Developments and Uncertainties in Hydrogen Fuels Risk Assessment

Michael D. Moosemiller, Senior Principal Consultant – Supervisor/Hazard ID
Baker Engineering and Risk Consultants, Inc., 840 West Bryan Mawr Ave., Suite 720, Chicago, IL 60631 USA

Robert J. Magraw, Principal Consultant – Operations Manager
BakerRisk Europe Limited, Regus House, Heronsway, Chester CH4 9QR, United Kingdom

The widespread adoption of hydrogen fueled vehicles as part of the transition to low-carbon energy consumption is reliant on the development of a comprehensive infrastructure able to supply hydrogen fuel in an accessible, reliable, and safe manner. Whilst organisations such as ISO and IEC are developing standards for this technology, for many countries this is lagging or in parallel with the design, siting, and operation of many fueling facilities. While hydrogen has obviously been present in industrial environments for many decades, the risks associated with its use as a consumer fuel still have many uncertainties.

Risks are defined as the cumulative combination of all possible failure outcomes and the frequencies of those outcomes. In the context of the hydrogen fueling infrastructure, uncertainties in calculating risks include:

(a) incomplete understanding of hydrogen explosion phenomena,
(b) highly variable experiences with the ignitability of hydrogen releases, and
(c) very limited experience with the consumer interaction at hydrogen fueling facilities.

Regarding hydrogen explosion phenomena, research is showing that hydrogen explosions occur at higher energies than were previously expected compared to explosions of other chemicals. This reflects not only the higher fundamental burning velocity of hydrogen, but also the extension of the energy input to the explosion beyond the boundaries of confined/congested spaces in the area of the release, as verified by full scale testing conducted at BakerRisk's test facilities but still not widely acknowledged in industry.

Subject matter experts also disagree wildly on the probability of an ignition for a given hydrogen release situation in industrial environments. Experiments over the past decade or so have demonstrated why these varying experiences may have occurred, and suggest how these insights may, rightly or wrongly, inform the discussion of hydrogen ignitions in a consumer fuel environment. This paper reviews these opinions, experiments, and the results of recent field testing at BakerRisk facilities.

Since the hydrogen consumer fuels industry is relatively nascent compared to hydrogen as an industrial commodity, failure data for consumer fuel station components such as fueling nozzles, as used by members of the public, are very limited. The shortcomings are discussed, along with some potential surrogates for component failure rates that might be used until more definitive data are developed. These are compared to events that have already occurred at existing public hydrogen fuel stations.

This paper explores the above uncertainties – what is known and what is still obscure, the path forward for resolving the unknowns, and the potential consequences of failure to adequately understand and address in risk analysis studies during the design, siting, and operation of hydrogen fueling facilities.

1 Introduction

Since there is relatively limited operating experience with hydrogen fueling facilities, and (thankfully) limited experience with incidents involving fires or explosions at such facilities, it is difficult to describe with confidence the risks that may be associated with the larger societal usage of hydrogen as a motor vehicle fuel. One universal expectation is that the hydrogen fueling experience should be comparable to that associated with gasoline fueling. Given the arguably more severe conditions associated with hydrogen fueling (much higher pressure, low ignition energy) relative to gasoline, this may be asking too much. In any case, this paper explores the risks associated with fueling operations to determine where shortcomings in technology, or in knowledge lie.

2 Severity of Hydrogen Explosions

Testing and numerical simulations performed by BakerRisk and others have demonstrated that vapour cloud explosions (VCEs) due to H_2 releases can be more severe than with most other flammable materials (Thomas 2015). H_2 is also more likely than other fuels to undergo a deflagration-to-detonation transition (DDT), which can incorporate a significant amount of energy from parts of the cloud that are outside congested volumes. Testing by BakerRisk, in both unconfined and confined test rigs, has shown that DDTs can occur with lean (i.e., non-optimal) H_2-air mixtures (Thomas 2017, Horn 2018). Numerical evaluations have also been performed to examine the potential for DDTs in ambient vaporizers (Thomas 2018). The potential for explosions due to H_2 jet releases has also been considered (Miller 2015, Jallais 2017). These studies indicate that the hazards/risks of H_2 usage have likely been misunderstood by many, but our understanding is rapidly developing.

