RISK BASED SAFETY DISTANCES FOR HYDROGEN REFUELING STATIONS

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ABSTRACT

This paper introduces a risk-based methodology for hydrogen refueling stations. Momentarily, four stations are present in the Netherlands. This number is expected to increase to around twenty in the next years. For these stations, a quantitative risk analysis (QRA) must be carried out to account for spatial planning. The presented method identifies the loss of containment scenarios and failure frequencies. Additionally, the results of this study may be used in legislative context in the form of fixed generic safety distances. Using the risk analysis tool Safeti-NL safety distances are determined for three different kinds of hydrogen refueling stations, distinguished by the supply method of the hydrogen. For the hydrogen refueling stations, a maximum safety distance of 35 m is calculated. However, despite the relatively small safety distances, the maximum effect distances (distance to 1% lethality) can be very large, especially for stations with a supply and storage of liquid hydrogen. The research was overseen by an advisory committee, which also provided technical information on the refueling stations.

1.0 INTRODUCTION

Within the Netherlands, ambitious Tank-to-Wheel (TTW) objectives were agreed in order to reduce the CO_2 emissions of the mobility sector and transport sector. These agreements are stipulated in the Energy Agreement, signed under the auspices of the Social and Economic Council (SER) in September 2013 [1]. In order to realize the goals set, there must be 3 million zero-emission-vehicles (30 – 35% of all passenger cars) in the Netherlands by 2030. Therefore, a 'vision on a sustainable fuel mix' has been compiled in collaboration with more than 100 organizations [2]. At the same time, policy is made addressing the safety issues regarding the introduction of these new sustainable fuels.

Within the vision four different future scenarios were discussed with regard to the use of renewable fuels. The scenario "New and all renewable" is seen as the most promising. Within this scenario electrification of road traffic leads to big market shares for electrical driven cars. The use of plug-in hybrid cars is seen as a transitional phase in the transformation towards hydrogen fueled cars. For different kinds of fuels, such as petrol/diesel, LPG, LNG/CNG, bio-fuels, plug in electrical and fuel cell (hydrogen) electrical a development trajectory is presented within the vision.

Concerning third party risk, the Netherlands uses a risk-based approach. In order to determine these risks, specific software is used in combination with modelling guidelines. Within this paper the trajectory for the development of hydrogen powered transport, the Dutch risk calculation method, results and legislative strategy for hydrogen filling stations are described in more detail.

2.0 HISTORY AND PROJECT OUTLINE

Third party risk refers to the risk of storage, production, use and transport of dangerous substances for people living or working in the vicinity of the source of risk. The risk may be due to chemical incidents, such as fires, explosions or releases of toxic substances. Risk is defined as the probability of failure multiplied by its consequences (effect). In the Netherlands, risk policy is expressed in terms of location specific risk (PR) and societal risk (SR). Along with location specific and societal risk, effect distances (1% lethality) for accidents are important for fire brigades and other emergency services. The general rules of risk determination for a stationary establishment (not transport related) are laid down in the ‘Reference Manual Bevi Risk Assessments’ (RMBRA) [3]. The RMBRA is based on the so-called ‘colored books’ for use in risk and consequence modelling.

- The Yellow Book (PGS 2, 2005) describes the modelling of physical consequences such as discharge, dispersion, pool fires and heat radiation. In general these effects are dictated only by the laws of physics and chemistry [4].

- The Green Book (PGS 1, 2005) describes models for the impact of toxic and flammable effects on human beings [5]. Flammable effects imply both overpressure and heat radiation effects.

- The Red Book (PGS 4, 2005) describes methods for determining the probability of undesired events [6]. In contrast to the ‘Yellow Book’ the ‘Red Book’ deals with the determination of the probability of events in the future on the basis of data from the past and fault tree analysis.

- The Purple Book (PGS 3, 2005) was used to determine risk scenarios, failure frequencies and other risk parameters [7]. It is now replaced by the Reference Manual.

The location specific risk is expressed as the risk of fatality per year; this is defined as the probability that an unprotected person residing permanently at a fixed location will be killed as a result of an incident. The location specific risk is displayed as a contour around an establishment or transport route. The societal risk is defined as the probability that a certain number of deaths will be exceeded during a single accident; it is expressed as the relationship between the number of people killed (N) and the frequency (F) that this number of fatalities will be exceeded. For both the location specific risk and societal risk, criteria limits are set. For dwellings and other vulnerable objects like schools and hospitals, the location specific risk limit is set at 10^{-6} per year. For less vulnerable objects like small office buildings, restaurants, shops and recreation facilities, the location specific risk contour of 10^{-6} per year is a guidance value. For societal risk, an indicative limit is set. For establishments, the indicative limiting frequency (F_{ind}) of an accident with N or more deaths is:

$$F_{ind} = \frac{10^{-3}}{N^2} \tag{1}$$

This means, for example, that the probability of 10 or more deaths must be less than one in a hundred thousand years. The probability of a hundred deaths must be less than one in 10 million years.

