ice formation which, however, depending on the amount of mass released, will be hindered due to the violent boiling of the cryogen, particularly if the momentum with which the cryogen hits the water surface is large. Unlike labscale testing (confined), ice formation was not often observed in field trials (unconfined).

The vaporization behavior is principally different for liquid and solid grounds. On liquid grounds, the vaporization rate remains approximately constant due to natural convection processes initiated in the liquid resulting in an (almost) constant, large temperature difference between surface and cryogen indicating stable film boiling. On solid grounds, the vaporization rate decreases due to cooling of the ground. The heat flux into the pool can be approximated as being proportional to  $t^{-1/2}$  (see also equation (2) in section 4.2). Differences were observed for the vaporization behavior on dry and wet concrete. The vaporization time is significantly reduced, if moisture is present in the ground due to a change of the ice/water properties and the liberation of the solidification enthalpy during ice formation representing an additional heat source in the ground. A 3 mm water layer on the concrete leads again to a longer vaporization time due to an insulation effect of the – then – ice layer, but the time was still shorter than in the "dry" case [1].

#### 2.2 Cryogenic Pool Spreading

Above a certain amount of cryogen released, a pool on the ground is formed, whose diameter and thickness is increasing with time until reaching an equilibrium state. After termination of the release phase, the pool is decaying from its boundaries and breaking up in floe-like islands, when the thickness becomes lower than a certain minimum which is determined by the surface tension of the cryogen (in the range of 1 to 2 mm). The development of a hydraulic gradient results in a decreasing thickness towards the outside.

The spreading of a cryogenic pool is influenced by the type of ground, solid or liquid, and by the release mode, instantaneous or continuous. In an instantaneous release, the release time is theoretically zero (or release rate is infinite), but practically short compared to the vaporization time. Spreading on a water surface penetrates the water to a certain degree, thus reducing the effective height responsible for the spreading and also requiring additional displacement energy at the leading edge of the pool below the water surface. The reduction factor,  $\delta$ , is given by the density ratio of both liquids telling that only 7% of the LH<sub>2</sub> will be below the water surface level compared to, e.g., more than 40% of LNG or even 81% of LN<sub>2</sub>.

During the initial release phase, the surface area of the pool is growing, which implies an enhanced vaporization rate. Eventually a state is reached which is characterized by the incoming mass to equal the vaporized mass. This equilibrium state, however, does not necessarily mean a constant surface. For a solid ground, the cooling results in a decrease of the heat input which, for a constant spill rate, will lead to a gradually increasing pool size. In contrast, for a water surface, pool area and vaporization rate are maximal and remain principally constant as was concluded from lab-scale testing despite ice formation. A cutoff of the mass input finally results in a breakup of the pool from the central release point creating an inner pool front. The ring-shaped pool then recedes from both sides, although still in a forward movement, until it has completely died away.

A special effect was identified for a continuous release particularly on a water surface. The equilibrium state is not being reached in a gradually increasing pool size. Just prior to reaching the equilibrium state, the pool

is sometimes rather forming a detaching annular-shaped region, propagates outwards ahead of the main pool (see Fig. 2) [2]. This phenomenon, for which there is hardly experimental evidence because of its short lifetime, can be explained by the fact that in the first seconds more of the the high-momentum liquid is released than can vaporize from the actual pool surface; it becomes thicker like a shock wave at its leading edge while displacing the ground liquid. It results in a stretching of the pool behind the leading edge and thus a very small thickness, until the leading edge wavelet eventually separates. Realistically the ring pool will most likely soon break up in smaller single pools drifting away as has been often observed in release tests. Whether the ring pool indeed separates or only shortly enlarges the main pool radius, is depending on the cryogen properties of density and vaporization enthalpy and on the source rate.



Figure 2. Comparison of the transient pool shape of a continuous (left) and instantaneous (right) release

Also so-called rapid phase transitions (RPT) could be observed for a water surface RPTs are "physical" ("thermal") vapor explosions resulting from a spontaneous and violent phase change of the fragmented liquid gas at such a high rate that shock waves may be formed. Although the energy release is small compared with a chemical explosion, it was observed for LNG that RPT with observed overpressures of up to 5 kPa were able to cause some damage to test facilities.

An additional significant influence on the pool spreading and vaporization behavior is given, if the pool propagation is limited due to obstruction or, e.g., the walls of an impoundment area. The smaller surface area results in a reduced vapor production rate.