One common misperception among some is that diatomic hydrogen, being around 1/15 the molecular weight of air, will simply float away upon release – this may be a case where 'some knowledge' is worse than 'no knowledge'. In fact, jets of high-pressure hydrogen can travel significant distances before dissipating, and buoyancy effects are virtually non-existent by the time the concentration of the released hydrogen in air has been diluted to near its lower explosive limit. Additionally, one needs to account for the potential for hydrogen fueling station infrastructure to confine a potential release (e.g., under large awnings or roofs), which would potentially allow hydrogen to accumulate and participate in an explosion if ignited. In addition, stable clouds could form indoors or outdoors depending on the type (pressurised or cryogenic) and location (above-ground or below-ground) of the storage unit. ISO Standard 19880-1:2016 (ISO 2016) illustrates some of the design options (Figure 1).

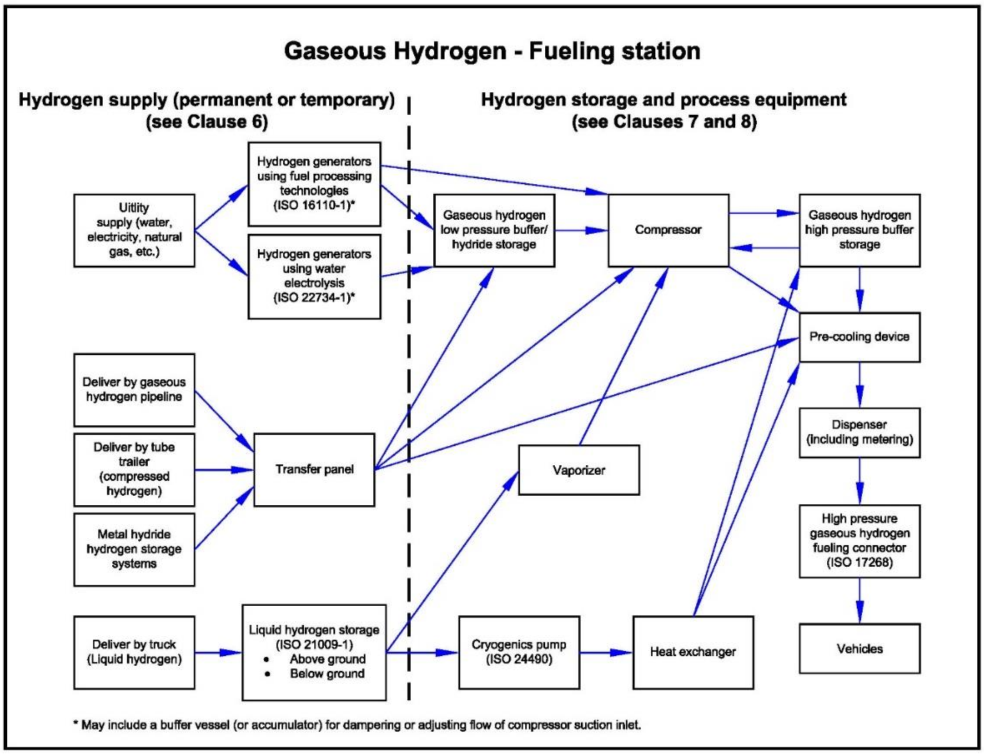

Figure 1. Hydrogen Fueling Infrastructure Options (from ISO 2016)

3 Ignitability of Hydrogen Releases

As ubiquitous as hydrogen is, and given its long history as an industrial chemical, it is remarkable that there is such a divergence of experience and opinion on its ignitability. In researching for a book on estimating ignition probabilities for releases of flammables into the atmosphere (CCPS 2014), industry subject matter experts (SMEs) were solicited for their opinions on a range of hypothetical release/ignition situations. Reasonable agreement was achieved among the SMEs for most fuels. However, in the case of H_2 releases, there was substantial divergence in opinion ranging from near-zero expectation of ignition to 100% ignition probability for the same event (Table 1). A corresponding divergence in ignition probability models was noted by Jallais (Jallais 2010).

