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The Impact of the Configuration of a Hydrogen Refueling Station on Risk Level

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Abstract: The paper discusses potential hazards at hydrogen refueling stations for transportation vehicles: cars and trucks. The main hazard analyzed here is an uncontrolled gas release due to a failure in one of the structures in the station: storage tanks of different pressure levels or a dispenser. This may lead to a hydrogen cloud occurring near the source of the release or at a given distance. The range of the cloud was analyzed in connection to the amount of the released gas and the wind velocity. The results of the calculations were compared for chosen structures in the station. Then potential fires and explosions were investigated. The hazard zones were calculated with respect to heat fluxes generated in the fires and the overpressure generated in explosions. The maximum ranges of these zones vary from about 14 to 30 m and from about 9 to 14 m for a fires and an explosions of hydrogen, respectively. Finally, human death probabilities are presented as functions of the distance from the sources of the uncontrolled hydrogen releases. These are shown for different amounts and pressures of the released gas. In addition, the risk of human death is determined along with the area, where it reaches the highest value in the whole station. The risk of human death in this area is 1.63×10^{-5} [1/year]. The area is approximately 8 square meters.

Keywords: hydrogen; refueling station; hazard; fire; explosion; risk

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1. Introduction

Hydrogen technologies are becoming more significant with the transformation of the power generation sector. These technologies are estimated to be an important alternative to hydrocarbon fuels.

Climate neutrality, being one of the focal points of the European Union (EU) policy, requires major investments in technologies based on the renewable energy sources, including hydrogen. However, economical and sociological factors also have to be taken into account in order to successfully incorporate hydrogen into the energy sector. Many research efforts have been performed to tackle these problems. The paper [1] presents the model of international hydrogen trade based on production potentials and cost curves employed to analyze scenarios in which different priorities like energy independence, security or cost were the main objectives. Roadmaps and strategies used in large-scale hydrogen production were discussed in the paper [2]. Moreover, the authors also presented technological advancement in hydrogen-related technologies. Social, industrial and environmental aspects of the hydrogen technology were discussed in the paper [3] in the context of hydrogen's role in the green-energy society.

The paper [4] examines the decarbonization of three coupled energy sectors: electricity, transport, and heating industries. The decarbonization of these sectors may involve hydrogen. Electricity may be generated using hydrogen from electrolysis, with the gasification of coal and the reforming of natural gas as roles for hydrogen with the first one being the desired solution, as a renewable energy source may be applied. Hydrogen may also be used in gas turbines as an alternative fuel. Transportation fleets may gradually be replaced with vehicles with fuel cells running on hydrogen.

A detailed discussion on hydrogen production, storage and transportation is presented in the review [5]. The paper discusses the recent advancements in hydrogen technologies including hydrogen production, storage and transportation in the aspects of the kinetics of processes, cyclic behavior, toxicity and cost-effectiveness. The review [6] takes a sociotechnical perspective to examine the full range of industries and industrial processes for which hydrogen can support decarbonization and the technical, economic, social and political factors that will impact hydrogen adoption. The paper [7] reviews the most recent developments of power-to-hydrogen-to-power systems: conversion of power to hydrogen, and its storage, transport and re-electrification, with emphasis on their technical characteristics, novel modeling approaches and implementation challenges. In the paper [8], a comprehensive review of recent studies in green hydrogen energy systems was conducted, highlighting techno-economic aspects from the component to the technology and broader system level. The technological principles and recent progress of different green hydrogen generation, storage and utilization technologies are summarized.

Fuel cells and electric engines supplied with hydrogen might compete with traditional engines, especially for large transport vehicles like trucks and buses. Right now, the number of hydrogen vehicles is low; although, the growth of their number may be stimulated due to a fast process of refueling. For this purpose, it is important to build a hydrogen infrastructure to guarantee its green generation and a dense grid of refueling stations. The number of public refueling stations gas reached several hundred, which are located all over the world with the highest numbers in China, the United States, Japan and the European Union. Recent investments resulted in new hydrogen stations in Poland located in Warsaw and Rybnik.

The planning model of an expressway hydrogen refueling station was discussed in the paper [9]. The model considered the application of a PV-wind system to produce hydrogen and also different operation constraints.

One of the most important problems that must be analyzed is the safety of the hydrogen systems in vehicles and refueling stations. The study [10] comprehensively reviewed and analyzed safety challenges related to hydrogen, focusing on hydrogen storage, transportation and application processes. Range-of-release and dispersion scenarios are investigated to analyze associated hazards. Approaches to quantitative risk assessment are also briefly discussed. In the article [11], a two-level risk assessment and design optimization approach is presented, in which risk screening with rapid consequence calculations and frequency assessments for release, dispersion, fire and explosion can be performed during the concept selection phase with the estimation of indicative hazard distances. Possible risks of concern are identified in this way and the design can be adjusted or mitigation measures can be introduced.

Preliminary hazard identification for qualitative risk assessment on onboard hydrogen storage and supply systems for hydrogen fuel cell vehicles is described in [12].

The aim of the study [13] was to analyze hydrogen compression and pipeline transportation processes with safety issues related to water electrolysis and hydrogen production for different values of the gas mass flow rate.

An important aspect of hydrogen transportation is the phenomenon of hydrogen embrittlement of pipeline steels that increases the risk of a pipe failure. A description of this process is presented for example in [14,15].

The safety in refueling stations is a topic that also has been present in scientific publications for the past several years. The cases of failures in hydrogen systems and their results were analyzed in [16,17]. The major result of the failures was an uncontrolled release of hydrogen and its propagation in a refueling station. Numerical simulations of those releases were investigated in many papers.

The paper [18] shows the consequence of hydrogen leakage and explosion in Korean refueling stations based on the results from the numerical simulations. Computational

Fluid Dynamics (CFD) was also employed in the research presented in [19] to analyze the impact of wind speed, its direction and the leakage direction on the explosion of a hydrogen storage at a refueling station. The hazards associated with the liquid hydrogen release were discussed in the paper [20], and remedies were proposed. Risk analysis of hydrogen release in refueling stations located in China was presented in [21]. Liquid hydrogen hazards were also discussed in [22]. Risk assessment at a Japanese refueling station was presented in [23]. Another investigation pertaining to the risk assessment of a gas and liquid hydrogen refueling station was shown in [24]. The impact of a high-pressure hydrogen refueling station located in an urban area on the risk levels was discussed in [25]. A mobile hydrogen refueling station in Shanghai was the object of investigation in the paper [26]. A quantitative risk determination for human life during the operation of a refueling station was performed in [27].