The history of risk calculations for hydrogen filling stations in the Netherlands goes back to 2006, when safety distances were determined for a hydrogen filling station by Matthijsen and Kooi [8]. They determined safety distances based on the PR 10^{-6} contour for a small (10 cars per day), medium (40 cars per day) and large (200 cars per day) hydrogen filling station operating at a filling pressure of 350 bar. At that time, the technical guidelines for hydrogen refueling stations were still under development. In 2010 the ‘Dutch practical guideline for fire safety, human safety and environmental safety of installations for distribution of hydrogen to road vehicles and water vessels’ (NPR 8099) [9] was published. This guideline served as a basis for development of the present guideline within the Dutch ‘Hazardous Substances Publication Series’. This guideline ‘Hydrogen; installations for delivery of hydrogen to road vehicles’ (PGS 35) [10] was published in 2015. Additionally, within the PGS 35 project group a report is produced with regard to internal safety distances for hydrogen filling stations [11]. An internal safety distance is defined as the minimal separation distance between a potential hazardous source (e.g. equipment involving dangerous substances) and an object (human, equipment or environment). It will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident (also known as domino effect). Both reports can be downloaded in English from the website of the PGS-series.

(http://www.publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS35.html)

At the same time the guideline PGS 35 was developed, the Dutch vision on a sustainable fuel mix [2] was compiled. Within this vision a development trajectory is presented for different kinds of transportation. The development trajectory for passenger cars for instance is given in Figure 1. The same kind of figures exists within the vision for delivery vans, trucks, busses, ships, airplanes and trains. Figure 1 shows that in the Dutch vision the plug-in hybrid car is seen as transitional phase until ca. 2030. After that time it will be rapidly replaced with full electric cars and hydrogen fueled cars.

In the meantime the European Directive for the deployment of alternative fuel infrastructure (2014/94/EU) [12] demands that member States, which decide to include hydrogen refueling points accessible to the public in their national policy frameworks, shall ensure that by 31 December 2025 an appropriate number of such points are available. This, to ensure the circulation of hydrogen-powered motor vehicles within networks determined by those Member States, including, cross-border links where appropriate. This led to the intention of the Dutch government to have at least 20 public hydrogen refueling stations in the Netherlands in 2020. Before building these stations, however, it is necessary to determine the safety distances for the hydrogen stations. Therefore, the Dutch Ministry of Infrastructure and the Environment (I&M) asked the National Institute of Public Health and the Environment (RIVM) to advice in this matter.

