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## A Model of Hydrogen Ignition Probability based on Leak Data from Hydrogen Filling Stations

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The probability of ignition of hydrogen leaks is one of the main uncertainties when analysing the risks of hydrogen infrastructure. Several ignition probability models are available, but they are mainly based on judgement and give widely differing results.

To develop an improved model, this paper collects available data on 168 leaks from hydrogen filling stations (HFS) and tube trailer transfer at similar facilities, using incident reports collected from public domain sources. The dataset is dominated by leaks in Japan and the USA, and has only one leak in China and none at all in Germany and South Korea, despite these countries all having large HFS populations. Although there are differences between the data from different countries, the study maximises the dataset by combining all available data.

A new ignition probability model (HFS-2024) is based on this dataset, expressing ignition probability as a function of the hydrogen release rate. The confidence ranges of the data quantify the uncertainty in the new model, as well as validating some previous models in specific release rate ranges, but HFS-2024 provides the best fit to the data over the whole release rate range.

The paper discusses the limitations in the work, which illustrate the need for better data on both ignited and unignited hydrogen leaks. The new approach provides a pathway for updating the model as experience with hydrogen leaks is accumulated.

*Keywords:* Risk assessment, hydrogen filling stations, ignition probabilities.

### 1. Introduction

Hydrogen is easily ignited. Compared to hydrocarbon fuels, hydrogen has extremely wide flammability limits (4-74% in air) and very low energy required for ignition (DOE 2004).

If a hydrogen leak does ignite, it may form an intense jet fire or an explosion, which has the potential to detonate, and is likely to injure people and damage equipment and buildings. Nevertheless, leaks of hydrogen may disperse harmlessly without igniting.

High storage pressures and hydrogen's high speed-of-sound combined with low density mean that leaks typically form high momentum jets

which rapidly expand, creating large gas clouds in the direction of the leak, before buoyancy lifts them and they disperse in the air. Leak detection and automatic shut-down systems aim to isolate the leak, which may therefore last only a few seconds, but an ignitable gas cloud can still be generated. If the leak does not ignite, this is mainly due to lack of ignition sources within the cloud.

Quantitative risk assessments (QRA) of hydrogen infrastructure need to estimate the probability that a given hydrogen leak will ignite. Unlike hydrocarbon fuels, whose ignition probabilities have been studied extensively over

many years, there is little information on hydrogen ignition probabilities. Hydrogen QRAs typically find that the ignition probability is one of the largest uncertainties. Several ignition probability models exist, but they are mainly based on judgement and give widely differing results, as this paper will demonstrate.

There is, therefore, a need for better ignition probability models with a more robust basis, capable of being updated as experience with hydrogen leaks is accumulated. This paper presents such a model (named HFS-2024).

An early version of the model (named HFS-2023) was adopted in guidance for QRA of hydrogen installations in Hong Kong (EMSD 2024). This paper shows that both versions are consistent with the available data for the higher release rates that dominate most QRA results.

## 2. Existing Models

Ignition probability models attempt to predict the probability of ignition of specific leaks, making use of key parameters that influence the probability.

Advanced time-dependent models take account of transient cloud development and reference specific ignition sources in the vicinity. Such models were first developed for hydrogen (Rødsætre & Holmenfjord 2007) based on the time dependent ignition model for hydrocarbon (DNV 1996). This approach is currently being further developed in the SAFEN JIP (Fossan et al 2024). Although time-dependent models are costly to run, they are useful when optimizing ignition control since they can show the benefit of measures such as quicker shutdowns and reduction of ignition sources.

Simple models typically assume the ignition probability depends only on the initial release rate from the leak, and can be specific for different kinds of plants and fluids. Due to their simplicity, the models are quick to run and are therefore widely used. Four such models have been published for hydrogen leaks, known here as HyRAM, IOGP, HYEX and HySafe, as described below

### 2.1. HyRAM

HyRAM is a methodology for QRA of hydrogen infrastructure and transport systems published by Sandia National Laboratories (2022). It uses default ignition probabilities shown in Table 1. It

splits the probabilities into immediate and delayed ignition, modelled as producing jet fires and explosions respectively. They are non-conditional probabilities, so the total ignition probability is the sum of the two. For example, the largest modelled ignition probability (for releases over 6.25 kg/s) for hydrogen is 0.35.