This paper focuses on potential hazards and risk analysis in a hydrogen refueling station of a typical layout with one distributor. The hydrogen is delivered to the station in a trailer at a pressure of 20 MPa. After compression, the hydrogen is stored in high-pressure tanks and delivered to a dispenser with a required mass flow. This paper presents a comprehensive analysis of risk related to the operation of such a station. The first step of the analysis is a series of simulations of hydrogen releases from the main facilities of the station and the range of the hydrogen concentration in the air that is within the limit of hydrogen ignition. The paper also includes a description of the calculations for the heat radiation resulting from hydrogen fire and the overpressure wave that is a consequence of an explosion. The final result of the analysis presented here is a quantitative measure of the risk for the main structures of the station. The obtained results allow one to determine the location and the size of the areas with the highest death risk in the station.

In this work the result of the risk analysis, namely the map of the highest risk areas, was used to evaluate and modify the arrangement of the main structures in the refueling station. The overlapping areas of risk generated from different structures cause the accumulation of the risk. The rearrangement of the structures decreases the size of the risks intersection area and results in the improved safety for drivers and maintenance crew at a refueling station. Such actions can be taken during the planning of a hydrogen refueling station and will significantly contribute to reducing the hazards resulting from an uncontrolled release of hydrogen as a result of the failure of station structures: distributor, trailer, HP (high pressure) tank, LP (low pressure) tank, etc.

2. Hydrogen as a Fuel

Currently, hydrogen is used mostly in the refinery industry in the production of fertilizers and in industrial processes. Over time it has gained a status of an important and quickly growing base for a transformation of the power generation branch. It has been increasingly often considered a fuel for transport vehicles.

Hydrogen refueling stations store and distribute hydrogen for cars, trucks, buses, special vehicles and trains. The statistical data from the fourth quarter of the year 2023 show that in Europe there are 170 stations; although, some of them are restricted for public users. Most of the stations are located in Germany, France and the Netherlands (Figure 1). They allow one to deliver the fuel at the common pressure levels of 35 and 70 MPa [28].

This colorless and odorless gas has a wide range of concentrations required for ignition and very low ignition energy is required, which may affect the safety of the process in which it is used. The commonly known hazards that are connected with hydrogen properties, including its flammability, may occur in every process that involves hydrogen-fueled vehicles, but also in the hydrogen infrastructure, storages or delivery systems. Potential hazards are present during a refueling process but also during driving, when car accidents may happen [29,30].

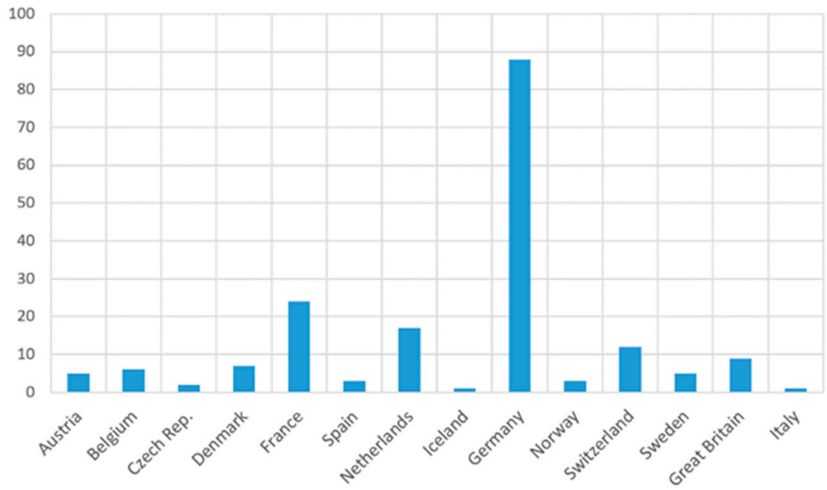

Figure 1. Number of hydrogen refueling stations in different countries in Europe.

The possibility of a fire or an explosion occurs when a hydrogen leakage is present. However, not every leakage leads to a hazardous situation. An ignition depends on the presence of ignition sources and an oxidizer, with the concentration of the hydrogen being in the range of flammability at the same time. These conditions are expressed in a fire triangle, as shown in Figure 2 [31].

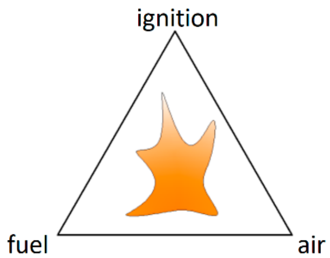

Figure 2. Fire triangle.

Compared to other fuels, hydrogen is characterized by a wide range of concentrations that may cause an ignition. The range is between 4% and 75%. Hydrogen's minimum ignition energy is 0.02 mJ. These values significantly affect the safety of hydrogen systems. For example, the minimum ignition energy for methane is 0.18 mJ, which is almost ten times greater. The very low ignition energy of hydrogen may lead to a fire caused even by friction. However, hydrogen also has many advantages, including the possibility of acquiring this gas from different processes or sources and storing it in different forms. In addition, the usage of hydrogen may improve environmental protection if renewable energy sources are applied to generate the gas [32,33].

Due to hydrogen's properties, every stage of its processing should be analyzed for safety in order to minimize the risk.

3. Methodology for the Assessment of the Risk Related to the Operation of a Refueling Station

Risk analysis is a standardized procedure that includes the following main steps: defining the system under analysis, identification of the hazards, qualitative assessment of the risk, quantitative assessment of the risk, risk evaluation under agreed criteria and corrective actions that result from the risk analysis. This scheme is presented in Figure 3.

The first step of the risk analysis is the definition of the system and its structure. Complex systems, such as a hydrogen refueling station, are divided into a number of subsystems, which in turn consist of objects or parts. A typical arrangement of a refueling station includes a refilling area with a dispenser, a storage system and a shop/cashier.

Hydrogen may be delivered to a station by road transport, through a pipeline or from an installation that generates hydrogen using, for example, the process of electrolysis. If the electrolysis is powered by renewable energy sources, then the hydrogen production does not generate any harmful emissions. In every method of hydrogen delivery, the pressure of the gas is lower than the storage pressure. For that reason, the storage area includes a compressor that fills the HP tanks. The pressure in the main facilities is shown in Figure 4 [34].