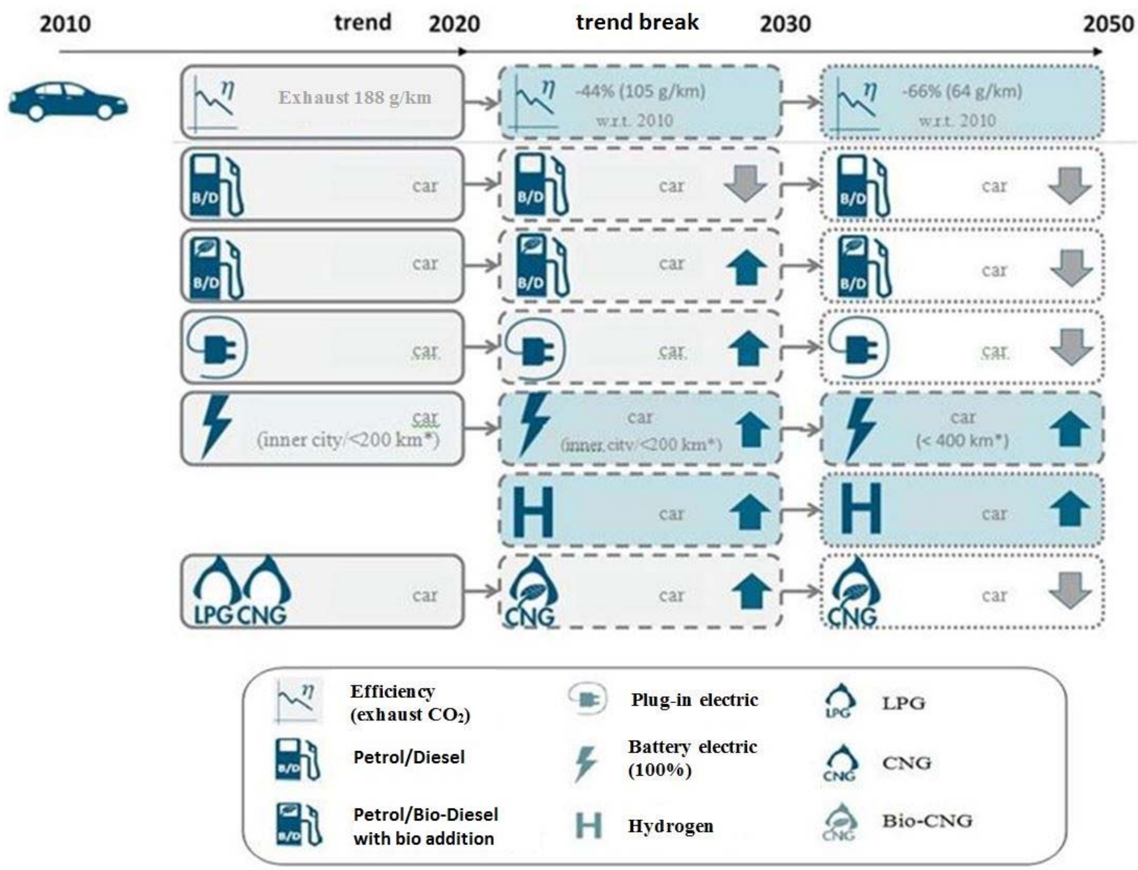

Figure 1. Development trajectory for cars according to the Dutch vision on a sustainable fuel mix [2]
Blue box indicate an objective. Arrow up = increase, Arrow down = decrease
(*daily distance)

By means of calculations on representative scenarios the safety distances with regard to third party risk and the effect distances for emergency response purposes are determined for three types of hydrogen refueling stations. Based on these indicative distances the government can decide to apply fixed safety distances or to develop a new guideline for calculating safety distances for hydrogen refueling stations.

Within the Dutch technical guideline ‘Hydrogen; installations for delivery of hydrogen to road vehicles’ (PGS 35) several types of hydrogen refueling stations are described, based on the supply of hydrogen. Three of these types are used to calculate the safety distances. Type 1 is supply of gaseous hydrogen by pipeline or by local production. Type 2 is supply of gaseous hydrogen by a tube- or cylinder-trailer and type 3 is supply of liquid hydrogen by tank car. These three types are schematically given in Figure 2. Although the supply differs for the different types, every type has the same technical installations and a dispenser.

