Accidental Hydrogen Explosions: Strength of Knowledge in Risk Assessments

Trygve Skjold
University of Bergen,
Bergen, Norway

Abstract

This paper reviews selected aspect of the *strength of knowledge* (SoK) in risk assessments for systems where hydrogen explosions represent a hazard. The analysis focuses on three fundamental aspects of risk assessments: the frequency analysis, the consequence analysis, and the effect of risk-reducing measures. The main objective is to highlight knowledge gaps and inherent sources of uncertainty in risk assessments that support decisions concerning the development, deployment, and operation of emerging hydrogen technologies. The discussion elaborates on inherent limitations in the predictive capabilities of model systems for hydrogen-air explosions in complex geometries. The suggestions for further work emphasise the importance of conducting large-scale explosion experiments in test facilities that capture the complexity and spatial scale of the actual systems found in industry or society, in conjunction with blind-prediction benchmark studies for developers and users of model systems.

1 Introduction

As part of the global energy transition, hydrogen and hydrogen-based fuels are expected to play an important role as energy carriers. At the same time, hydrogen is arguably the most reactive and easily ignitable of all fuels ever considered for widespread use in society. Hence, it is not straightforward to achieve and document the expected or required level of safety for hydrogen systems [1-2].

Fig. 1 shows a general schematic of the activities involved in risk analysis, risk assessment, and risk management. The concept of safety implies control over hazards that can result in losses, and an accident can be defined as an unintended and sudden event that results in loss. In this context, risk can be interpreted a measure of the expected losses for a specified system or activity. The primary purpose of risk assessments is to support decision-making, in various contexts, by stakeholders such as policy makers, authorities, investors, insurance companies, employers, employees, and the public.

Quantitative risk assessments (QRAs) entail the calculation of expectation values that combine event frequencies and consequences for a set of hazards identified for a specific system. The methods and models used are often developed and *de facto* standardised by industry. There is, however, increasing awareness and recognition of the importance of reflecting knowledge and expressing uncertainty in the understanding, analysis, assessment, management and communication of risk [3], and various researchers have proposed methods for assessing the *strength of knowledge* (SoK) in risk assessments.

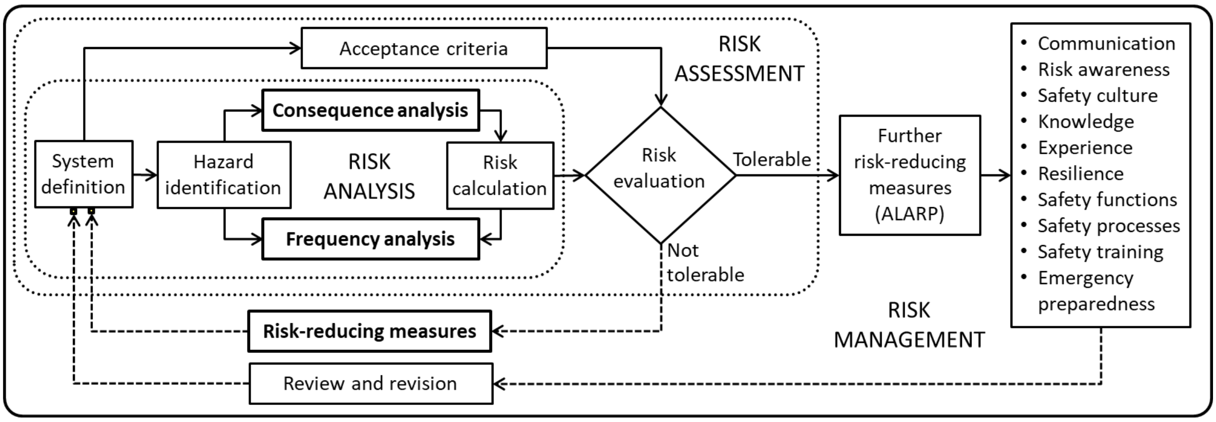

Figure 1: General schematic for risk analysis, risk assessment, and risk management.

The present study is part of several research projects that consider the SoK in risk assessments for systems where accidental hydrogen explosions represent a hazard. The approach adopted follows the crude direct grading approach proposed by Aven [4], where the SoK is considered weak if one or more of the following conditions are met:

1. The assumptions made represent strong simplifications.
2. Data are not available, or are unreliable.
3. There is lack of agreement/consensus among experts.
4. The phenomena involved are not well understood and/or models are non-existent or known/believed to give poor predictions.