Table 1. HyRAM Ignition Probabilities.

(a) Hydrogen			(b) Methane and Propane		
Release Rate (kg/s)	Ignition Probability		Release Rate (kg/s)	Ignition Probability	
	Immediate	Delayed		Immediate	Delayed
<0.125	0.008	0.004	<1	0.007	0.003
0.125-6.25	0.053	0.027	1-50	0.047	0.023
>6.25	0.230	0.120	>50	0.200	0.100

The original source of the hydrogen values was a QRA of hydrogen production facilities (DNV 2006). In the absence of any data on hydrogen ignition probabilities, this adjusted previous values for methane, which were based on judgements and offshore blowout data (Cox Lees & Ang 1990). It increased ignition probabilities by 16%, because of hydrogen's wider flammable range, and reduced the flow rate by a factor of 8, because its lower molecular weight directly affects the cloud size. The split between immediate ignition (67%) and delayed ignition (33%) was taken from methane and applied to all sizes of hydrogen leaks. In other words, this is a judgemental adjustment of an established model for hydrocarbons.

The step function in the HyRAM model is not realistic, especially near the steps (0.125 and 6.25 kg/s) but has the merit of providing ignition probabilities that are readily traced to their source. Despite its lack of calibration by any hydrogen data, the HyRAM model has been widely used, and informed standards such as NFPA 2 and ISO 19880-1.

### 2.2. IOGP

The International Association of Oil & Gas Producers (IOGP) published a Risk Assessment Data Directory for QRAs of oil & gas installations. It included ignition probabilities as functions of release rate for various scenarios, of which the most similar to small hydrogen installations is a small LPG plant (Scenario 5). For hydrogen, IOGP suggests doubling the ignition probabilities up to a maximum of 1 (IOGP 2019).

### 2.3. HYEX

The Norwegian Directorate for Civil Protection (DSB) published guidelines for QRA of facilities handling hazardous substances in Norway (Vysus 2021). DSB recommends an ignition model called HYEX, which is based on a factor of 3 increase of IOGP probabilities for methane in offshore platforms (Scenario 21) below 0.125 kg/s, increasing to 1 above 12.5 kg/s. It has the same split as HyRAM between immediate and delayed ignition, and immediate is interpreted as within 1 s (Aarskog et al 2020).

### 2.4. HySafe

The International Association for Hydrogen Safety (HySafe) published an ignition probability model for hydrogen, which is based on the IOGP probabilities for large LPG plants (Scenario 8) modified by the DNV method used for HyRAM. It has the same split as HyRAM between immediate and delayed ignition (Guzzetta-King et al 2023).

### 2.5. Comparison of existing models

Figure 1 compares the existing models. While they show similar trends, they vary over more than an order of magnitude. The differences reflect differing judgements about the difference between hydrogen and hydrocarbon gases, and the best way to model the trend with release rate.

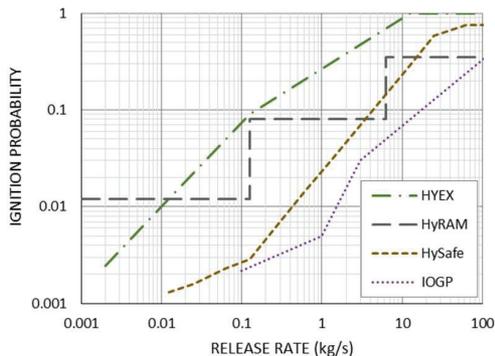


Fig. 1. Existing Hydrogen Ignition Probability Models

## 3. Data Collection

To provide a better basis for an ignition probability model, this study has collected reports of actual hydrogen leaks that identify whether or not they were ignited.

Hydrogen facilities vary widely, so to provide a broadly consistent release environment the study focusses on leaks of gaseous hydrogen from hydrogen filling stations (HFS). These are facilities that refill the on-board fuel tanks of hydrogen fuel cell vehicles. They are typically replenished by hydrogen tube trailers or on-site hydrogen generation.