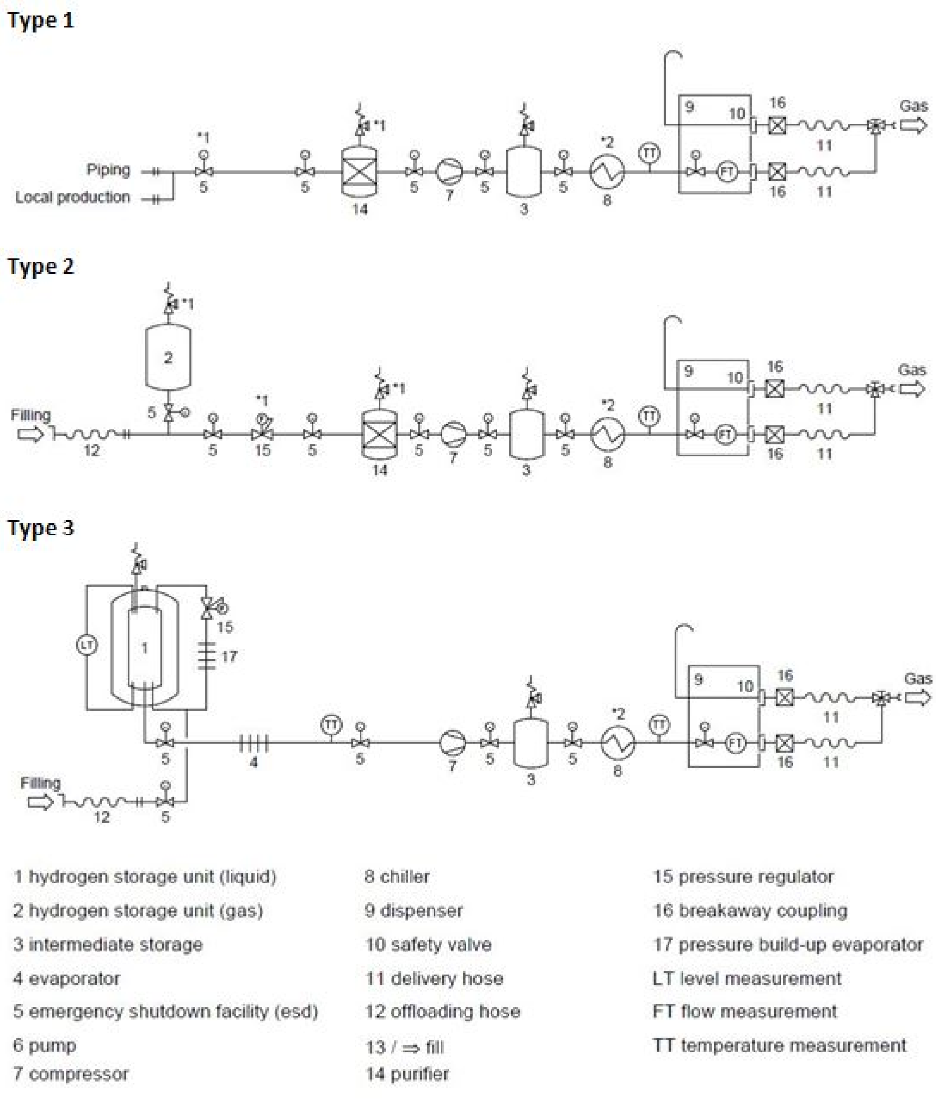

Figure 2. Schematic drawing of three types of hydrogen refueling stations [10] that are used to calculate he safety distances: Type 1 with gaseous supply by means of pipeline or local production. Type 2 with gaseous supply by tube- or cylinder-trailer. Type 3 with supply of liquid hydrogen by means of a tank car.

3.0 QUANTITATIVE RISK ANALYS

For the three types of hydrogen refueling stations given in figure 2 the safety distances and effect distances (1% lethality) are calculated. For the calculations of the safety- and effect distances the basic assumptions, with regard to the standard calculation methods, of the 'Reference Manual Bevi Risk Assessments' are met. Also, the Dutch standard calculation methods for LPG stations [13] and LNG stations [14] are taken as a reference. However, some deviations from the standard calculation methods were inevitable. For instance, the probability of direct ignition of hydrogen during a release is set higher as the standard values. Also, a different version of the calculation model is used. As the reference manual legislatively prescribes Safeti-NL 5.4, the calculations are done with Safeti-NL 6.7.

3.1 Assumptions on all calculations

For every type of hydrogen refueling station the following specific assumptions and basic principles exist:

- All system parts of the refueling station are modelled on the same location;
- For weather type, wind speed and wind direction the mean value for the Netherlands is used;
- The roughness length is defined as an artificial length scale describing the wind speed over a surface and characterizing the roughness of the surface. For these calculations it is set at 0.3 m;
- The site border for the hydrogen refueling station is set at a square of 10 x 10 meter. The incident scenarios are located in the center of this square;
- The probability of direct ignition of gaseous hydrogen during a release is set at 1.0;
- The probability of direct ignition of liquid hydrogen during a release is set at 0.9;
- Environmental temperature is set at 9°C;
- The settings deviate from the basic settings for SAFETI-NL 6.7 on the following points:
  - The 'relative tolerance for dispersion calculations' is changed from 0.001 to 0.01. This change was necessary to avoid failure messages in the numerical simulations.
  - The 'atmospheric expansion method' describes the expansion from orifice conditions to ambient pressure and is changed from 'Closest to Initial Conditions' to 'Conservation of Energy'. Validation experiments showed that this setting is more appropriate for hydrogen calculations [15].
  - Since the speed of sound in hydrogen is much higher than for most other gases, the 'Maximum release velocity' is changed from 500 m/s to 1500 m/s.
- All safety- and effect distances are rounded up towards the nearest 5-fold.

3.2 Assumptions on the hydrogen refueling plant installations

With regard to the modelling of the installation parts, the following assumptions are made:

- For the failure probability of automatic emergency shutdowns (ESD) the 'Reference Manual Bevi Risk Assessments' gives a target value of 0.001 per use in combination with a reaction time until the release is stopped of 120 s. The advisory board of the project, however, recommended a higher failure probability of 0.01 in combination with a shorter reaction time of 5 s (semi-automatic ESD). In the calculations both settings are included.

- In line with the Dutch standard calculation method for LNG stations for the loading scenario's it is assumed that composite hoses are used for which a reduced failure rate can be applied. This implies a factor 10 lower failure rate for the scenario 'breaking of the hose' with respect to the standard failure rates in the 'Reference Manual Bevi Assessments'.

- Calculations are based on a throughput of 1000 kg hydrogen a day, 500 kg is delivered to cars and 500 kg is delivered to buses. For cars, 5 kg hydrogen per fill up is assumed at a pressure of 700 bar. The delivering time is 3 minutes. For buses, per fill up 20 kg is delivered in 11 minutes.

