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Hazards Associated with Hydrogen Infrastructure

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Abstract

The finite nature of fossil fuel reserves is driving interest in hydrogen as a renewable, clean-energy source. Combined with the potential of nuclear power and other renewable energy sources, electricity generation from hydrogen is an area rich in prospects. However, the pre-requisite for harnessing power from hydrogen is research not only on the possibility of gas production, use and storage, but also on the safety of each of these stages. Uncontrolled release of hydrogen poses a serious risk to humans and the environment. This article presents potential hazards related to hydrogen production, pipeline transport and storage tanks.

Keywords: hydrogen infrastructure; hazards; fire

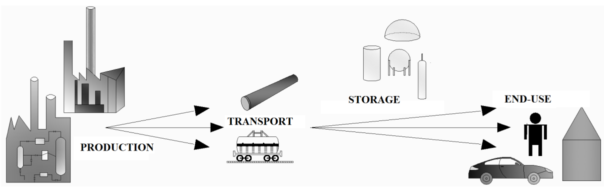

Figure 1: Hydrogen infrastructure

1. Introduction

Depletion of fossil fuel resources and the resulting higher cost of electricity have led to a greater interest in renewable energy sources. Hydrogen plays a significant role here. While not the basic source of energy, it can be used for energy storage purposes and utilized when and where it is needed. Therefore, in many countries hydrogen is viewed as an essential alternative to fossil fuels, and research has been conducted on utilization of the gas [1, 2].

For a future hydrogen-based economy, the sites of the gas production as well as the methods of storage, distribution and application will have to be determined. Hydrogen can be produced either in large centralized plants or in smaller installations built to meet the specific needs of individual companies and/or factories. Large-scale production will require a distribution network consisting of pipelines and tanks to deliver the hydrogen to the utilization sites (Fig. 1) [2–4]. Before committing to heavy investment in large-scale hydrogen

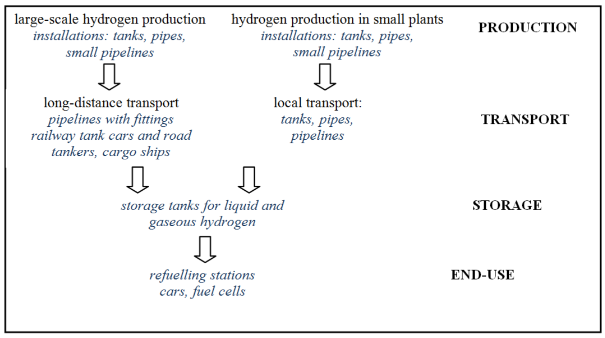

Figure 2: Hydrogen-based economy elements

infrastructure in the economy, research and analysis must be carried out on a number of technological and commercial aspects as well as on issues related to health and safety and risk to the environment. The hazards posed by hydrogen arise evidently from its physiochemical properties. The gas is highly flammable, with a wide range of flammability and low minimum ignition energy, and, in the event of uncontrolled release and ignition of hydrogen, considerable amounts of energy may be released through fire and/or explosion [3, 5].

2. Hydrogen infrastructure

The elements required for the purpose of hydrogen infrastructure will depend on the processes of gas production, storage and end-use (Fig. 2). The basic components and equipment elements are: tanks, pipelines, pipeline fittings, etc. Hydrogen contained or flowing in them may be in gaseous or

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liquid state, and each element of the infrastructure should be made with extreme care to ensure safety of use. Hydrogen may be produced on a vast scale in large plants based on renewable energy sources and then transported through a network of tanks and pipelines to utilization or storage sites. In the case of small-scale production, however, the gas may be used entirely on the production site. There is no need then to build a large transmission network—installation elements will merely be required to transport hydrogen within the plant itself. In its gaseous or liquid form, hydrogen may be stored in special tanks and used when and where needed. For example, end-users could use hydrogen as fuel for cars [3, 5].

The most common cause of hydrogen-related hazardous failures is mechanical damage or damage due to material defects, corrosion, enhanced embrittlement of storage tanks in low temperatures and human error. The effects of a hydrogen installation failure, besides fire damage, include the consequences of explosion and boiling liquid expanding vapor explosion (BLEVE), causing damage due to the impact of pressure waves and flying debris from ruptured tanks [2, 5–7].

3. Hazards related to the use of hydrogen

The precondition for introducing a hydrogen-based economy is the development and construction of appropriate infrastructure. Every one of its elements can create potential hazards for humans and the environment, especially in the event of a failure and uncontrolled release of hydrogen into the atmosphere. Detailed analysis of all of them lies outside the remit of this paper. This in particular concerns installations and equipment whose structural properties are not yet fully known.