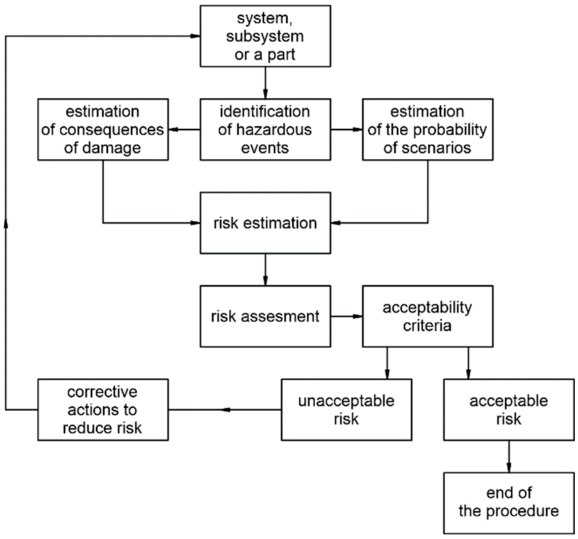

Figure 3. Scheme of the risk analysis procedure.

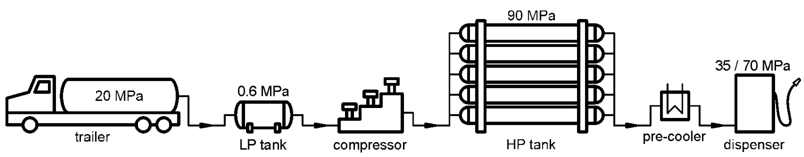

Figure 4. Pressure in the structures of the hydrogen station.

The next step in the analysis is the identification of hazardous scenarios related to the operation of a refueling station. An example of a development of hazardous scenarios triggered by an uncontrolled release of hydrogen is shown in the form of an event tree analysis (ETA), as shown in Figure 5.

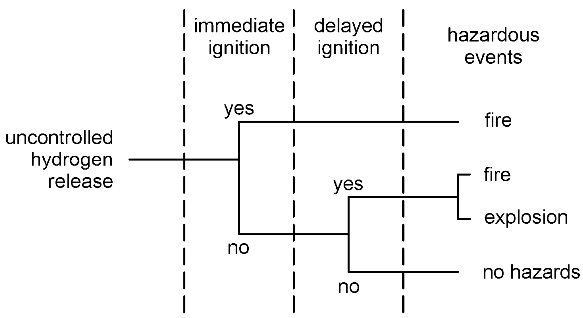

Figure 5. Event tree analysis for the uncontrolled release of hydrogen.

According to the procedure of the risk analysis shown in Figure 3, an essential step is the determination of the consequences of the hazardous events. In the case of a hydrogen fire, the consequences dangerous for people and the surroundings are as follows: a direct exposure to a flame and an exposure to the heat flux from a flame. In case of a hydrogen explosion, the negative effects are the following: an exposure to an overpressure wave and the debris from the structures that were torn apart. In order to determine the level of fire and explosion effects due to an uncontrolled hydrogen release from refueling station structures (trailer, dispenser, HP tank) the Phast v6.7 software was used. The calculations involved the surface model for the fires and the TNT (trinitrotoluene) model for the explosions. The result of the calculations for fires is the value of the heat flux generated by the burning hydrogen as a function of the distance from the point of the hydrogen release and ignition. The result for explosions is the value of the overpressure, also as a function of the distance from the center of the explosion [35].

The essential step of the risk analysis is the assessment of the risk. The risk R is understood as the product of the probability of the hazardous scenario and the consequences of the scenario, e.g., a threat of injury or death.

$$R = \sum P_i C_i \quad (1)$$

where P_i is the probability or frequency of occurrence of a hazardous event and C_i are the consequences of an occurrence of an event.

In this paper the consequences of the potential fires and explosions are expressed as a probability of death for people present within the hydrogen refueling station. The probability of death is calculated using probit functions. They allow one to determine the probability of death due to a specified amount of negative effect like a heat flux or an overpressure wave. The general form of the probit function P_r according to [36] is as follows:

$$P_r = a + b \cdot \ln V \quad (2)$$

where a and b are constants that depend on the type of injury and type of negative factor and V is the dose of the negative factor.

The results of a quantitative assessment are the value of the risk established for the scenarios, structures and the whole system. Depending on the results, further actions are undertaken, including those that aim to lower the level of the risk. The actions are a part of the risk management process.

The next sections present a comprehensive analysis of the risk related to the operation of a hydrogen refueling station.

4. Hazards in Hydrogen Systems

4.1. Hydrogen Cloud

Despite its advantages, hydrogen remains a dangerous fuel. It tends to leak more easily than other gases. Hydrogen flows through holes with a velocity that is 1.2 to 2.8 times greater than the velocity of natural gas. The small density of hydrogen causes its fast dispersion in the air, which is much faster than petrol, propane or natural gas. High flammability contributes to the possibility of a fire or an explosion, which increases the level of danger [33].

An analysis of safety for hydrogen refueling stations must take into consideration the potential locations of leakages. They may occur in the whole infrastructure of a station, which includes pipes, valves, storage tanks, dispensers and intermediate tanks for hydrogen delivery. The potential locations of leakages also include the cars in the refueling process. If a leakage happens and the conditions of the fire triangle are satisfied, then hazardous events may occur such as a jet fire, a flash fire or a fireball. An explosion may occur as well. All of these events lead to negative consequences for persons and objects surrounding a station in the form of death or injury and the destruction of the infrastructure.

The graphs in Figures 6–8 show the range of the cloud with the concentration of hydrogen in the air between 4% (blue color) and 75% (red color). These values correspond to the lower and the upper limits of hydrogen flammability. The figures show the cloud in the top view and the side view. The side view is shown for the moment when the cloud starts to separate from the source of the release. The presented results refer to the three main facilities in the station: a trailer, a dispenser and a high-pressure tank.