Table 1. Example of Variability of Survey Reponses on Probability of Immediate Ignition

Release Conditions	T = 38C (100F), P = 7 barg (100 psig), Hole Diam. = 25 mm (1 inch), Release Duration = 100 sec., Weather = typical daytime, Release into Class I Div.1 area					
Estimated Probability*	**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Expert 6**
Immediate Ignition	0	0.1	0.1	0	0.1	0.1
Delayed Ignition	1	0.75	0.01	1	0.9	0.01

* The total ignition probabilities do not add up to 1 in some cases (i.e., there is a probability of non-ignition)

Mechanisms that have been proposed for igniting H_2 include those listed in Table 2.

Table 2. Hydrogen Ignition Mechanisms

Mechanism	Description
Electrostatic ignition	Ignition due to sparks, brush discharges and corona discharges
Reverse Joule-Thompson effect	Hydrogen is atypical in that its temperature can rise upon depressuring, potentially reaching its autoignition temperature (AIT).
Hot surface ignition	Hydrogen can be ignited by a hot surface, although this requires temperatures substantially higher than the reported AIT.
Diffusion ignition	Ignition of a gas at a temperature well below its AIT has been reported experimentally in a shock tube at high speeds.
Adiabatic compression/turbulence	The equipment geometry at or near the point of release drives compression that results in a shock wave that leads to ignition.

However, even this list may not be exhaustive (Gummer 2008). In addition, these mechanisms are not universally agreed upon, or in some cases may not be significant enough to cause ignition in H_2 fuel applications. This broad span in H_2 ignition probability opinions illustrated in Table 1 suggests that there were underlying factors that led to such varying experiences among the SMEs. In fact, the literature published within the past 15 years (Dryer 2007, Swain 2007, Grune 2011, Hooker 2011) suggests that physical phenomena unique to H_2 releases might reasonably result in these differing experiences. The results of field tests at BakerRisk facilities are consistent with this prior work – namely, that spontaneous ignition of pure hydrogen releases *in a clean environment* requires pressures that are upwards of 20 bar (300 psig).

4 Failure Rates for Commercial Hydrogen Facilities

4.1 Data for Existing Hydrogen Commercial Facilities

Operating History

The operating history of personal vehicle hydrogen refueling stations is limited and constantly increasing. For the purposes of this analysis the following approximations are made:

- There are a total of 500 hydrogen refueling stations in the world (Wikipedia n.d. a).
- The average station has been in operation for 3 years.
- The average station performs 20 fillings per day (7,000 per year) (Kurtz 2019).
- There are 30,000 hydrogen automotive vehicles in the world (Wikipedia n.d. b).
- The average vehicle has been on the road for 2 years.
- The average vehicle is refilled 25 times per year.

Note that one or more of these assumptions are likely significantly in error, therefore the mathematics above and in the following are intentionally fuzzy so as to not give a false impression of accuracy.

In combination, the first three bullets above suggest that there is a history of over 10 million fillings, while the final three bullets suggest a history of only 1.5 million fillings. This illustrates the uncertainty in this calculation, but even this range may not represent the full degree of uncertainty in calculating failure rates. As noted in the next section, there have been two reasonably well-known events at hydrogen filling facilities. These two events occurred in countries that represent perhaps 10% of the worldwide number of hydrogen filling stations. If it happened that those two countries were the only ones whose events were reported in the popular press, that might suggest a failure rate ten times that otherwise expected. Do we necessarily know of events that have happened in all other countries? It is questions such as these that need to be answered in order to arrive at accurate failure rate data – that is, we need to collect data from sources for which both the numerator (number of events) and denominator (number of operating years) are known.

Incident History/Risk

Although there is no certainty to this, BakerRisk is aware of only two prior incidents of hydrogen fueling station fires or explosions: one in Norway and one in California (Nisewanger 2019, Guess 2019, Huang 2019), one of which was a storage failure so may or may not be worthy of inclusion in 'filling' statistics. In combination with the number of fillings that have been performed, this represents a fire probability of one per million fillings (1E-6) – noting that it is not known to BakerRisk whether the events resulted from the filling activity or not. This is contrasted with gasoline filling incidents next.