Due to hydrogen's great capacity for leakage, a wide range of flammability and low ignition energy combined with the potential for causing enhanced embrittlement of metals, the safety aspects of gas utilization includes a number of issues related to the processes involved. The hazards related to the use of hydrogen may be divided into the following three general categories [4]:

- Physiological hazards, which are related to the effect of hydrogen on humans. A reduction in oxygen concentration in air due to hydrogen may cause breathing problems (dyspnea). If a storage tank or a pipeline is damaged or if hydrogen is released into the atmosphere, a fire or an explosion may occur. The dangerous consequences of these phenomena for humans may be the direct impact of flames and thermal radiation in the case of fire and the impact of the pressure wave and of flying debris from ruptured tanks in the case of an explosion. Another hazard posed by the gas to humans are cryogenic burns to the skin caused by exposure to large amounts of condensed, cooled hydrogen (hypothermia may occur).

- Physical hazards, which are related to properties of metals and to the phenomenon of hydrogen embrittlement. Depending on the temperature and pressure, the duration of exposure to hydrogen and the state of the metal, degradation of the metal mechanical properties occurs, damaging seals and causing leakage. The hydrogen embrittlement phenomenon intensity increases in the 200–300 K range of temperatures. This process may be prevented by using oxygen coatings and appropriate metal alloys, eliminating stress concentrations and introducing special additives to hydrogen.

- Chemical hazards, which are related to the properties of hydrogen. The gas is characterized by very low ignition energy—0.02 mJ. Accordingly, electrical or heat-generating appliances and any open flame sources should be isolated from the hydrogen installation operation site. The gas is also characterized by a wide range of flammability, which adds to its hazardous nature.

4. Scenarios of hazardous events

The hydrogen-related scenarios of hazardous events depend on the elements applied in the installation and on the processes involved in gas production, storage, etc. The most damage-prone elements of hydrogen installations are tanks, pipelines and pipes. The effects of a potential failure depend on the way it proceeds. For example, a complete and extreme rupture may result in tank contents being released in their entirety in a very violent way. If the pipeline suffers partial damage, hydrogen may be released less violently but continuously, i.e. the gas will keep flowing out until its inflow is stopped by closing the inlet valves and cutting off the damaged segment of the pipeline.

The basic hazards created due to the failure of these elements are as follows [1, 4, 5, 7, 8]:

- hydrogen release, which may displace oxygen from the room and cause dyspnea to humans;

- low-temperature hydrogen release, which may cause cryogenic burns;

- fire, which is related to uncontrolled release and ignition of hydrogen. This phenomenon presents a hazard to humans due to the direct impact of the flame or thermal radiation. One of its forms is a jet fire, characterized by a long steady flame arising if highly-pressurized hydrogen is released, e.g. through a hole in the pipeline wall.

- the BLEVE phenomenon—i.e. the boiling liquid expanding vapour explosion. This phenomenon may arise in the event of a hydrogen tank rupture. The hazard posed to humans is related to the impact of the pressure wave and of flying debris from the ruptured tank, as well as to direct thermal radiation and contact with the flame—if the phenomenon is accompanied by a fireball.

- explosion, which may occur due to uncontrolled release of hydrogen from a tank or pipeline. Here, the hazard posed to humans and the environment is related to the impact of the pressure wave and of flying debris from the ruptured tank.

Example effects of disasters caused by hydrogen release are presented below.

Fig. 3 shows the range of hazard zones with an increased thermal radiation level in the case of a jet fire of hydrogen released from a pipeline of diameter d = 150 mm through a 5-cm hole in a 30-metre long transmission segment. The gas outflow is vertical and horizontal to the transmission pipeline axis (Fig. 3 and Fig. 4, respectively). The calculations were made using the PHAST program for hydrogen at a pressure of 0.5 MPa and temperature of 20°C. The air temperature and the wind speed are assumed at 15°C and 1 m/s, respectively, [9].

Analyzing the figures presented above, it can be observed that the zone with the highest, lethal thermal radiation value of 37.5 kW/m^2 will arise only in the case of a horizontal release of hydrogen due to pipeline damage, and its range will reach about 24 metres. The zone with the thermal radiation value of 2 kW/m^2, which may be considered as fairly safe to humans [6], extends over an area with a range of about 35 and 56 metres (vertical and horizontal outflow, respectively).

Another example of a hazardous failure related to the use of hydrogen is a disastrous, complete rupture of a railway tank car transporting liquid hydrogen (Fig. 5). In the adopted scenario of the occurrence of a hazardous event it is assumed that 100 t of liquid hydrogen are transported at a pressure of 7 bar and temperature of -253.2°C. The tank car rupture results in a release of liquid gas, which is followed by evaporation and delayed ignition causing a phenomenon termed a pool fire. It is assumed in the calculations that the air temperature and wind speed are 20°C and 5 m/s, respectively, [9].