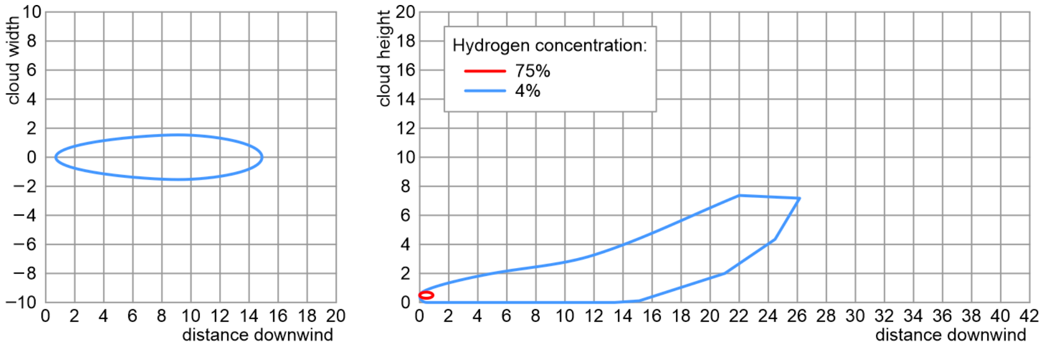

Figure 6. Hydrogen cloud released from a trailer (hydrogen mass: 100 kg, pressure: 20 MPa).

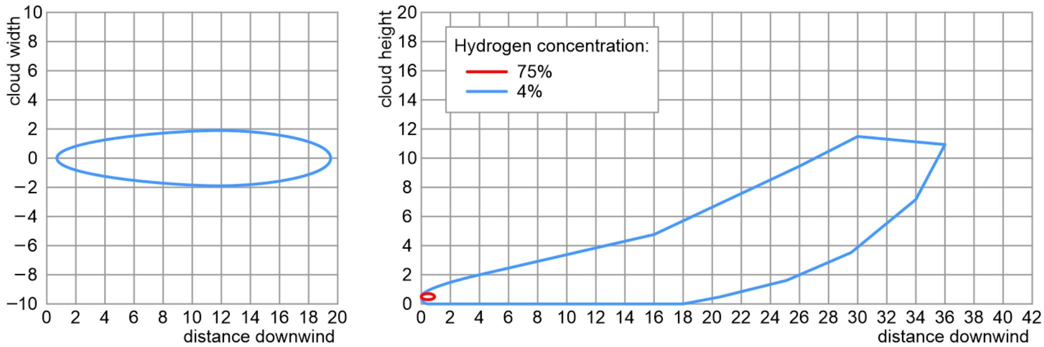

Figure 7. Hydrogen cloud released from a dispenser (hydrogen mass: 25 kg, pressure: 35 MPa).

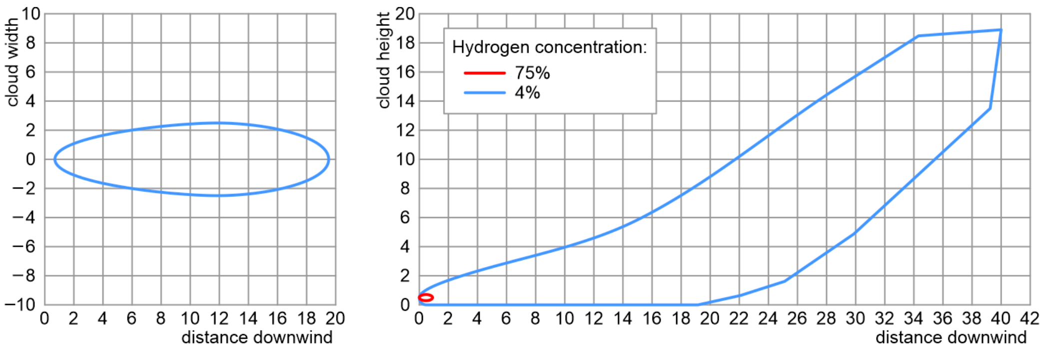

Figure 8. Hydrogen cloud released from an HP tank (hydrogen mass: 25 kg, pressure: 90 MPa).

The graphs in Figures 6–8 were obtained from the calculations performed with the PHAST software version 6.7 [35]. The cases under investigation are gathered in Table 1. They are described by the amount of the released hydrogen, its pressure and the wind velocity. The wind velocity for the results in Figures 6–8 is 2 m/s and the size of the leakage—the diameter of the round hole—is equal to 10 mm. Table 1 also includes the time between the beginning of the hydrogen release and the moment when the cloud separates from the source.

Table 1. Uncontrolled hydrogen release—cases under investigation and cloud separation time.

Facility	Mass [kg]	Pressure [MPa]	Wind Velocity [m/s]		
			2	4	6
			Cloud Separation Time [s]		
trailer	100	20	4.3	3.0	2.7
dispenser	25	35	5.9	4.0	3.5
HP tank	25	90	7.0	4.8	4.1

The presented graphs indicate that in every analyzed case of a leakage, the range of the area with a concentration above 5% reaches the length of 15–19 m at ground level. Above the ground the size of the cloud is different. In a trailer leakage, the maximal distance of a cloud from the source is 26 m. For a dispenser this distance is 36 m and for an HP tank 40 m. Figures 6–8 show the concentration between the lower and the upper ignition limit. The concentration at the upper limit occurs directly at the leakage source only.

A significant factor that affects the size of the cloud is the wind velocity. A comparison for different velocities is shown in Figures 9–11 for leakage from a trailer, a dispenser and an HP tank, respectively. For each facility, the figures show three shapes of the hydrogen cloud, each at the moment of separation from the source and each for the different velocity of the wind. The shapes of the clouds represent the volume of hydrogen concentration in the air equal to or above 4%. The figures show the top view at the ground level and the side view of the clouds with the source of the gas release at the point of the coordinates (0, 0, 0.5) meters.

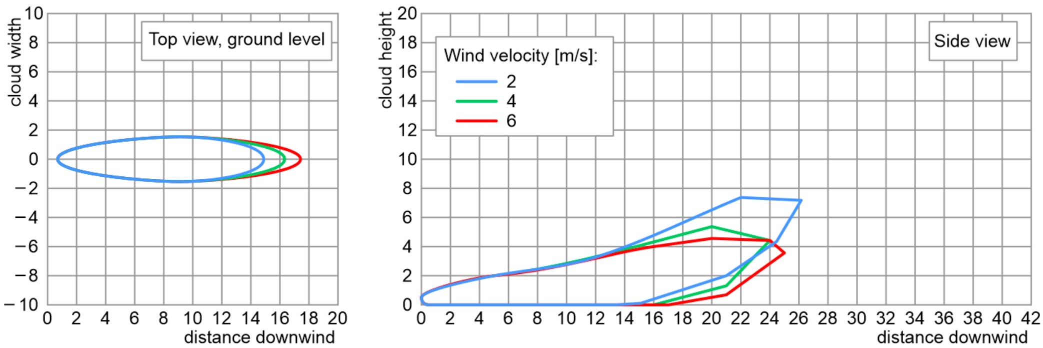

Figure 9. Hydrogen cloud released from a trailer for different wind velocities (hydrogen mass: 100 kg, pressure: 20 MPa).