For the sake of brevity, the analysis will focus on the last condition above, and only consider a category of accident scenarios that has large potential for resulting in major losses and that is particularly challenging to model: *loss of containment of compressed or liquefied hydrogen, followed by delayed ignition, flame acceleration (enhancement), and possibly deflagration-to-detonation transition (DDT).*

Fig. 2 shows the explosion pentagon and a general event tree for accidental fuel-air explosions initiated by loss of containment. Although a primary objective of process safety is to prevent the formation of explosive atmospheres, numerous hard-earned lessons from past accidents have demonstrated that this is inherently difficult to achieve. Although it is important to focus on inherently safe design whenever possible, as well as design, operation, and maintenance in accordance with established best-practice and safety standards, it is imperative to keep in mind that most accidents are caused by human error [5].

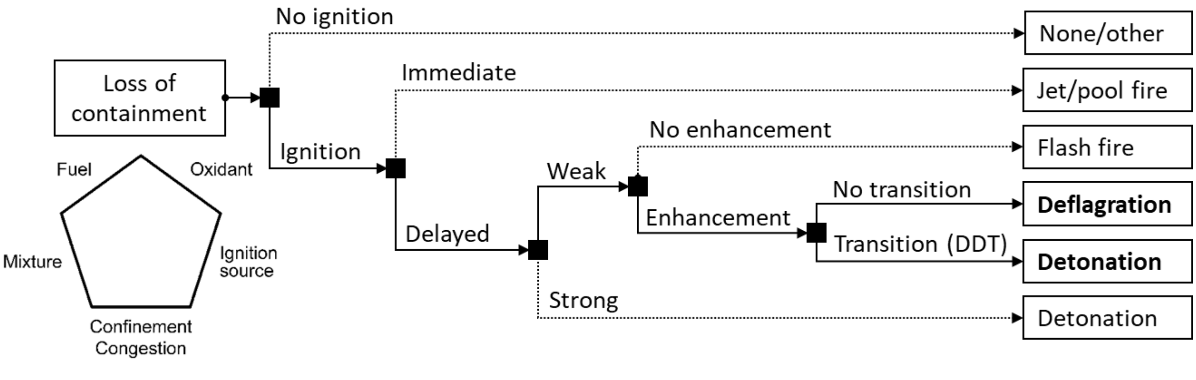

Figure 2: The explosion pentagon and a general event tree for accidental fuel-air explosions.

The limited number of outcomes illustrated in Fig. 2 is somewhat misleading. In reality, there are innumerable accident scenarios that can be realised for a given system. As such, a comprehensive risk assessment should account for a reasonable distribution of potential release points, leak directions and time dependant flow rates, wind speeds and wind directions, as well as the timing, location and type of potential ignition sources. Furthermore, realistic modelling of accidental gas explosions should account for congestion and confinement, i.e. the actual three-dimensional (3D) geometry of the facility, as well as risk-reducing measures such as natural or forced ventilation, deflagration venting, isolation and suppression systems, blast and fire walls, soft barriers, water deluge, etc. Finally, it is important to keep in mind that major accidents usually entail escalating accidents scenarios [6].

The wider consequences of the hydrogen explosion at the refuelling station in Sandvika on 10 June 2019 shows that the development of the 'hydrogen economy' is fragile [1]. All hydrogen refuelling stations in Norway remained closed for several years, planned developments of new stations were cancelled, and the import of cars stopped. Hence, it is reasonable to assume that new severe accidents, especially in the public domain, will delay or even terminate further development. To this end, it is imperative that all stakeholders realise that the implications of future severe accidents in hydrogen systems will not be limited to the companies that own or operate the affected installations.

The following sections elaborate on three fundamental aspects of risk assessments: the frequency analysis, the consequence analysis, and the effect of risk-reducing measures.

2 Frequency analysis

The inherent lack of relevant experience data from the emerging hydrogen technologies represents a fundamental challenge when it comes to estimating event frequencies, i.e. leak and ignition frequencies, that can be used in conventional probabilistic explosion studies. Furthermore, there is significant uncertainty associated with the physical phenomena involved in various ignition mechanisms that are particularly relevant for hydrogen [7], such as: diffusion ignition [8], corona discharges [9], electrostatic discharges induced by entrained particles [10], mechanical impacts [11], and spontaneous ignition caused by the release of liquified hydrogen into water [12].