Analyzing Fig. 5, it can be observed that the effects of the disaster are much more serious than the release and ignition of hydrogen from a transmission pipeline. The range of the risk of death zone due to high radiation is about 189 meters. The safe area with no hazard to humans will be more than 585 m away from the site of the railway tank car failure.

Fig. 6 presents the effects of an explosion of a tank containing 2000 kg of hydrogen at a pressure of 450 bar. Such a tank may be used to store or transport hydrogen. The analysis is performed assuming wind speed of 1 m/s [9].

An analysis of the figure indicates that in the event of an explosion of 2 t of hydrogen released from a ruptured tank, no zone with a pressure wave value exceeding 483 kPa, which can cause internal fatal injuries, will arise. The range of the zone with a pressure wave value causing damage to the human eardrum will be about 150 meters, and the range of the zone causing damage to lungs—about 45 meters.

5. Conclusions

Due to its properties, hydrogen seems to be the energy carrier of the future. However, it may also pose serious hazards. Therefore, all infrastructure serving the needs of production, storage and distribution should be analyzed in terms of the potential risk and hazards it may present to humans and the environment. The results of the example analyses of the cases considered herein show that the degree of the risk and hazards relate to factors such as the amount of hydrogen involved, its parameters and the type of failure.

In the event of a hydrogen leak through a 5 cm hole in a hydrogen installation pipe with a diameter of 150 mm, the range of the zone with a dangerous level of thermal radiation of 37.5 kW/m^2 posing a hazard to humans will be 24 metres (if the gas outflow is horizontal). This hazardous zone will become substantially larger (about 8 times larger) if a failure occurs in a tanker carrying 100 t of hydrogen. In the case of an explosion of a hydrogen storage or transport tank, the range of the zone presenting a hazard to humans with a pressure wave value of 100 kPa, corresponding to damage to human lungs, will be about 45 meters.

When designing elements of hydrogen production, transport and storage installations, it is absolutely necessary to conduct a risk analysis and determine the range of zones of potential hazards.

Acknowledgments

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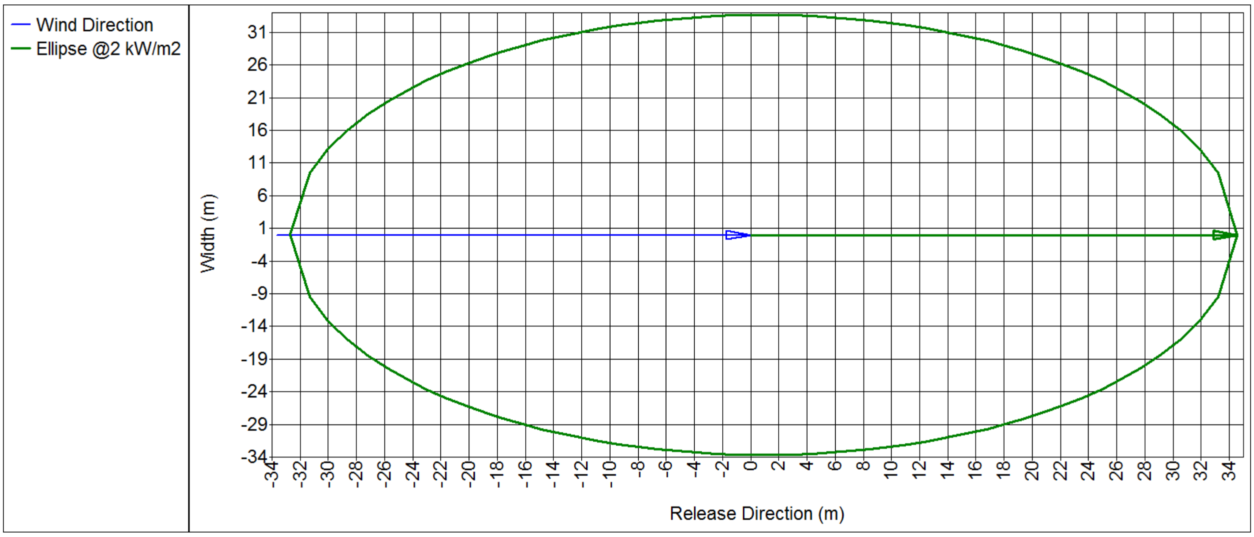

Figure 3: Hazard zone ranges (vertical outflow)

Figure 4: Hazard zone ranges (horizontal outflow)