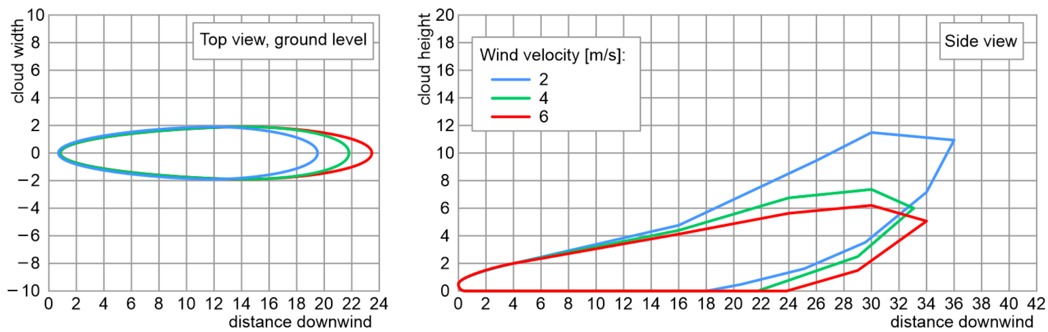

Figure 10. Hydrogen cloud released from a dispenser for different wind velocities (hydrogen mass: 25 kg, pressure: 35 MPa).

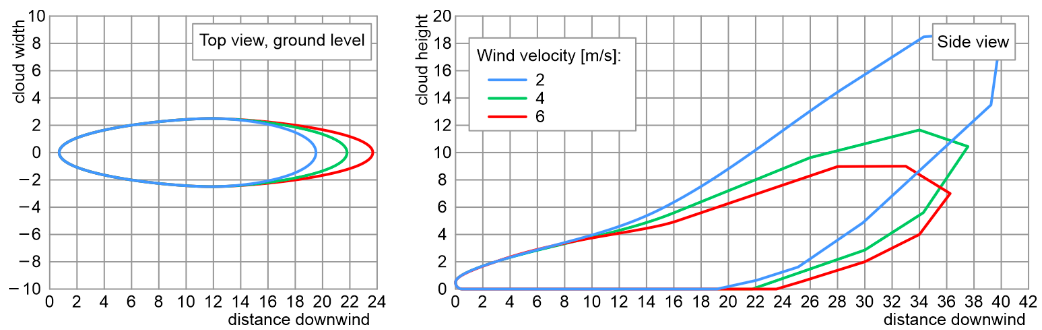

Figure 11. Hydrogen cloud released from an HP tank for different wind velocities (hydrogen mass: 25 kg, pressure: 90 MPa).

The obtained results indicate that faster wind causes a cloud of a larger range at the ground level. However, in the vertical direction, the height of the cloud is smaller for faster wind. This is due to the dispersion of the hydrogen in the air under strong wind.

An uncontrolled release of hydrogen from the facilities in a refueling station may lead to the creation of areas with a concentration of hydrogen in the air above the lower flammable limit that may result in hazardous events for humans and the surroundings if a source of ignition is present. Figure 12 presents the maximal size of the areas, where the concentration of hydrogen may exceed the lower flammable limit for an uncontrolled release from a dispenser, a trailer and an HP tank. The areas are shown for the maximal range of the hydrogen cloud with the wind velocity of 2 m/s over a bird-eye view of a station that follows the structure shown generally in Figure 4. The areas are circles with radii R given in the figure.

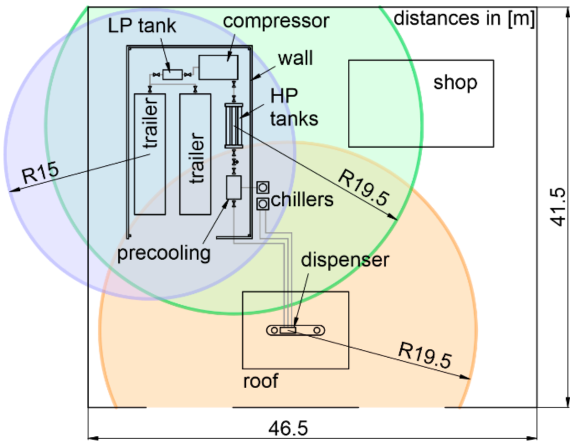

Figure 12. Areas of hydrogen concentration above the lower flammability limit (wind velocity 2 m/s).

If a source of ignition is present in the areas shown in Figure 12, then the fire triangle is completed and a fire may break out at a refueling station.

4.2. Hydrogen Fire

As mentioned above, an uncontrolled release of hydrogen in a refueling station may result in a fire. Depending on the course of the ignition process, the size of the leakage and the amount of the released hydrogen, the fire may have different forms. When hydrogen is stored or transported in pressure vessels under high pressure an ignition may evolve into a jet fire. It has a long and stable flame that derives from the jet of hydrogen released from a hole and being burned. For relatively small release velocities the flame appears in the vicinity of the outlet. For higher velocities, the flame is separated and becomes stable at a distance from the release hole. This phenomenon causes problems when evaluating the geometry of the flame, especially when the velocity and the direction of the wind are also important [37].

Another form of a fire that may occur in case of a rapid uncontrolled rupture of a hydrogen installation is a fire in the shape of a fireball and the accompanying BLEVE (boiling liquid expanding vapor explosion) phenomenon. Generally, the size of the fireball and the period of the phenomena depend on the type and the amount of the released substance [12].

The negative consequences of a fire for humans and the environment are direct interaction with a flame that may ignite other fires and a heat flux generated by the fire. The flux may result in skin burns when above 12.5 kW/m^2 or death when above 37.5 kW/m^2 [38].

Potential hazard zones with the possibility of the heat flux resulting in human death are shown in Figure 13 (jet fire) and Figure 14 (fireball). The zones are plotted over a bird-eye view of a station just like in Figure 12.