To increase the dataset, the study includes leaks from tube trailers during transfer operations at three similar types of facility:

- Filling tube trailers at hydrogen production facilities.
- Transfer filling of tube trailers with gaseous hydrogen from liquid hydrogen tank trucks.
- Unloading tube trailers at consumer sites, typically industrial plants.

Ideally, the dataset should include a large and comprehensive collection of hydrogen leaks. Each incident should be thoroughly documented and openly published. In reality, few authorities have shared incident experience, and incident reports rarely estimate the release rate or identify the ignition source. Therefore, this study collects leak incidents that are currently reported in the public domain, and estimates the relevant parameters such as release rate from the available descriptions. The resulting uncertainties and biases in this approach are considered below.

### 3.1. Data sources

The study uses the following sources:

- The Hydrogen Incidents and Accidents Database (HIAD) database. This includes 706 incidents involving hydrogen during 1937-2021 (Wen et al 2022), of which 8 were leaks from HFS and tube trailer transfer.
- The Hydrogen Lessons Learned (H2LL) database. This includes 221 incidents involving hydrogen during 1969-2019 (H2Tools 2024), of which 16 were leaks from HFS and tube trailer transfer.
- The hazmat incidents database collected by the US Pipeline and Hazardous Materials Safety Administration (PHMSA 2024). This includes 105 compressed hydrogen incidents in highway transportation during 1971-2024, of which 11 were leaks during tube trailer transfer.

- The gas incidents database collected by the High Pressure Gas Safety Institute of Japan (KHK 2024). This includes 752 hydrogen incidents during 1963-2023. Because incidents in 2022-23 are mostly still under investigation, this analysis only uses 133 leaks from HFS and tube trailer transfer up to 2021.
- The Major Hazard Incident Data Service (MHIDAS) collected by UK Health & Safety Executive. This includes 116 incidents involving hydrogen during 1959-2005, of which 2 were leaks during tube trailer transfer.

**3.2. Selected dataset**

Table 2 summarises the numbers of incidents from each country. They occurred between 1967 and 2021. Most incidents were from Japan and the USA. This is partly as expected, since these were two of the five countries with most HFS (Samsun 2020), but the lack of reports from the other three, Germany, China and South Korea, highlights the inconsistencies in reporting.

Table 2. Summary of Selected Leak Dataset.

Country	Leaks	Ignited	Ignited proportion
Japan	133	3	2%
USA	27	12	44%
UK	2	0	0%
France	2	0	0%
Norway	2	1	50%
Switzerland	1	1	100%
China	1	1	100%
Total	168	18	11%

Table 2 also shows the proportion of events that ignited in each country. The differences are partly due to the small numbers of events, but also reflect the different reporting levels in each country. Japan has the most comprehensive reporting, including many pinhole leaks. The USA has reported fewer leaks, but the high proportion of ignited events suggests many more unignited ones may have occurred without being reported.

**4. Ignition Probability Model**

At its simplest, given a dataset of N leak events, of which F have ignited (including both fires and

explosions), the ignition probability (P) can be estimated as:

$$P = F/N$$

Different datasets will vary for random reasons, yielding different probability estimates. So the ignition probability is better conceived as a probability distribution, bounded between 0 and 1, which converges on P as the dataset grows. The simplest and most commonly used is a beta distribution, which is defined by two parameters,  $\alpha=F$  and  $\beta=N-F$ .

To handle cases where no events have ignited (and also the uninformative starting case with no data at all), the beta distribution parameters are adjusted to  $\alpha=F+1$  and  $\beta=N-F+1$ , which in effect assumes that one of the next two events will ignite.

The best estimate of the ignition probability is the 50%ile of the beta distribution, which is shown on Figures 2-8 below. The uncertainty can be expressed as the interval between the 5%ile and 95%ile of the distribution, also shown on Figures 2-8.

**4.1. Release parameters**

To explore which parameters affect the ignition probability, the leak events are segmented into groups based on the release rate, release duration and release quantity. Segmenting a small dataset in this way inevitably increases the uncertainties in each group, so only 3 groups are used for each parameter.