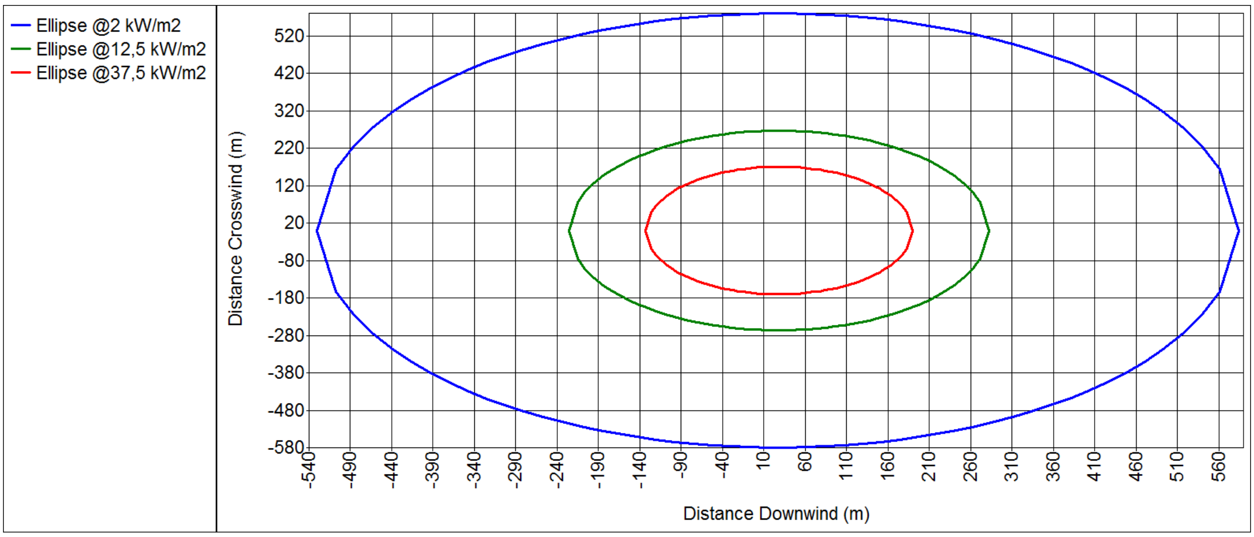

Figure 5: Hazard zone ranges (railway tank car)

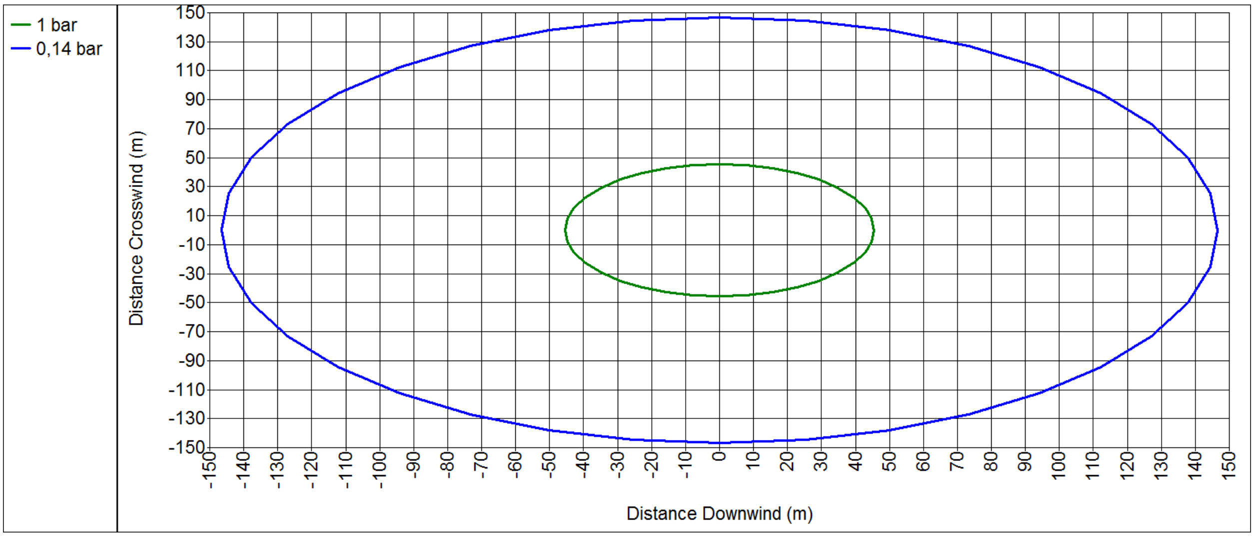

Figure 6: Hazard zone ranges (tank explosion)