- It is assumed that the compressor is running for 10 hours per day.

- It is assumed for the calculations that two buffer storages are present. One buffer storage at a pressure of 440 bar (40 kg) and one buffer storage at a pressure of 950 bar (20 kg).

3.3 Scenarios and failure frequencies

For the three types of hydrogen refueling stations, the only difference is in the supply of hydrogen to the station. The delivery side of the station is equal for all three types. Table 1 gives the models and scenarios and the failure frequencies for the different scenarios for the situation where the failure rate for the ESD is set at 0.01.

Table 1. Scenarios and failure frequencies of a hydrogen refueling station with a throughput of 1000 kg/day: ESD failure rate 0.01 and reaction time ESD is 5s.

Scenario	**General failure frequency**	**Length or fraction per year used**	**ESD**	**Failure frequency per year**	**Source reference**
TYPE 1: Gaseous supply by pipeline or local production					
Supply pipeline break – ESD succeeds	$1.00 \cdot 10^{-6}$ m^{-1} year^{-1}	10 m [1]	0.99	$9.90 \cdot 10^{-6}$	[3]
Supply pipeline break – ESD fails	$1.00 \cdot 10^{-6}$ m^{-1} year^{-1}	10 m	0.01	$1.00 \cdot 10^{-7}$	[3]
Supply pipeline leak	$5.00 \cdot 10^{-6}$ m^{-1} year^{-1}	10 m		$5.00 \cdot 10^{-5}$	[3]
TYPE 2: Gaseous supply by tube- or cylinder trailer					
Tubetrailer: instantaneous release	$5.00 \cdot 10^{-7}$ year^{-1}	2435 hour per year[2]		$1.39 \cdot 10^{-7}$	[3]
Tubetrailer: largest connection fails	$5.00 \cdot 10^{-7}$ year^{-1}	2435 hour per year		$1.39 \cdot 10^{-7}$	[3]
Delivery hose breaks – ESD succeeds	$4.00 \cdot 10^{-7}$ h^{-1}	1825 hour per year	0.99	$7.23 \cdot 10^{-4}$	[3]
Delivery hose breaks – ESD fails	$4.00 \cdot 10^{-7}$ h^{-1}	1825 hour per year	0.01	$7.30 \cdot 10^{-6}$	[3]
Delivery hose leaks	$4.00 \cdot 10^{-5}$ h^{-1}	1825 hour per year		$7.30 \cdot 10^{-2}$	[3]
Tubetrailer: fire during supply - fireball	$5.80 \cdot 10^{-10}$ h^{-1}	1825 hour per year		$1.06 \cdot 10^{-6}$	[3]
Tubetrailer: fire in	$4.00 \cdot 10^{-8}$ h^{-1}	2435 hour		$9.74 \cdot 10^{-5}$	[13]

[1] Failure of connections like flanges and welds are supposed to be part of the failure frequency of the pipeline. For that reason a minimum length of a pipeline of 10 m is prescribed.

[2] A tube trailer takes 1.5 h for the supply of 300 kg and is present for 2.0 h per supply. With a throughput of 1000 kg per day: 1000/300*2*365.25 = 2435 hours per year present of which (1000/300*1.5*365.25=) 1825 hours supplying.