For example, release rate groups, based on the initial flow rate (defined as the mass released in the first second) through the leak, are:

- Pinhole: <0.01 kg/s
- Small: 0.01-1 kg/s
- Large: >1 kg/s

Some leak reports estimate these parameters. In other cases, they can be estimated using assumptions about typical inventories and equipment sizes. Where there is no better information, they are grouped using judgement based on the available descriptions, as follows:

- Pinhole leaks typically result from loose screw connections or worn seals. They are usually revealed by hydrogen detectors, and it may be difficult to find the leak location. They are not normally modelled in QRAs.

- Small leaks may result from cracks in equipment or damaged seals. They may be detected by abnormal noise or pressure drop in the leaking equipment. The release rate bands above also include some flows through pressure relief devices.
- Large leaks result from major damage such as sheared valve or pipe connections. They involve rapid depressurisation of the leaking equipment, and the source of the leak is readily apparent.

This judgemental interpretation is one of the main limitations of the study and better leak descriptions would greatly improve it.

**4.2.Effect of release rate**

Figure 2 shows the effect of release rate on ignition probability. There are significant differences between the three groups, confirming the importance of release rate for the model.

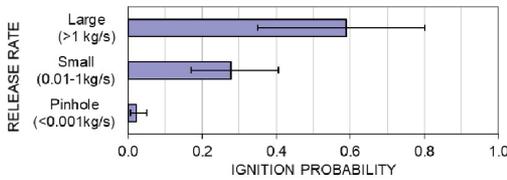


Fig. 2. Effect of Release Rate

These results show that the overall ignition probability in any dataset depends strongly on proportion of small and pinhole leaks within it. This partly explains why Table 2 shows a low ignition proportion for Japan, which reports mainly small and pinhole leaks, but a higher proportion for the USA, which reports mainly small and large leaks. However, even after splitting the data into release rate groups, substantial differences remain between Japan and other countries (Figure 3).

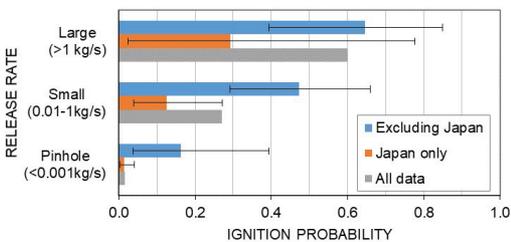


Fig. 3. Effect of Release Rate and Country

**4.3.Effect of other release parameters**

Since the relationship between hole size and release rate depends only on pressure, which is similar at many hydrogen facilities, the effect of hole size is virtually identical to the effect of release rate.

Short duration leaks have significantly lower ignition probability than medium or long ones. Figure 4 shows the combined effect of release rate and duration. This suggests that a model combining release rate and duration might be preferable.

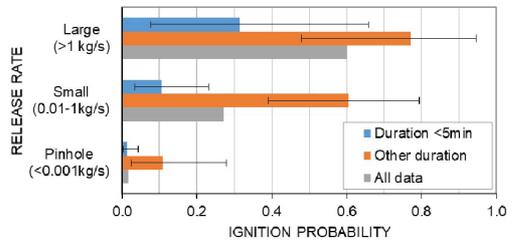


Fig. 4. Effect of Release Rate and Duration

Release quantity provides a simple combination of release rate and duration. Figure 5 shows the effect of release quantity on ignition probability. This is similar to the effect of release rate. The quality of information on release quantity is somewhat better than release rate, because it is reported explicitly in the data from Japan.

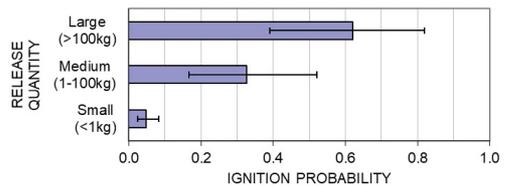


Fig. 5. Effect of Release Quantity

Overall, while the data confirms that release rate strongly affects the ignition probability, supporting its use for a simple ignition model, a model combining release rate and duration might be preferable.