#### **3.0 EXPERIMENTAL WORK WITH LIQUID HYDROGEN**

Most experimental work with cryogenic liquefied gaseous fuels began in the 1970s concentrating mainly on LNG and LPG, commodities which were shipped around the world to a tremendously increasing extend. Main goal of these works was the investigation of accidental spill scenarios during maritime transportation. A respective experimental program for liquid hydrogen was conducted on a much smaller scale, initially by those who considered and handled  $LH_2$  as a fuel for rockets and space ships. Main focus was on the combustion behavior of the  $LH_2$  and the atmospheric dispersion of the evolving vapor cloud after an  $LH_2$  spill. Only little work was concentrating on the cryogenic pool itself, whereby vaporization and spreading never were examined simultaneously. In 1994, the first (and only up to now) spill tests with  $LH_2$  were conducted in Germany, where pool spreading was investigated in further detail.

### 3.1 Early Works

Experimental activities with the release of liquid hydrogen started in the late 1950s. The Lockheed Skunk Works in the USA investigated in a series of tests the detonability of LH<sub>2</sub> by subjecting small amounts of the liquid to various impacts. Spill experiments with LH<sub>2</sub> amounts ranging between 5 l and 19 m<sup>3</sup> were conducted by Arthur D. Little Inc. simulating the conditions of storage and transport with the objective to test safe handling, establish quantity-distance relationships, and compare with hydrocarbon fuels. There was, however, no instrumentation employed for pool measurements. Zabetakis examined on a lab-scale the LH<sub>2</sub> vaporization behavior due to heat transfer using a 65 mm dia glass dewar and a block of paraffin wax as "hot" surface. Fig. 3 compares the experimental data by measuring the rates of gas evolution with a dry gas meter to the theoretically derived pool regression rate. The solid curve assumes the heat influx rate to be conduction limited; the initial flash vaporization rates are probably film and nucleate boiling limited [3].



Figure 3. Regression rate of liquid hydrogen on a paraffin wax ground

The NASA LH<sub>2</sub> trials in 1980 [4] were initiated, when trying to analyze the scenario of a bursting of the 3000 m<sup>3</sup> of LH<sub>2</sub> containing storage tank at the Kennedy Space Center at Cape Canaveral and study the propagation of a large-scale hydrogen gas cloud in the open atmosphere. The spill experiments consisted of a series of seven trials, in five of which a volume of 5.7 m<sup>3</sup> of LH<sub>2</sub> was released near-ground within a time

span of 35-85 s. Pool spreading on the "compacted sand" ground was not a major objective, therefore only scanty data from test 6 only are available. From the thermocouples deployed at 1, 2, and 3 m distance from the spill point, only the inner two were found to have gotten contact with the cold liquid, thus indicating a maximum pool radius not exceeding 3 m.

# 3.2 FZJ Tests on Liquid Hydrogen Pool Spreading

The BAM, Germany, conducted in 1994  $LH_2$  release trials on a much smaller scale. In four of these tests, the Research Center Juelich (FZJ) studied in more detail the pool behavior by measuring the  $LH_2$  pool radius in two directions as a function of time [1]. The release of  $LH_2$  was made both on a water surface using a circular swimming pool with 3.5 m dia (two tests) as depicted on the left in Fig. 4, and on a solid ground represented by a square aluminum sheet with 2 m side length and 20 mm thickness. By means of a diffuser and a catching pot, the initial momentum of the exiting liquid was to be minimized (Fig. 4, right). A cross-shaped trestle was constructed to be arranged above the respective ground. On two perpendicular branches of the trestle, a total of 18 thermocouples were fixed every 0.1 and 0.2 m, respectively, in radial direction. They were adjusted approximately 1 mm above the surface of the ground and served as indicator for presence of the spreading cryogen.



Figure 4. Experimental arrangement of LH<sub>2</sub> pool spreading on water

The spill tests on water were performed over a time period of 62 s each at an estimated rate of 5 l/s of LH<sub>2</sub>, a value which is already corrected by the flash-vaporized fraction of at least 30%. After contact of the LH<sub>2</sub> with the water surface, a closed pool was formed, clearly visible and hardly covered by the white cloud of condensed water vapor. The "equilibrium" pool radius did not remain constant, but moved forward and backward within the range of 0.4 to 0.6 m away from the center. This pulsation-like behavior, which was also observed by the NASA experimenters in their tests, is probably caused by the irregular efflux due to the violent bubbling of the liquid and release-induced turbulences. Single small floes of ice escaped the pool front and moved outwards. After cutting off the source, a massive ice layer was identified where the pool was boiling. Also long-shaped ice tracks leading radially away could be observed.