4.2 Potential Analogs for Commercial Facility Failure Rates

Commercial Gasoline Filling Station Incident History

While thousands of fires occur at commercial gasoline filling stations each year in the U.S., only 50 or so on average are positively identified as being sourced at the fuel tank or fueling line (Ahrens 2020). Most sources in the research are identified, so a significant undercounting of events at those locations is not expected. Considering there are approximately 16 billion refuelings in the U.S. per year (Albert 2013), this yields an extremely low fire probability of about one in 300 million (3E-9) per transfer.

How the incidence of gasoline filling fires would compare to hydrogen filling fires is complicated by many factors, such as:

- The likelihood of gasoline vs. hydrogen filling equipment to release vapors
- The propensity of hydrogen to ignite vs. gasoline.

On the first bullet, there is currently very limited data. Based on molecular size, severity of storage condition (high pressure or cryogenic), and industrial experience there is reason to believe that, all else being equal, hydrogen would leak more easily than gasoline. One presumes that hydrogen storage and filling equipment components are designed to compensate for that tendency.

Regarding the second bullet, hydrogen has a famously low ignition energy compared to gasoline. This, coupled with the potential for static discharge to serve as an ignition source, suggests that ignition probability of a hydrogen filling operation might be significantly greater than gasoline. This is particularly the case for cold climates, where both (a) the humidity is lower, increasing the chance of static formation, and (b) despite warning signs, drivers are more likely to re-enter their car during fueling and generate static by rubbing on the vehicle seats, etc.

Industrial Hydrogen Storage Tanks

For pressurised storage tanks, the literature suggests leak rates of about 1E-4, 3E-5 and 1E-5/year for small, medium, and large/rupture leaks, respectively. For double-walled cryogenic storage tanks, typical values are about an order of magnitude lower. In some cases, a commercial hydrogen storage tank might be more likely to leak than an industrial version, since there might be non-expert users or greater cycling of conditions in the tank. In other cases, a commercial tank could also be argued as being safer, since it is less subject to exposures from other operations that exist at an industrial siting.

Transfer Equipment (loading hose)

BakerRisk has developed its own proprietary approach for estimating the likelihood of a transfer hose failure during a loading operation (in a process plant). This approach considers published failure rates from several sources, then modifies the baseline failure rate by ~ 20 different modifiers that reflect a number of design and operating characteristics. A hydrogen filling station is obviously a different context than a chemical industry loading hose operation, but as an experiment, inputs that were assumed to most closely reflect a hydrogen filling station operation were input to the model. This yielded an estimated failure rate of 1.6E-5/transfer, which is dramatically worse than the experience with gasoline filling stations. It is yet to be determined whether this is a reflection on the inadequacy of the model for a hydrogen filling operation (probably) or somehow reflective of lower expected reliability of commercial hydrogen systems.

4.3 Failure Rate Suggestions from Others

Others have suggested failure rates for hydrogen service. For dispenser failures for example, the following have been proposed:

Table 3: Some Proposed Hydrogen Fueling Dispenser Failure Rates

Failure Mode	RIVM (Timmers 2017)	Sandia (Ehrhart 2021)
Dispenser delivery hose leaks	4E-5/hour	
Dispenser delivery hose breaks and ESD fails	4E-9/hour	
Nozzle pop-off		8.2E-7/filling
Nozzle failure to close		2E-3
Drive-off with hose still attached		5.2E-5/filling
Overpressure during fueling		1.1E-5/filling

These sources provide failure rates for other hydrogen infrastructure as well, although arguably the dispenser failures might be of most interest to society because that is the most likely point of contact with the public.

In any case, the comparison above demonstrates the need to come to an agreement on what failure modes/causes to consider, and whether the failure likelihood for each cause is more dependent on time in service or on number of usages. For example, given that hoses will almost always be restored to a proper storage condition between uses, failures may be more dominated by time (ongoing exposure to weather). On the other hand, one can argue that degradation may result more from repeated pressure cycling than weather, which is presumably a function of the hose design. The issues are not trivial, but they are finite and so should be able to be resolved, given collection of sufficient high-quality data.

5 Summary

This paper presented the major features that should be resolved in order to develop a robust and accurate hydrogen fueling system risk analysis programme, once enough statistically-significant failure data from actual retail refueling facilities become available. This presumes that formal data collection efforts are in place that accurately collect failure and equipment service life data, including failure cause/source information, and that there is reasonable agreement among analysts about the ignitability and impacts of hydrogen releases.

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