Safety distances for hydrogen filling stations

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In the context of spatial planning, the Dutch Ministry of Housing, Spatial Planning and the Environment asked the Centre for External Safety of the National Institute for Public Health and the Environment (RIVM) to advise on safe distances pertaining to hydrogen filling stations. The RIVM made use of failure modeling and parameters for calculating the distance in detail. An imaginary hydrogen filling station for cars is used in the determination of 'external safety' or third-party distances for the installations and the pipework for three different sizes of hydrogen filling stations. For several failure scenarios 'effect' distances are calculated for car filling at 350 and 700 bar (5000 and 10 000 psi). Safe distances of filling stations from locations where people live and work appear to be similar for compressed hydrogen, gasoline (petrol) and compressed natural gas. Safe distances for LPG are greater. A filling unit for hydrogen can be placed at gasoline filling stations without increasing safety distances.

The 'external risk' or third-party risk refers to the risk to which people living or working in the vicinity of large amounts of hazardous substances are exposed. This exposure may be due to chemical incidents, such as fires, explosions or releases of toxic substances. These dangerous substances may be present in plants, storage or transport systems such as pipelines, trains or road trucks. Risk is defined as the probability of failure multiplied by the effect. In the Netherlands, risk policy is expressed in terms of individual risk (IR) and societal risk (SR). Along with individual and societal risks, effect distances for accidents are important for fire brigades and other emergency services. Dutch legislation encompasses a set of three books (known as the 'colored books') for use in risk and consequence modeling:

- The Purple Book[1] is used to determine risk scenarios, failure frequencies and other risk parameters.
- The Yellow Book[2] is used for modeling the physical consequences of chemical releases such as discharge, dispersion and distance to heat radiation levels caused by fires.
- The Green Book[3] is used for modeling the impact of toxic and flammable effects on human beings.

The IR is displayed as a contour around an establishment or transport route. An imaginary person 'located' on a 10^{-6} contour for 24 h per day has a probability of one in a million per year of dying as a result of an accident involving hazardous substances in the establishment or on the transport route. No vulnerable objects, such as dwellings, larger offices and hospitals, are allowed within the 10^{-6} contour.

The SR represents the probability (F) of several deaths (N) at a time as a consequence of an accident. The 'acceptable' FN curve for the SR is given by the relation $F \leq 10^{-3}\ N^{-2}$ per year. This means, for example, that the probability of 10 deaths must be smaller than one in 100 000 per year, and the probability of 100 deaths smaller than one in 10 million/year. SR depends on the population density.

Releases of hydrogen can be either instantaneous (*e.g.* the rupture of a compressor or buffer cylinder) or continuous (*e.g.* a leak in a pipe). Ignition of an instantaneous release will result in a vapor cloud fire. The consequences of continuous release will depend on the time of ignition; direct ignition results in a jet fire, while delayed ignition results in a flash fire.[4]

An explosion may occur if the released hydrogen gathers in a confined area, or if there is a considerable amount of pipework in the cloud envelope. Such conditions are not likely for a release of a few kilograms of hydrogen in open air. For reasons of conservatism, however, a probability of 40% is assigned to an explosion event (in the case of a delayed ignition), and a probability of 60% to a flash fire.[1] The effect distance is the distance from the release location to the spot where heat radiation equals 9.8 kW/m^2, which corresponds to 1% lethality.

The filling station

Calculations were done on three imaginary filling stations with different capacities (**Table 1**). For the production of hydrogen we assumed electrolysis at the small and medium stations, and natural gas reforming for the large station.[5] The three chosen capacities are adequate for the short, and medium term. About 15% of all Dutch cars could be provided with hydrogen if all existing gasoline filling stations in the Netherlands were to install a hydrogen filling unit (a small hydrogen filling unit at a small filling station etc.). The large hydrogen filling station can serve 200 cars per day, which is comparable to a medium-sized gasoline and diesel oil filling station with sales of 2500 m^3 gasoline/year.

A schematic diagram of the filling station is shown in **Figure 1**.

Filling station	Cars on hydrogen per day	Sales (kg H_2 per day)	Sales (Nm^3 H_2)	Production of H_2 by	Buffer contents (kg H_2)
Small	10	25	275	Electrolyzer	25
Medium	40	100	1100	Electrolyzer	100
Large	200	500	5500	Reformer	500

Table 1. The three sizes of hydrogen filling stations examined in this study.