surrounding - fireball		per year			
Tubetrailer: external interference – fireball	$9.60 \cdot 10^{-10}$ h^{-1} [3]	2435 hour per year		$2.34 \cdot 10^{-6}$	[13]
TYPE 3: Liquid supply by tank car					
Tank car instantaneous release	$5.00 \cdot 10^{-7}$ $year^{-1}$	365 hour per year[4]		$2.08 \cdot 10^{-8}$	[3]
Tank car largest connection fails	$5.00 \cdot 10^{-7}$ $year^{-1}$	365 hour per year		$2.08 \cdot 10^{-8}$	[3]
Tank car: fire during supply – BLEVE	$5.80 \cdot 10^{-10}$ h^{-1} *0.05[5]	219 hour per year		$6.35 \cdot 10^{-9}$	[14]
Tank car: fire in surrounding – BLEVE	$4.00 \cdot 10^{-8}$ h^{-1} * 0,05 * 0,19[6]	365 hour per year		$1.39 \cdot 10^{-7}$	[14]
Tank car: external interference – instantaneous release	$9.60 \cdot 10^{-10}$ h^{-1} [7]	365 hour per year		$3.50 \cdot 10^{-7}$	[14]
Delivery hose breaks – ESD succeeds	$4.00 \cdot 10^{-7}$ h^{-1}	219 hour per year	0.99	$8.67 \cdot 10^{-5}$	[3]
Delivery hose breaks – ESD fails	$4.00 \cdot 10^{-7}$ h^{-1}	219 hour per year	0.01	$8.76 \cdot 10^{-7}$	[3]
Delivery hose leaks	$4.00 \cdot 10^{-5}$ h^{-1}	219 hour per year		$8.76 \cdot 10^{-3}$	[3]
General parts for all types					
Purifier instantaneous release	$5.00 \cdot 10^{-6}$ $year^{-1}$			$5.00 \cdot 10^{-6}$	[3]
Purifier 10 minutes release scenario	$5.00 \cdot 10^{-6}$ $year^{-1}$			$5.00 \cdot 10^{-6}$	[3]
Purifier 10 mm leak	$1.00 \cdot 10^{-4}$ $year^{-1}$			$1.00 \cdot 10^{-4}$	[3]
Compressor supply line breaks – ESD succeeds	$1.00 \cdot 10^{-4}$ $year^{-1}$	10 hour per day	0.99	$4.13 \cdot 10^{-5}$	[3]
Compressor supply line breaks – ESD fails	$1.00 \cdot 10^{-4}$ $year^{-1}$	10 hour per day	0.01	$4.17 \cdot 10^{-7}$	[3]
Compressor supply line leaks	$4.40 \cdot 10^{-3}$ $year^{-1}$	10 hour per day		$1.83 \cdot 10^{-3}$	[3]
Storage/Buffer instantaneous release	$5.00 \cdot 10^{-7}$ $year^{-1}$			$5.00 \cdot 10^{-7}$	[3]
Storage/Buffer 10 minutes release scenario	$5.00 \cdot 10^{-7}$ $year^{-1}$			$5.00 \cdot 10^{-7}$	[3]
Storage/Buffer 10 mm leak	$1.00 \cdot 10^{-5}$ $year^{-1}$			$1.00 \cdot 10^{-5}$	[3]
Process pipeline break – ESD succeeds	$1.00 \cdot 10^{-6}$ m^{-1} $year^{-1}$	15 m	0.99	$1.49 \cdot 10^{-5}$	[3]
Process pipeline break – ESD fails	$1.00 \cdot 10^{-6}$ m^{-1} $year^{-1}$	15 m	0.01	$1.50 \cdot 10^{-7}$	[3]
Process pipeline leak	$5.00 \cdot 10^{-6}$ m^{-1} $year^{-1}$	15 m		$7.50 \cdot 10^{-5}$	[3]
Dispenser delivery hose 440	$4.00 \cdot 10^{-7}$ h^{-1}	1691 hour	0.99	$6.70 \cdot 10^{-4}$	[14]

[3] Incorporation of this scenario is in line with the Dutch standard calculation methods for LPG-stations and LNG-stations and is conservative with respect to the Reference Manual Bevi Risk Assessments. The RMBRA states that, when crash prevention measures are taken, this scenario wouldn't be incorporated. For this scenario it is assumed that the placement of the tube trailer is on a lane with maximum speed limit 70 km/h.

[4] A tank car delivers 1000 kg per supply in 40 minutes and is present for 1 hour. With a throughput of 1000 kg per day, this means 365 hours per year present of which 219 hours per year supplying.

[5] For a double-walled tank car, in line with the standard calculation method for LNG tank stations, for the scenario failure due to fire the reduced failure frequency for a coated LPG tank car is used (reduction factor 0,05).

[6] For a double-walled tank car, in line with the standard calculation method for LPG- and LNG tank stations, a reduction factor of 0.19 is applied that can be justified by the fact that in 90% of the incidents the tank wall will be cooled by the liquid inside the tank.

[7] Incorporation of this scenario is conform the standard calculation method for LPG- and LNG tank stations but conservative with respect to the Reference Manual Bevi Risk Assessments which states that, when protection measures are taken, this scenario can be left out.

bar breaks - ESD succeeds		per year [8]			
Dispenser delivery hose 440 bar breaks - ESD fails	$4.00 \cdot 10^{-7}$ h^{-1}	1691 hour per year	0.01	$6.76 \cdot 10^{-6}$	[14]
Dispenser delivery hose 440 bar leaks	$4.00 \cdot 10^{-5}$ h^{-1}	1691hour per year		$6.76 \cdot 10^{-2}$	[14]
Dispenser delivery hose 950 bar breaks - ESD succeeds	$4.00 \cdot 10^{-7}$ h^{-1}	1826 hour per year [9]	0.99	$7.23 \cdot 10^{-4}$	[14]
Dispenser delivery hose 950 bar breaks - ESD fails	$4.00 \cdot 10^{-7}$ h^{-1}	1826 hour per year	0.01	$7.31 \cdot 10^{-6}$	[14]
Dispenser delivery hose 950 bar breaks	$4.00 \cdot 10^{-5}$ h^{-1}	1826 hour per year		$7.31 \cdot 10^{-2}$	[14]