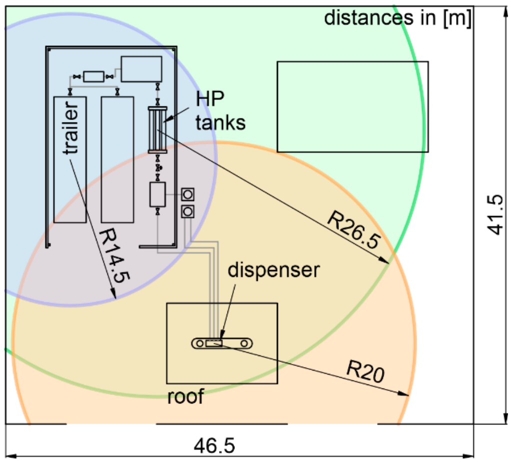

Figure 13. Hazard areas where heat flux may cause human death (jet fire).

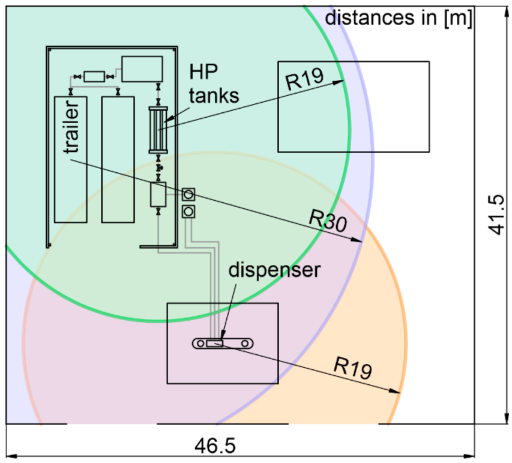

Figure 14. Hazard areas where heat flux may cause human death (fireball).

4.3. Hydrogen Explosion

According to the event tree shown in Figure 4, uncontrolled release of hydrogen at a refueling station may also cause an explosion. This hazard scenario may be a result of the presence of an ignition source in a floating hydrogen cloud at a distance from the point of the hydrogen release or at the point of the release. The hazard level related to the explosion is affected by, among others, the amount of the ignited hydrogen. If the explosion occurs at the point of the hydrogen release then the amount of the gas is higher than in the case of a moving cloud, which occurs when the hydrogen disperses in the air due to a wind. The negative effects of the explosion are the flying debris from the parts of the ruptured structures and the generated pressure wave. They are a threat to people and structures [12]. According to data from technical publications, an overpressure wave of 13.8 kPa is a threshold above which eardrums are injured [38]. An overpressure wave between 55.2 kPa and 110.3 kPa may cause the threat of tossing standing people. The values between 82.7 kPa and 103.4 kPa are the threshold for internal bleeding of the lungs, depending on the body type of the effected individual. Values above 100 kPa lead to the death of 1% of the people in the affected area and values above 206.8 kPa cause 100% of the effected people to die due to lung-related injuries. As for the infrastructure damages, the data from the literature state that an overpressure wave from 20 kPa to 30 kPa damages steel truss structures and the range of 50–100 kPa causes the displacement of tanks and the damage of pipelines. An overpressure wave of 70 kPa causes the total destruction of buildings and substantial damage to heavy machinery and installations [39,40].

The zones related to 1% of the effected people dying due to lung-related injuries are compared in the figures below. Figure 15 shows the case when the ignition occurs at the point of the gas release and Figure 16 when the ignition occurs at a given distance from the source of the release. The locations of the ignition were chosen according to the worst-case scenario. They are at the maximal distance from the point of hydrogen release where the gas concentration in a moving cloud is still above the minimum limit of flammability. For a dispenser and an HP tank, this distance is 50 m from the point of the gas release, and for a trailer, it is 30 m. The differences between these values depend on the amount and the parameters of the hydrogen in the given structure. The zones are plotted over a bird-eye view of a station just like in Figure 12.

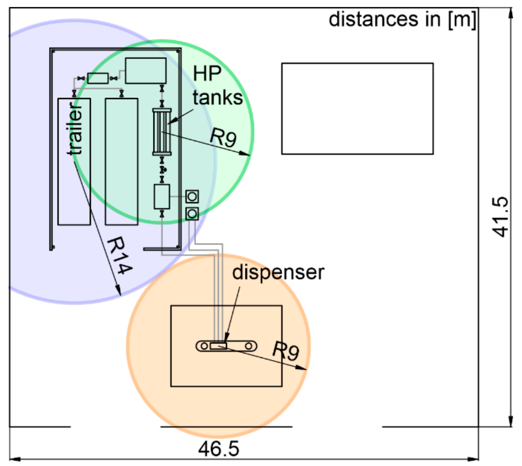

Figure 15. Hazard areas where overpressure may cause human death (ignition at the point of hydrogen release).

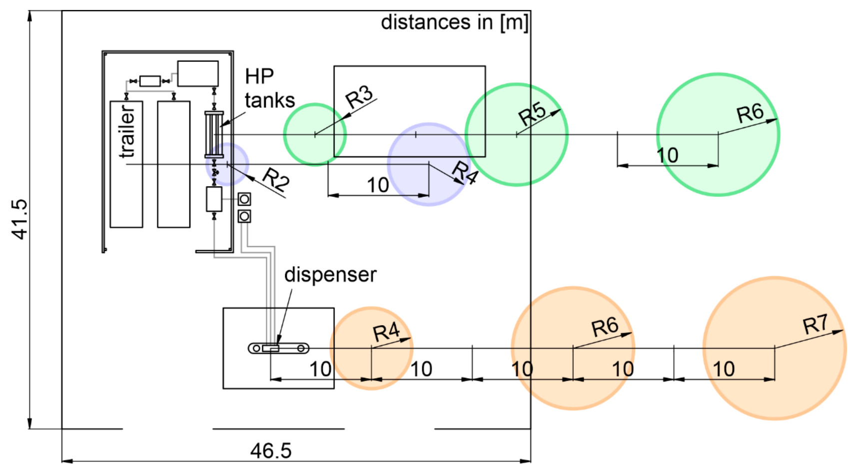

Figure 16. Hazard areas where overpressure may cause human death (ignition at a given distance from the point of hydrogen release).

The presented results indicate that the hazard zones of the pressure wave that causes 1% of the effected people dying, including the largest area with a radius of 14 m for hydrogen released from a trailer and immediately ignited. The amount of hydrogen released from a dispenser and an HP tank is similar, so the ranges of the explosions of the hydrogen released from these structures are the same and reach 9 m. If the ignition occurs in a cloud of hydrogen at a distance of 10 m from the point of the release then the radius of the 1% human death zone is 2, 3 and 4 m for the trailer, the dispenser and the HP tank, respectively. The areas of the zones are bigger at larger distances from the points of the release.