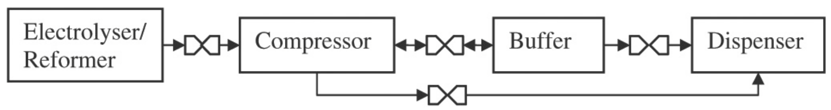

Figure 1. Hypothetical hydrogen filling station for cars.

Production and compression

Hydrogen is produced at 8 bar (114 psi) by electrolysis or by reforming natural gas. Production takes place in a building of approximately 3 m × 4 m and a height of 2.5 m. Next to this building a compressor is placed in a structure having the same dimensions. These buildings are ventilated eight times their volume per hour, and provided with a roof that is lifted if there is an explosion, so as to discharge the explosion energy in a vertical direction. The compressor increases the hydrogen pressure to 450 bar (6430 psi).

Buffer

The buffer is situated in the open air next to the compressor room. The buffer contents are equal to the daily production (Table 1), which is quite large. Such a large buffer has the advantage that production and compressor capacity can be used for many hours a day, making this arrangement economically attractive. The buffer consists of two sections of cylinders, a low- and a high-pressure section, all at 300 bar (4285 psi) when fully filled. Both sections have the same volume, and contain cylinders of 50 liters each. Each section has a safety valve.

Dispenser

The filling hose is assumed to be 5 m long, with an internal diameter of 10 mm. It is equipped with an inline breakaway coupling at each end.

Pipework and safety valves

The different installations, anywhere from those for production of hydrogen to the tank of the car, are connected by pipework with an internal diameter of 10 mm. The cylinders in the buffer are connected by pipes of 4 mm diameter. Excess flow shutoff valves are placed between the different installations, which cut off the gas flow when – in the case of a rupture – the flow rate is higher than the adjusted maximum flow. These valves are installed in front of and behind the electrolyzer or reformer; behind the compressor, buffer and dispenser; on each side of the filling hose; and on the car. The two valves between the buffer and the hose will normally close in the case of the filling hose rupturing. These valves will not close in case of a leak. The natural gas pipeline feeding the reformer is supposed to be laid deep enough underground so as not to contribute to the external risk.

Filling

One fill is estimated to be 2.5 kg of hydrogen, thus giving a car an 'action radius' of about 250 km. The future efficiency of a fuel cell vehicle is estimated to be 4.5 g H_2/km;[6] the action radius will increase to about 1000 km with a future tank pressure of 700 bar (10 000 psi). A car will tank first from the low-pressure section of the buffer, and then from the high-pressure section. Gas flow is driven by the pressure difference between the buffer section and the car tank. Finally, the compressor will fill the car tank from the buffer up to 350 bar (5000 psi).

Modeling

In the calculations, we assume the distance from production to the compressor to be 5 m,

Scenarios	Maximum quantity released (kg)	Initial failure probability (per year)		Probability of direct ignition	Probability that valves work	Total probability (per year)
Electrolyzer	2	5×10^{-6}		0.2	1	10^{-6}
Catastrophic rupture of reaction vessel (8 bar)						
Release from reaction vessel (10 min)	2	5×10^{-6}		0.2	1	10^{-6}
Leak in reaction vessel (10 mm)	2	10^{-4}		0.2	1	2×10^{-5}
Compressor			Time fraction			
Catastrophic rupture of compressor (450 bar)	1	1.9×10^{-2}	50%	0.2	1	1.9×10^{-3}
Buffer (50 l, 300 bar, 20°C)			Cylinders			
Catastrophic rupture of cylinder	1.12	10^{-6}	89	0.2	1	1.78×10^{-5}
Leak in cylinder (4 mm)	50	10^{-6}	89	0.2	1	1.78×10^{-5}
Filling cars			Time fraction			
Rupture in filling hose (10 mm, 27 m; two safety valves fail)	50	3.5×10^{-2}	8.3%	0.1	0.9964	4.2×10^{-6}
Leak in filling hose (1 mm)	50	3.5×10^{-2}	8.3%	0.1	1	1.17×10^{-2}
Pipework		Per m/per year				
Rupture in pipe/buffer/dispenser (10 mm, 25 m)	50	10^{-6}		0.2	0.06	3×10^{-7}
Leak in pipe/buffer/dispenser (1 mm)	50	5×10^{-6}		0.2	1	2.5×10^{-5}
Rupture in pipe/compressor/buffer (10 mm, 10 m)	50	10^{-6}		0.2	0.06	2.4×10^{-7}
Leak in pipe/compressor/buffer (1 mm)	50	5×10^{-6}		0.2	1	2×10^{-5}

Table 2. Data used for a medium-sized hydrogen filling station.