In the two tests on the aluminum sheet, conducted at an  $LH_2$  release rate of (corrected) 6 l/s over 62 s each, the pool front was also observed to pulsate showing a maximum radius in the range between 0.3 and 0.5 m. Pieces of the cryogenic pool were observed to move even beyond the edge of the sheet. Not always all thermocouples within the pool range had permanent contact to the cold liquid indicating non-symmetrical spreading or ice floes which passed the indicator. The very low kinematic viscosity of hydrogen certainly has an influence on the stability of the pool front, its breakup, and its pulsation behavior. Also wind probably had an effect, which may explain the irregularities in the measured pool front (see also section 4.3).

# 4.0 STATE-OF-THE-ART MODELING

### 4.1 Historical Overview on Models

Parallel to all experimental work on cryogenic pool behavior, calculation models have been developed for simulation purposes. At the very beginning, purely empirical relationships were derived to correlate the spilled volume/mass with pool size and vaporization time. Such equations, however, were according to their nature strongly case-dependent. A more physical approach is given in mechanistic models, where the pool is assumed to be of cylindrical shape with initial conditions for height and diameter, and where the conservation equations for mass and energy are applied [e.g., 5 and 6]. Gravitation is the driving force for the spreading of the pool transforming all potential energy into kinetic energy. Drawbacks of these models are given in that the calculation is terminated when the minimum thickness is reached, that only the leading edge of the pool is considered, and that a receding pool cannot be simulated.

State-of-the-art modeling applies the so-called shallow-layer equations, a set of non-linear differential equations based on the conservation laws of mass and momentum, which allows the description of the transient behavior of the cryogenic pool and its vaporization. Several phases are being distinguished depending on the acting forces dominating the spreading:

- gravitational flow determined by the inertia of the cryogen and characterized by a hydraulic gradient at the front edge;
- gravitational viscous flow after pool height and spreading velocity have decreased making sheer forces at the boundary dominant;
- equilibrium between surface tension and viscous forces with gravitation being negligible.

During spreading, the pool passes all three phases, whereby its velocity is steadily decreasing. For cryogens, these models need to be modified with respect to the consideration of a continuously decreasing volume due to vaporization. Also film boiling has the effect of reducing sheer forces at the boundary layer.

Based on these principles, the UKAEA code GASP (Gas Accumulation over Spreading Pools) has been created by Webber [7] as a further development of the Brandeis model [2]. It was tested mainly against LNG and also slowly evaporating pools, but not for liquid hydrogen. Brewer also tried to establish a shallow-layer model to simulate  $LH_2$  pool spreading. But his version was plagued by severe numerical instabilities allowing to present only two successful predictive calculations for  $LH_2$  aircraft accident scenarios [8].

## 4.2 LAUV Model Description

FZJ has developed the computer code LAUV [1] also based on the shallow-layer equations, which allows for the description of pool height and velocity as a function of time and location. It addresses the relevant physical phenomena in both instantaneous and continuous (at a constant or transient rate) type releases onto either solid or liquid ground. Heat conduction from the ground is deemed the dominant heat source for vaporizing the cryogen, determined by solving the one-dimensional or optionally two-dimensional Fourier equation. Other heat fluxes are neglected.

Considering the volume of a incremental pool element, the mass conservation equation is given by balancing the volume change in time with the sum of all volume fluxes passing the element's boundaries. For a pool with cylindrical geometry:

$$\frac{\partial(rh)}{\partial t} + \frac{\partial(urh)}{\partial r} + r(v - w) = 0, \qquad (1)$$

where h=h(r,t) – pool height, m; r – radius, m; t – time, s; u=u(r,t) – horizontal (depth-averaged) pool spreading velocity, m/s; w – liquid fuel source rate, m/s; v – liquid fuel vaporization rate, m/s. From the simple one-dimensional analytical solution of the Fourier equation, the vaporization rate per unit surface can be derived as

$$v = \frac{\lambda \Delta T}{\rho_l H \sqrt{\pi a} \sqrt{t - t'}},\tag{2}$$

where  $\lambda$  – thermal conductivity of ground, W/mK;  $\Delta T$  – temperature difference between liquid and ground, K;  $\rho_l$  – density of liquid, kg/m<sup>3</sup>; H – vaporization enthalpy, J/kg; a – thermal diffusivity, m<sup>2</sup>/s; t' – time moment from which surface element gets into contact with pool, s. The code includes optionally a two-dimensional numerical solution, which is able to consider also the effects of heat sources (e.g., solidification enthalpy in moist ground) or temperature increase during intermittent times of no coverage with the cryogen.