5. Analysis of the Risk Related to the Hydrogen Release

The properties of hydrogen discussed in Section 2, especially its flammability limits, create a hazard that may lead to a fire or an explosion in hydrogen installations for processing, transport and storage. These types of hazards may also be present at refueling stations. An unfortunate course of failure initiated by a hydrogen release may cause a significant hazard for people and the environment, which is confirmed by the hazard zones presented in Section 4. Therefore, it is important to be aware of the hazards and conduct all the actions related to hydrogen in a way that minimizes the risk. The safety in processes involving hydrogen may be provided, for example, by appropriate technology for leakage detection or the correct location of the valves that separate potential leakage areas. In case of potential fires, firewalls should be applied as well [39].

The risk assessment of the hazards resulting in hydrogen fires or explosions and the attempt to minimize the negative effects of these hazards may use the hazard zones presented here in the previous sections. Knowledge of the potential range of the negative effects of fires and explosions, which is the death levels of heat fluxes and overpressure waves, allows one to apply an appropriate arrangement of the structures in a refueling station at its design stage. It makes it possible to minimize the probability of human death and reduce the level of damages and material losses.

The risk of human death in a refueling station may be evaluated for the probabilities of the established hazard scenarios and the range of the consequences of hazards, as shown in Section 4. The probabilities of the hazard scenarios are assigned in the event trees like the one presented initially in Figure 2. The event trees for the structures analyzed in this paper are shown in Figure 17 for the dispenser and in Figure 18 for the trailer and the HP tank [36,40].

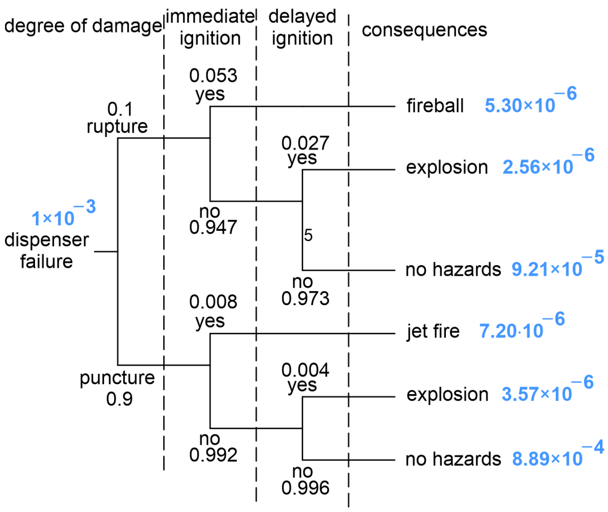

Figure 17. Event tree for a hydrogen release from a dispenser.

Figure 19 presents all the zones related to the hazards in the form of a jet fire, a fireball or an explosion due to hydrogen release from the three main structures in the refueling station, which are under analysis here. The most dangerous zone would be the area where all of the circles indicated in Figure 19 would overlap. However, there is no such area since no point is covered by all of the circles. For that reason, the most dangerous zone is determined as the area that is covered by the highest number of circles. This area is highlighted in the figure as a conjunction of a number of hazard zones. In the highlighted area the negative effects of the hydrogen release followed by either a fire or an explosion may lead to human death. The risk of human death in this zone is 1.63×10^{-5} [1/year]. The area of this zone is approximately 8 square meters.

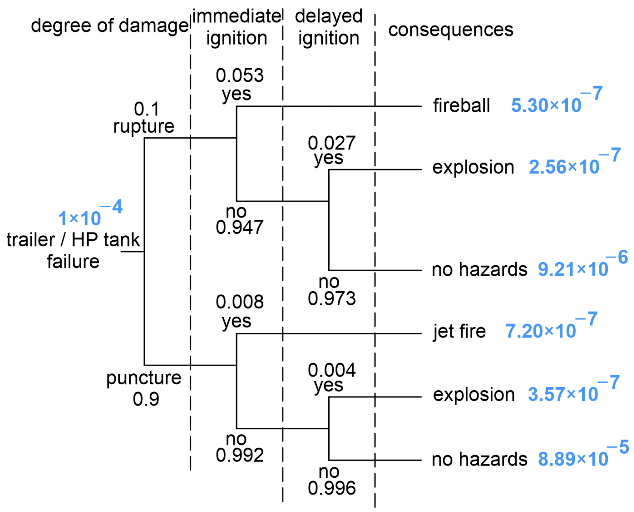

Figure 18. Event tree for a hydrogen release from a trailer or an HP tank.

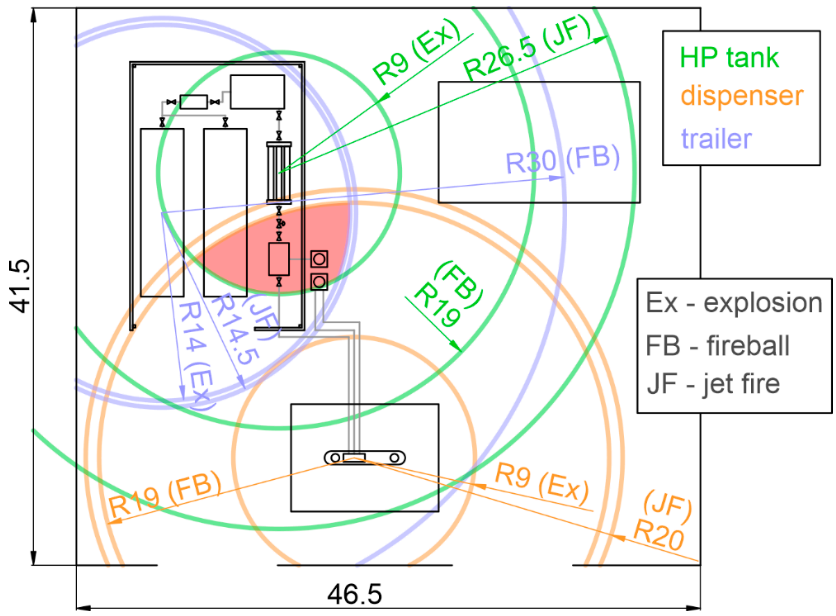

Figure 19. Hazard zones related to fires and explosions of hydrogen released from a trailer, a dispenser or an HP tank (dimensions in meters) with the area of the highest risk marked in red.