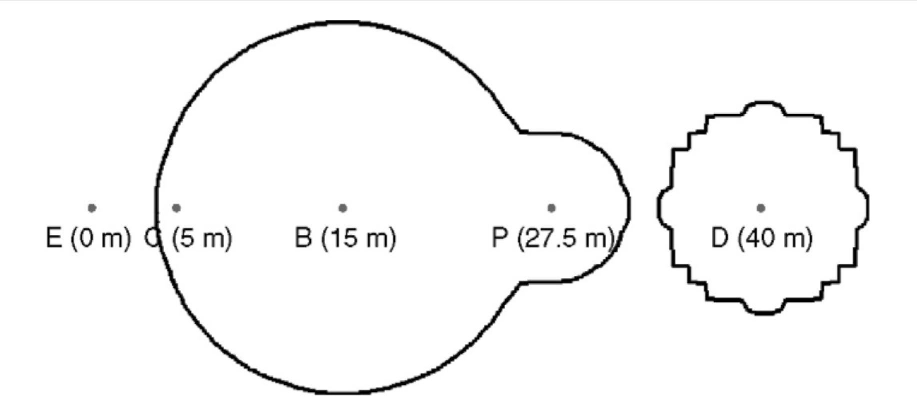

Figure 2. Individual risk (IR) 10^{-6} contour for the medium-sized hydrogen filling station.

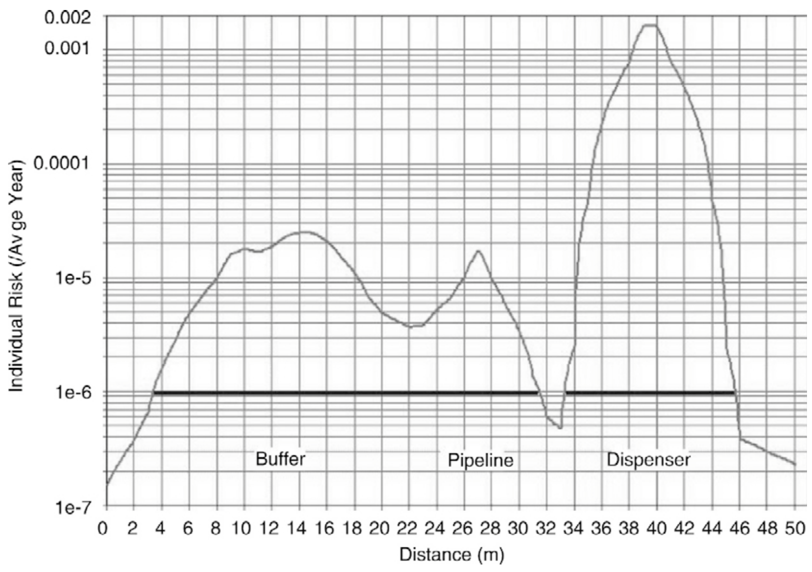

Figure 3. Risk transect for the medium-sized hydrogen filling station.

between compression and the buffer at 10 m, and between the buffer and dispenser at 25 m. The large station contains a second dispenser at 5 m from the first dispenser. All installations are assumed to stand in line.

The data from **Table 2** are used for calculations for the medium-sized hydrogen filling station. For the small and large stations, the buffer contents and time fractions vary linearly with the number of cars per day (Table 1). In the calculations for the large station we used the reformer contents of 1 kg hydrogen, with two dispensers instead of one.

The scenarios and data on initial frequencies of failure and the probability of direct ignition are taken from the Purple Book,[1] except for the frequency of compressor failure, which is taken from AMINAL.[7] The time fraction is the time (percentage) that cars are being filled. Assuming that it takes 3 min to fill a car, 40 cars will be filled in 2 h, which is 8.3% of 24 h. The mass of hydrogen for the electrolyzer unit and the compressor is estimated in accordance with suppliers.

In the case of a catastrophic rupture of a cylinder, the contents of only one cylinder will be instantly released. It is not to be expected that several cylinders will rupture simultaneously. The rupture of a cylinder can cause a 'domino effect'. As the peak overpressures are not likely to coincide, the effects of the domino event will not be considerably larger than the effects of a single event.