The momentum conservation equation is determined by the balance of forces attacking the incremental pool volume taking account of buoyancy and friction forces:

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial r} \left( \frac{u^2}{2} + \delta g h \right) + \frac{F}{h} = 0, \qquad (3)$$

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where g – acceleration of gravity, m/s<sup>2</sup>; F = F(u,h) – friction force per mass unit, kg;  $\delta$  – reduction factor (= 1 for solid ground). The friction force is chosen according to the approach in GASP considering distinct contributions from laminar and turbulent flux. The friction force is chosen considering distinct contributions from laminar and from turbulent flux.

The above shallow-layer differential equation system (1) and (3) is solved by applying an explicit finitedifference scheme. It is valid under the following initial and boundary conditions:

- Spreading is horizontal in radial direction (one-dimensional) in unobstructed terrain.
- For instantaneous release, the pool is initially at rest (zero momentum), i.e., purely gravitational spreading. The initial pool height h(r) is assumed to be a (negative) square function of the radius.
- For continuous release, the source is a volume flow per unit surface (a speed) downwards and perpendicular to the spreading. Source is always in the center.
- Vaporization is a volume loss per unit surface (a speed) upwards through the pool surface.
- No vertical velocity profile within the pool (which is realistic for shallow layers and low friction).
- Densities of ground and cryogen remain constant, i.e., no influence by bubble formation.

Furthermore, the LAUV model includes the possibility to simulate moisture in a solid ground connected with a change of material properties when water turns to ice. For a water ground, LAUV contains, as an option, a

finite-differences submodel to simulate ice layer formation and growth on the surface. Assumptions are a plane ice layer neglecting a convective flow in the water, the development of waves, and a pool acceleration due to buoyancy of the ice layer.

### 4.3 Validation of the LAUV Code

For comparison purposes with the British GASP code, LAUV was applied to the only available LNG pool spreading experiment, for which data were available. From all information found and despite some differences in the boundary conditions assumed (e.g., release rate, surface roughness), the agreement both between the codes and between code and measurements was found to be quite good [1].

Trial 6 of the NASA test series was also subject of a postcalculation with the LAUV model. The nominal release rate of 134 l/s of LH<sub>2</sub> reduced by the flash-vaporized fraction leads to an estimated 87 l/s rate over 38 s contributing to pool spreading. The maximum pool radius was calculated to be about 6.5 m, more than double as much as was observed in the test. The calculated pool lifetime is 43.5 s, which is about the figure of 43 s estimated by the experimenters. The discrepancy in pool size is most certainly due to percolation of the liquid into the sand, furrows developing on the test site enlarging the surface area, and last but not least the release process itself with the LH<sub>2</sub> first splashing on a deflection plate before hitting the ground. These all are aspects which were not simulated in the calculation and which may significantly reduce the pool size [9].

An important part of the LAUV code validation process was the simulation of the  $LN_2$  release experiments on the KIWI test facility at the Research Center Juelich, which was used for a systematic study of phenomena during cryogenic pool spreading on a water surface [1]. Fig. 5 shows two examples of a comparison between measurements and postcalculation, an instantaneous release of 40 l of  $LN_2$  (left-hand side) and a continuous release at a varying rate of 2.5 l/s over 73 s following by a linearly decreasing rate to zero at t = 121 s (right-hand side).



Figure 5. Comparison of  $LN_2$  pool measurements with respective LAUV calculations instantaneous release of 40 l (left) and continuous release at a varying rate over 121 s (right)

The leading edge of the  $LN_2$  pool is usually well reproduced. There is, however, a higher uncertainty with respect to the trailing edge whose precise identification was usually disturbed by waves developed on the water surface and the breakup of the pool into single ice islands when reaching a certain minimum thickness. The right figure shows one of the rare cases, where in a continuous release, the receding front on the inside of the pool could be exactly observed and, even better, was found to be in excellent agreement with the respective LAUV postcalculation.

Postcalculations of the FZJ experimental investigation of LH<sub>2</sub> pool spreading with the LAUV model are shown in Fig. 6. The symbols represent the outermost positions which had definite contact with the cryogen,

meaning that the principal uncertainty for the pool radius is given by the distance to the next measuring position (see error bars). The shaded area describes the pulsation range according to what was observed from the video recording.