The comparison of the hazard zones for the three main structures in the station, namely the dispenser, the trailer and the HP tank, reveals that the zones related to fires are significantly larger than the zones related to explosions of the released hydrogen. It may also be observed that relocating the dispenser 14 m to the right side of the station decreases the risk of human death. This is because relocating the dispenser also moves the hazard zones related to this structure and the highest number of the overlapping zones becomes lower, therefore indicating lower risk. If the dispenser is moved 14 m to the right then the risk decreases to 3.76×10^{-6} [1/year]. The arrangement of the station after the dispenser is relocated is shown in Figure 20.

It should be noted that the proposed changes to the original arrangement of the station result only from the risk analysis and represent the optimal solution with regard to safety. Design modifications must also conform to other criteria including economical criterion, permissions for the structures placement and process limitations criteria.

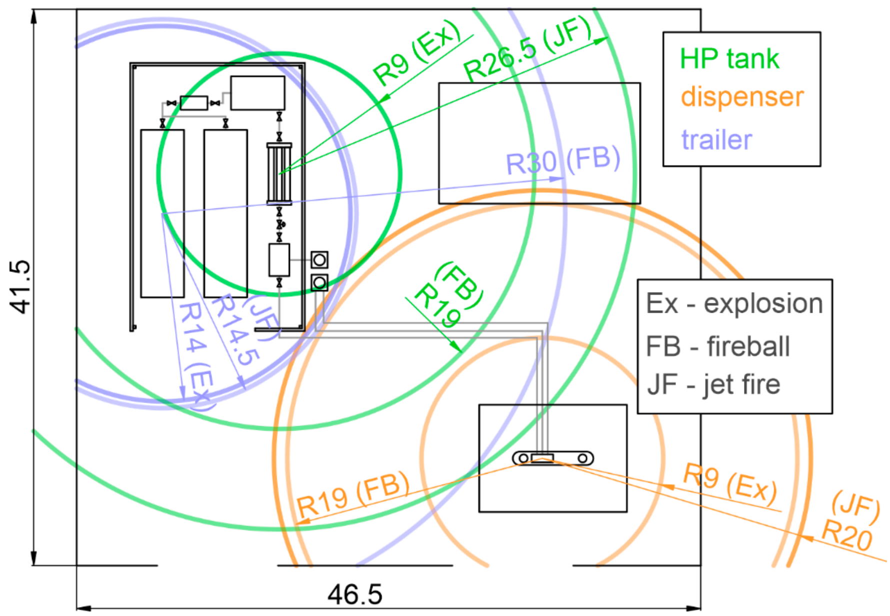

Figure 20. Hazard zones in refueling station after the relocation of the dispenser.

Changing the arrangement of the structures, the operating conditions of the installations and the dimensions of a station affects the final value of the human death risk due to hydrogen installation failures. Important factors are hydrogen parameters in the installations (pressure and mass) and weather conditions, including first of all the velocity of the wind.

6. Summary

The results of the research presented here prove that the use of hydrogen as a fuel for transport vehicles is related to hazards that derive from the properties of the gas. These hazards are related to uncontrolled releases of the gas and the possibility of fire and/or explosion. Depending on the degree of damage, the dangerous consequences of failures include a jet fire, a fireball and/or an explosion. The amount of released hydrogen and its parameters in different structures of a refueling station have a direct impact on the level of hazard for people and the environment.

For the cases analyzed here, of the uncontrolled hydrogen release from three main structures in a station (a dispenser, a trailer and an HP tank), the resulting hazard zones related to human death are larger for fires than for explosions. The probability of death is also higher for fires. This is true for partial and total damage of the structures—a puncture and a rupture, respectively. The largest hazard zone of a 30-m radius occurs for a rapid hydrogen release from a ruptured trailer, which is due to the highest amount of hydrogen kept in this installation. In case of partial damage—a puncture—the largest zone of a 27-m radius occurs for an HP tank, which is due to the highest pressure inside this structure.

If a failure leads to an explosion at the point of the hydrogen release and the whole volume of the released hydrogen is ignited, then the largest death hazard zone of a 14-m radius is generated for a trailer. The hazard zones for an HP tank (a single tube) and a dispenser have a similar range of 9 m, because of almost the same amount of hydrogen present in these structures. If a hydrogen cloud is formed after a puncture and moves away from the source of the release, then the death zones radii are 2, 3 and 4 m for a trailer, an HP tank and a dispenser, respectively.

The analysis described here also allowed one to assess the risk of human death. The risk at the level of 1.63×10^{-5} per year is related to the area of 8 square meters. In this area of the refueling station the hazard zones from each of the main structures overlap. This risk may be reduced, for example, by relocating the structures in the station. The analysis conducted for the presented case allowed a better arrangement of the main structures to bed obtained due to the safety criterion. For the analyzed station, a lower risk is achieved when the dispenser is relocated 14 m to the right. The modifications to the arrangement eliminated the areas of high risk concentration. This action allowed for a decrease in the human death probability to the level of 3.76×10^{-6} per year.

The improvement of safety in hydrogen refueling stations requires a number of actions undertaken at different stages of the existence of these installations, especially at the design stage and the operation stage. The results presented here showed that an appropriate arrangement of the main structures inside a station at the design stage allows one to decrease the zones of high death risk and minimizes the possibility of a domino effect, which is the damage of consecutive structures due to heat flux or a pressure wave caused by an uncontrolled hydrogen release from just one of these structures. These results may also help to select appropriate locations for firewalls, which provide additional protection for people, key structures and the environment. The safety analysis at the design stage should also include the objects in the direct vicinity of the station, especially those that might be a potential source of hydrogen ignition.

Hydrogen refueling stations must also be equipped with an expanded leakage detection system with alarming signals delivered to the operators. This system should cover the whole hydrogen processing path including a trailer, low- and high-pressure tanks, a compressor, pipelines, heat exchangers and a dispenser.

A significant factor in hydrogen processing is the training of the hydrogen users. Training should concern not only the employees in the station or the outsourced maintenance crew, but also the drivers who refill their vehicles. Drivers' training should cover the topics related to the hydrogen refilling process and potential hazards due to hydrogen's properties, which make it more dangerous than hydrocarbon fuels.

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