4.0 RESULTS

For all three types of hydrogen refueling stations, the following results have been generated:

- The distance to the PR 10^{-6}, 10^{-7}, 10^{-8} and 10^{-9} contour is given in Table 2.
- A graph with location specific risk level as function of distance to the incident (Figure 3).
- The distance to the location specific risk value 10^{-6} per year (10^{-6}-contour) and the representative scenario's that set this risk level with their maximum effect distances. The effect distance is equal to the 1%-lethality level. These results are given in Table 3.
- The three scenario's with the largest effect-distances (1% lethality) (Table 4).

Figure 3 shows a gradual decrease of location specific risk with distance for the type 3 refueling station. The risk for type 1 and 2 refueling stations drops to 10^{-9} around 30 and 60 meter. No additional loss of containment scenarios with a frequency above 10^{-9} and with effect distances beyond 30 and 60 meter exist.

Table 2. Distance to the location specific risk contour of 10^{-6}, 10^{-7} and 10^{-8} for three types of hydrogen refueling stations with a throughput of 1000 kg hydrogen per day.

Type of station	Distance to PR 10^{-6} (m)	Distance to PR 10^{-7} (m)	Distance to PR 10^{-8} (m)
Supply of gaseous hydrogen by piping or local production	30	35	35
Supply of gaseous hydrogen by tube- or cylinder trailer	35	55	55
Supply of liquid hydrogen by a tank car.	30	95	130

[8] It is assumed that ca. 500 kg per day is delivered to buses and trucks. A bus takes ca. 20 kg hydrogen and 11 minutes per fill. This results in use of the dispenser during 4,63 hours per day.
[9] It is assumed that ca. 500 kg per day is delivered to cars. A car takes ca. 5 kg hydrogen and 3 minutes per fill. This results in use of the dispenser during 5 hours per day.

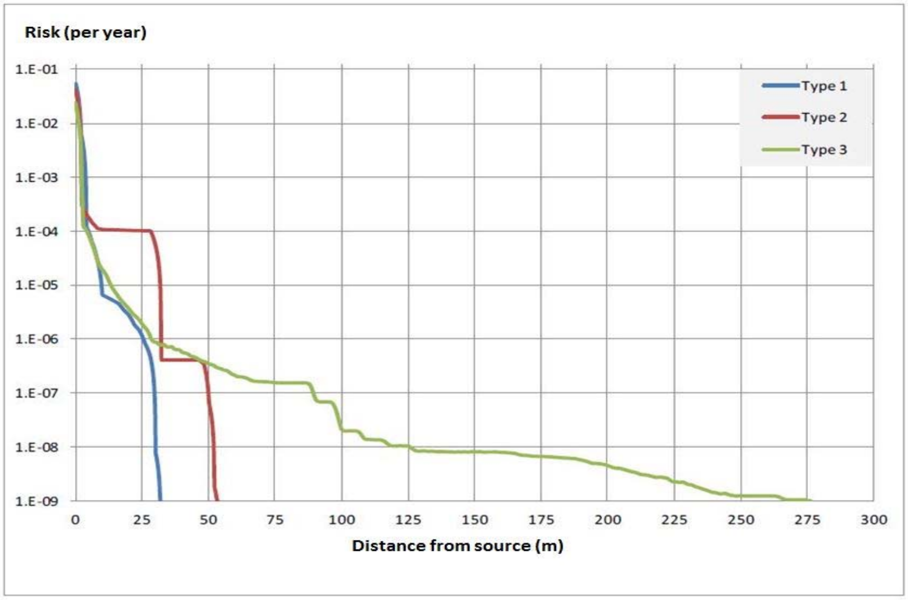

Figure 3. Location specific risk level as a function of the distance from the source, for three types of hydrogen refueling stations with a throughput of 1000 kg hydrogen per day.

Table 3. Distance to the location specific risk contour of 10^{-6}, the risk determining scenarios and their effect distances for three types of hydrogen refueling stations with a throughput of 1000 kg hydrogen per day.