The contents of one section will be released in the case of a catastrophic rupture of a cylinder or a pipe failure in the buffer. A leak in a filling hose or pipework will also result in the release of a whole section. In the case of a full bore rupture, the pressure drop along the pipeline is taken into account.

A closing time of a fraction of a second is assumed for the valves. For this reason the scenario containing the filling-hose rupture with two functioning safety valves is ignored. This also applies to the scenario in which there is an instantaneous release or a leak in the car tank or false connection of the nozzle, since we estimated the frequency of failure to be relatively small.

The filling time for a car is 3 min. If the hose ruptures, the safety valve will fail to close in 6% of the cases.[8] The probability of the two valves not closing in line then is 0.0036, and the probability that one or two valves will close is 0.9964. A leak or rupture of a pipe is modeled at half the length of the pipes. In reality, rupture may occur anywhere along the pipe.

Results and conclusions

Calculations were carried out with risk software Safeti 6.42 from Det Norske Veritas.[9] This software is applicable for hazardous substances in general, but is not specifically validated for hydrogen.

The results for the medium-sized filling station serve as an example for all the stations. The 10^{-6} IR contour calculated is shown in **Figure 2**, and a transect of the risk along the line through the installations in **Figure 3**.

The points in Figure 2 represent, from left to right, the electrolyzer (E), compressor (C), buffer (B), pipeline (P) and dispenser (D). The two circles are the calculated 10^{-6} IR contours. The electrolyzer and the compressor have no significant influence on the contours. In the case of the medium-sized station, the buffer has a larger contour than the dispenser. The bulge on the right-hand side of the left contour is caused by a rupture of the pipe between the buffer and the dispenser. This rupture was modeled to take place in the middle of this 25 m pipeline. In practice the IR 10^{-6} contour is parallel to the pipeline at a distance of 4.5 m.

The risk transect on a line through the installations, as shown in Figure 3, demonstrates that IR exceeds 10^{-6} from 3 to 32 m (buffer and pipeline) and from 33 to 46 m (dispenser). The circular risk contour round the buffer has a safety distance (radius) of 11 m; around the dispenser this is 6.5 m. As stated before, the pipeline has a 10^{-6} contour at 4.5 m.

The risk contour around the buffer is caused by the 'catastrophic rupture of a cylinder' scenario, and that around the dispenser by the scenario known as 'rupture of the filling hose and both safety valves fail'.

Station	IR 10^{-6} contour radius (m)		
	Buffer	Pipeline	Dispenser
Small	10	4.5	5
Medium	11	4.5	6.5
Medium (700 bar)	15	5.5	8.5
Large	13.5	4.5	11

Table 3. Safety distances based on the IR 10–6 risk contour.

Scenario	Effect distance (m)	
	350 bar	700 bar
Catastrophic rupture of buffer cylinder	5	12
Leak in buffer cylinder	17	32
Rupture of filling hose and two defective safety valves	18	44
Leak in filling hose	5	12
Rupture in pipe between buffer and dispenser	21	31
Leak in pipe between buffer and dispenser	5	11
Rupture in pipe between compressor and buffer	29	70
Leak in pipe between compressor and buffer	5	12

Table 4. Effect distances for the medium-sized filling station.

The safety distances for the medium-sized hydrogen filling station are also determined at 700 bar (10 000 psi).

The radii of the IR 10^{-6} contours for the three riskiest installations, referring to the three different-sized hydrogen filling stations, are presented in **Table 3**.

The safety distances for a buffer at a filling station for 200 cars per day are about 35% greater than for 10 cars per day. The safety distance for the dispenser at the large station is twice as much as for the small station; this is because there are two dispensers at the large station. Safety distances may be smaller for the underground pipework and buffer. An explosive gas mixture has to be prevented, for example, by effective ventilation.

The SR will not exceed the accepted FN curve, not even in the case of a large filling station of 200 cars per day and with a high population density around the filling station of 300 persons per hectare. There is no need to limit the allowed number of vulnerable objects like dwellings, larger offices and hospitals outside the 10^{-6} IR contour.

The effect distances (1% lethal) for the different scenarios are independent of the size of a station. This is because all the parameters determining an effect, such as pressure and released volume, are the same for all three stations (**Table 4**). The jet fire and flash fire distances at 350 bar were almost equal for all the scenarios. At 700 bar the flash fires were larger than the jet fires, sometimes even by a factor of 2. (See Table 4 for the largest effect distance per scenario.)