Figure 6. Comparison of LH<sub>2</sub> pool measurements with respective LAUV calculations for a continuous release over 62 s at 5 l/s on water (left) and at 6 l/s on an Al sheet (right)

For the spill tests on water (left-hand side of the figure), both measurement and calculation reveal the pool front at the beginning to have shortly propagated beyond the steady state presumably indicating the phenomenon of a detaching pool ring typical for continuous releases. The radius was then calculated to slowly increase due to the gradual temperature decrease of the ice layer formed on the water surface. Equilibrium is reached approximately after 10 s into the test, until at time 62.9, i.e., about a second after termination of the spillage, the pool has completely vaporized. Despite the given uncertainties, the calculated curve for the maximum pool radius is still well within the measurement range. The ice layer thickness could not be measured during or after the test; according to the calculation, it has grown to 7 mm at the center with the longest contact to the cryogen.

The spill tests on the aluminium ground (right-hand side) conducted with a somewhat higher release rate is also characterized by a steadily increasing pool radius. Here is no sign of a detaching ring as slightly indicated by the first measurement points due to the (calculated) high heat flux, which makes the ring immediately decay away. The fact that the attained pool size here is smaller than on the water surface is due to the rapid cooling of the ground leading soon to the nucleate boiling regime and enhanced vaporization, whereas in the case of water, a longer film boiling phase on the ice layer does not allow for a high heat flux into the pool. This effect was well reproduced by the LAUV calculation.

# 5.0 DETERMINISTIC ANALYSIS OF ACCIDENTAL LH2 SPILL SCENARIOS

#### **5.1 CRYOPLANE Fuel Tank**

The first example of a predictive calculation with the LAUV model refers to the CRYOPLANE project considering a hydrogen propelled aircraft of the type Airbus A310. This aircraft has been designed to contain its total fuel of 240 m<sup>3</sup> of LH<sub>2</sub> in two 40 m<sup>3</sup> capacity active tanks plus two 80 m<sup>3</sup> capacity reserve tanks, all arranged above the passengers' section. The hazard of an LH<sub>2</sub> tank rupture associated with a complete spill of the contents was subjected to a simulation with the LAUV code [1].



Figure 7. Instantaneous and continuous LH<sub>2</sub> release from Cryoplane fuel tank compared with an instantaneous LNG release of the same energy contents

The results (no flash-vaporization assumed) given in Fig. 7 show that the LH<sub>2</sub> of one large tank is estimated in an instantaneous spill to spread in a pool with a maximum radius of 27 m and with a lifetime of 18 s. The pool breaks up at the center already after a few seconds. A spillage of the contents of all four tanks (assuming one central release spot) leads to a 42 m radius pool and a 25 s lifetime. As compared with an LNG fuel tank of the same energy contents, translating into  $30.2 / 90.5 \text{ m}^3$  of LNG, the developing LNG pool has, despite a smaller volume, a larger maximum radius of 32 / 50 m and a longer lifetime of 60 / 80 s.

# 5.2 Comparison of Different Cryogens

Another predictive study with the LAUV code was made to analyze the differences in the spreading behavior of the cryogens  $LH_2$ , LOX, LNG, and  $LN_2$  on solid ground (macadam) for the case of a 40 m<sup>3</sup> volume representative of a tank truck load [6]. Results are shown in Fig. 8 for an instantaneous spill (left) and a continuous spill at a rate of 1 m<sup>3</sup>/s.

A remarkable difference for both release modes is the small size and the short lifetime of the  $LH_2$  pool compared to all other pools. Its lifetime of about 13 s for the instantaneous spill and maximum surface area of about 5000 m<sup>2</sup> are lower by a factor of 4 compared to the respective LNG or LOX data. The maximum vaporization rate of  $LH_2$  is largest if volume-related (4.0 m<sup>3</sup>/s), but lowest if mass-related (280 kg/s) compared to the other liquids.

For the more realistic case of a continuous release over 40 s at a constant rate, maximum  $LH_2$  pool size will be reduced down to approx. 1800 m<sup>2</sup>, whereas all other pools are only slightly reduced in size. After the release is terminated, the  $LH_2$  will have disappeared after 5 more seconds, whereas, e.g., the LNG pool will survive longest with 54 more seconds.



Figure 8. Comparison of pool spreading behaviour of 40 m3 of four different cryogens in an instantaneous release (left) and in a continuous release over 40 s (right)

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