The fact that the minimum ignition energy (MIE) of hydrogen-air mixtures is about one order of magnitude lower that for conventional gaseous fuels, such as methane and propane, implies that a wider range of ignition sources must be considered. Even if it might be reasonable to assume that the ignition probabilities are similar for electrical equipment certified for Gas Groups IIA, IIB and IIC used for methane/propane, ethylene, and hydrogen, respectively [13], hydrogen-air mixtures have a higher residual probability of ignition caused by mechanisms not related to electrical equipment.

Finally, in addition to leak and ignition frequencies, the extreme reactivity of hydrogen-air mixtures, relative to conventional fuels such as natural gas, petrol and diesel, implies that it will be increasingly important to consider DDT frequencies for deflagrations in large-scale complex geometries.

3 Consequence analysis

The laminar burning velocity S_L of gaseous fuel-air mixtures is generally considered a reliable measure of the relative reactivity of different fuels [14]. However, most accidental fuel-air explosions involve turbulent flow conditions, that typically are strongly influenced by boundary conditions such as congestion, confinement and the initial flow field [15]. It is also important to consider various hydrodynamic, thermo-diffusive and thermo-acoustic instabilities [16], and the results from the extensive research conducted in the aftermath of the Buncefield explosions highlight the crucial importance to assessing the likelihood, and the potential consequences, of DDT and detonations [17-18].

Skjold et al. [2] summarised results from two medium-scale test series conducted with hydrogen and other fuels conducted in the same geometrical configurations [19-20]. The maximum explosion pressures observed for near stoichiometric mixtures in the partly confined and congested geometries was typically one order of magnitude higher for hydrogen, compared to conventional fuels such as methane and propane.

Tools for estimating the consequences of accidental fuel-air explosions range from empirical correlations and phenomenological models to advanced numerical model systems [6]. For large-scale complex geometries, it is common practice to use engineering models based on computational fluid dynamics (CFD) that rely on subgrid models for capturing important physical phenomena. There is however considerable uncertainty associated with the model predictions, especially for highly reactive fuels, such as hydrogen.

The validation work for the commercial model systems relies heavily on the large-scale experiments conducted with natural gas in geometries that resemble offshore installations. The experiments were rarely repeated, with a few notable exceptions [21]. The inherent spread in the maximum absolute explosion pressures observed in the repeated large-scale experiments with natural gas that included significant flame acceleration is typically within a factor two [2]. This provides an indication of the level of accuracy that can be achieved with consequence models.

A recent blind-prediction benchmark study, conducted as part of the EU funded HySEA project, revealed significant spread, by more than one order of magnitude, in model predictions submitted by different modellers using the same model system [22]. The experiments involved hydrogen releases in 20-foot containers, with or without internal congestion, followed by delayed ignition in the stratified layer near the ceiling and explosion venting through commercial vent panels on the roof. The results illustrate the importance of not only improving the modelling of physical phenomena, but also making sure that the users of the model systems are properly trained.

4 Risk-reducing measures

Several of the risk-reducing measures frequently used for conventional fuels have limited applicability for hydrogen. The extreme reactivity of hydrogen-air mixtures implies that deflagration venting of weak enclosures, such as containers, buildings and ships, is not straightforward [23]. It is also challenging to develop solutions for explosion suppression, explosion isolation and chemical inhibition [24]. Finally, most of the mitigating measures that are used in industry today are not applicable for detonations.

5 Conclusions

The inherent lack of relevant experience data for the emerging hydrogen technologies implies significant uncertainty in the estimation of event frequencies for hydrogen systems with non-trivial levels of complexity. Furthermore, the inherent complexity of the physical and chemical phenomena involved in hydrogen explosions in large-scale complex geometries, and the limited data available for model validation, represents a significant challenge for both modellers and users of commercial model systems. Finally, there are limited possibilities for reducing the risk of hydrogen explosions, compared to conventional fuels. In summary, the strength of knowledge in risk assessments for accidental hydrogen explosions is weak, and this uncertainty should be reflected in the level of conservatism in the design of hydrogen installations.

6 Suggestions for further work

Safe design of hydrogen installations requires reliable and efficient consequence models that can reproduce important trends observed in experiments. To this end, future research should focus on developing and validation consequence models for industrial applications. Blind-prediction benchmark studies that are arguably the only reliable way of documenting the predictive capabilities of advanced model systems, as well as the users of such models. In a longer perspective, it will be valuable to develop databases for leak and ignition frequencies in various systems, such as refuelling stations, cars and ships.

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