At 350 bar, the effect distances for a medium filling station are larger than the risk-based safety distances: this is because the probability of an effect is very small (Table 2). Leaks in a buffer cylinder and ruptures in the filling hose or piping bring about the largest effect distances. Effect distances at 700 bar are approximately twice the distance at 350 bar.

Figures 4 and **5** show the influence of Pasquill stability class (B, D, E and F) and wind velocity (m/s) on the effect distance for the 'leak in a buffer cylinder' scenario.

At a wind velocity of 9 m/s, the effect distance for a jet fire is 12.5 m; at 1.5 m/s this distance is 17 m. The stability class is not relevant for effect distances.

In comparison with other transport 'fuels', safety distances in the Netherlands for gasoline (20–25 m), CNG and hydrogen (10–15 m) are of the same order of magnitude. Safety distances for LPG are larger: 15 m for the dispenser, 25 m for the underground buffer, and, depending on annual sales, 45–110 m for the filling point on the LPG tank trailer.[10]

The capacity of a hydrogen filling station does not appear to have a large influence on the safety distance. For this reason, a filling station for gasoline can also be equipped with a filling unit for hydrogen without increasing the external safety distances.

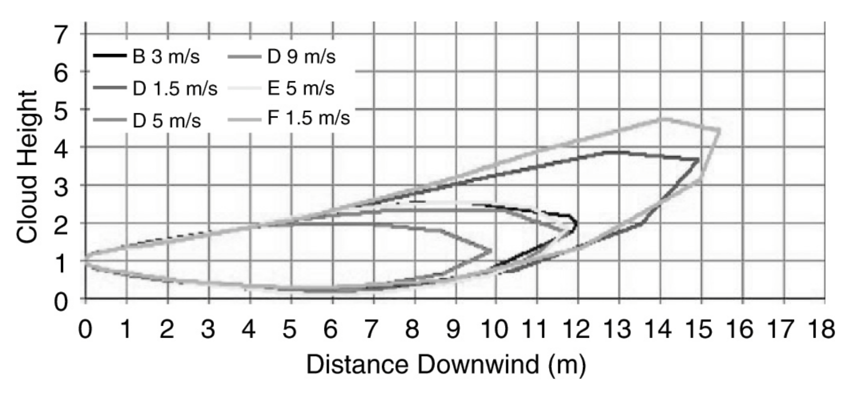

Figure 4. Influence of stability class and wind velocity on the flame envelope (vertical cross-section).

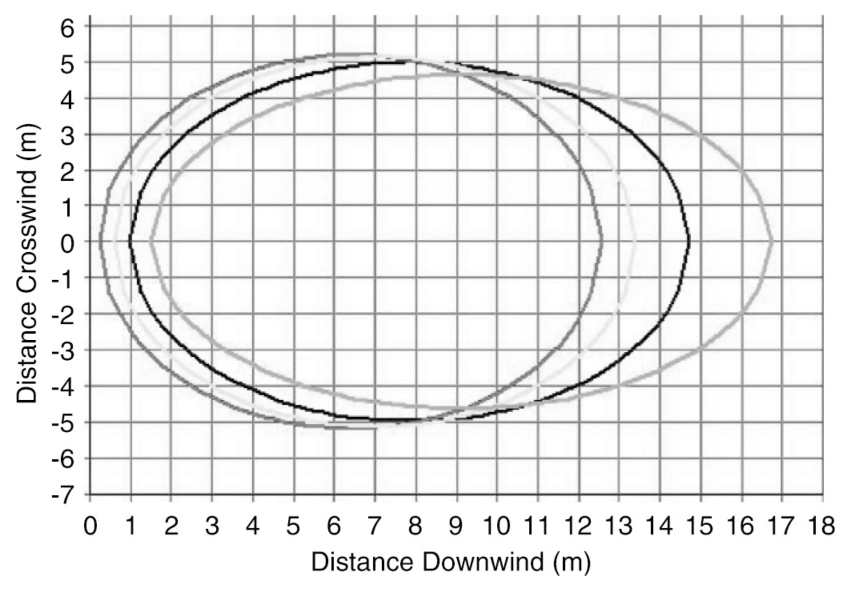

Figure 5. Influence of wind velocity on a 1% lethality contour (horizontal cross-section).

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