Type of station	**Distance to PR 10^{-6}**	**Risk determining scenarios** (% that scenario contributes to IR 10^{-6})	**Effect distance (1% lethality)**
1. Supply of gaseous hydrogen by piping or local production	30 m	Intermediate storage (20 kg) at 950 bar – leak (83%)	35 m
		Intermediate storage (40 kg) at 440 bar – instantaneous release (17%)	30 m
2. Supply of gaseous hydrogen by tube- or cylinder trailer	35 m	Tube trailer – fireball as a result of fire in the surrounding (96%)	35 m
3. Supply of liquid hydrogen by a tank car.	30 m	Tank car – instantaneous release asa result of external interference (33%)	1200 m
		Delivery hose breaks – ESD working (17%)	90 m
		Intermediate storage (20 kg) at 950 bar – leak (17%)	35 m
		Tank car – BLEVE as a result of fire in the surrounding (13%)	130 m

The sharp, almost discrete, drop in risk for type two refueling stations around 32 meters in figure 3 is caused by the loss of containment scenario's for the tube trailer. The fireball, associated with failure scenarios of the tube trailer, has an effect distance of 31 meter with a total location specific risk around 10^{-4} per year). At a distance of 32 meter the only remaining loss of containment scenario is failure of the buffer, with a location specific risk of $5 \cdot 10^{-7}$ per year. The effect distance of failure of the buffer is 54 meter, explaining the second sharp drop in the graph.

The results are determined for the situation with 5 s ESD reaction time as well as the 120 s ESD reaction time. Both results are comparable. This can be explained by the fact that the model Safeti-NL for jet fires always assumes a time of exposure of 20 s, independent of the actual release duration.

Table 4. Overview of the scenarios with largest effect distance (1% lethality) for three types of hydrogen refueling stations with a throughput of 1000 kg hydrogen per day.

Type of station	Scenario	Effect distance (m)
1. Supply of gaseous hydrogen by piping or local production	Intermediate storage (20 kg) at 950 bar – leak	35
	Intermediate storage (40 kg) at 440 bar – instantaneous release	30
	Intermediate storage (40 kg) at 440 bar – leak	25
2. Supply of gaseous hydrogen by tube- or cylinder trailer	Storage (400 kg) at 80 bar – instantaneous release	55
	Tube trailer - Fireball	35
	Tube trailer – instantaneous release	35
3. Supply of liquid hydrogen by a tank car.	Tank car – Instantaneous release (weather type F1.5)	1200
	Tank car – Instantaneous release (weather type D1.5)	490
	Tank car – Instantaneous release (weather type E5)	370

5.0 EVALUATION AND CONCLUSIONS

From the results it can be concluded that the safety distances, based on the PR 10^{-6} contour, for a hydrogen refueling station with a throughput of 1000 kg per day, is around 35 m. Figure 3 shows that for a hydrogen refueling station with supply by pipeline or local production, or supply by tube- or cylinder trailer the risk level is 10^{-9} or lower at a distance of 50 m from the station. When supply of liquid hydrogen is applied the risk level of 10^{-9} is reached at a much larger distance; 270 m from the source. This can be explained partly by the fact that delayed ignition is excluded for gaseous hydrogen, but not for liquid hydrogen. In the modelling of delayed ignition it is assumed that delayed ignition occurs outside the plant boundary and furthermore when the maximum cloud dimensions are reached. This results in relatively large effect distances. For type 3 hydrogen refueling stations, the scenario of instantaneous release of the content of the tank car as a result of external interference results, under calm weather conditions (F1.5), in an effect distance of 1200 m. Further research is recommended to investigate whether this (conservative) modelling assumption is valid for hydrogen.

When looking in more detail on the effect distances (1% lethality), it seems obvious that the delivery of liquid hydrogen by a tank car plays an important role for type 3 hydrogen refueling stations. The scenario of instantaneous release of the content of the tank car (2900 kg) as a result of external interference results in large effect distances of up to 1200 m. However, delayed ignition doesn't significantly contribute to the safety distance. This can be explained by the relatively low frequency of occurrence of this scenario. The frequency of this scenario is $3.5 \cdot 10^{-7}$ per year (Table 1). Since the probability of direct ignition is set at 0.9 this will, in 90% of the occasions, result in a flash fire with a much smaller effect distance. Delayed ignition, which gives a maximum effect distance of 1200 meter, occurs in only 10% of the occasions (probability of $3.5 \cdot 10^{-8}$ per year). It is obvious that delayed ignition therefore will not significantly contribute to the safety distance (IR 10^{-6}). It will only contribute to the PR 10^{-8}-contour or lower risk levels.

In the Netherlands, the government is setting up new regulations with regard to safety distances and third party risk. There is a large preference for prescription of a fixed set of safety distances for different kind of activities. The results of this study make it relatively easy to set a fixed safety distance for hydrogen refueling stations with gaseous supply. The safety distance for a hydrogen refueling station with supply of liquid hydrogen by a tank car is still under discussion. This type of refueling station is momentarily not widely spread and more research on the mechanism and changes of direct or delayed ignition is necessary to get a more well founded safety distance for this type of hydrogen filling stations.

6.0 REFERENCES

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