**4.4.Effect of facility type**

The dataset includes different environments. Figure 6 shows the ignition probabilities for HFS are lower than for tube trailer transfer at other types of facility. This is surprising since ignition control should be better at industrial facilities. It

could be due to better reporting of unignited leaks at HFS, or because HFS are relatively new and designed to better standards. Further data collection might allow the model to distinguish different types of facility, but at present the combined dataset is used.

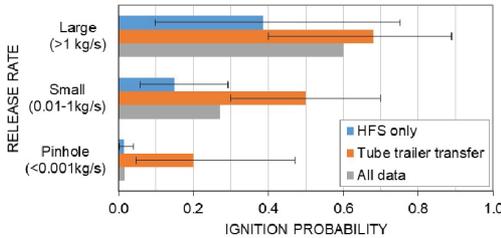


Fig. 6. Effect of Release Rate and Facility Type

**4.5. Model development**

To convert the segmented data into a model, the release rate groups are expressed as average release rates, using the events in which the actual release rate is known or can be estimated. For pinholes, the release rate is available for 12 out of 121 incidents, with a mean of 0.005 kg/s. For small leaks, the release rate is available for 19 out of 37 incidents, with a mean of 0.2 kg/s. For large leaks, the release rate is available for 9 out of 10 incidents, with a mean of 2 kg/s.

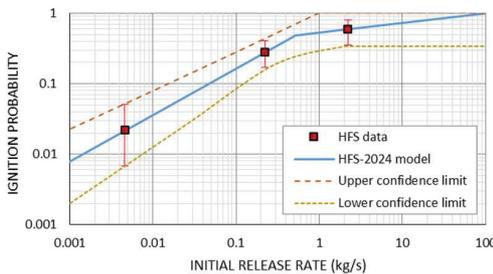


Fig. 7. Modelled Effect of Release Rate

Figure 7 shows the data plotted at these release rates, using log scales to expand the small probabilities. The confidence intervals refer only to random effects due to limited dataset sizes, and do not include other data limitations.

The data can be represented by a model (named HFS-2024) expressing ignition probability (P) as a function of the initial release rate (Q in kg/s) as follows:

$$P = 0.75 Q^{0.66} \text{ for } Q < 0.51 \text{ kg/s}$$

$$P = 0.53 Q^{0.14} \text{ for } 0.51 < Q < 100 \text{ kg/s}$$

$$P = 1 \text{ for } Q > 100 \text{ kg/s}$$

This updates an earlier version of the model (named HFS-2023), which was expressed as:

$$P = 0.4 Q^{0.2} \text{ up to a maximum of } 1.0$$

HFS-2023 was used in a QRA of hydrogen vehicles and infrastructure in Hong Kong, and is recommended in associated QRA guidance (EMSD 2024). HFS-2023 was based on an earlier collection of 42 leaks, which is now updated and expanded in HFS-2024.

**4.6. Comparison with existing models**

Figure 8 compares HFS-2024 with the previous models. The confidence intervals of the data validate HYEX above 2 kg/s and HFS-2023 above 0.1 kg/s, but HFS-2024 is the only model that matches the data over the whole release rate range.

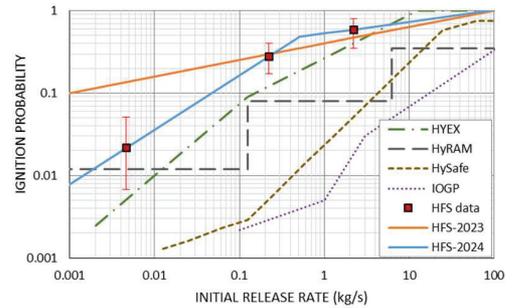


Fig. 8. Comparison of Ignition Probability Models

**4.7. Ignition delay model**

The results above all refer to the total probability of ignition given a hydrogen leak. QRAs typically distinguish immediate and delayed ignition because immediate ignition is assumed to produce a jet fire while only delayed ignition has the potential for an explosion.

Hydrogen incident reports rarely identify the ignition delay. Only two cases in the dataset indicated the time of ignition. Both ignited a few seconds after the start of the release and exploded, indicating they should be counted as delayed ignitions.

In the absence of better data, one way of estimating the conditional probability of delayed

ignition is to use the available descriptions of the ignited leaks. Where they were described as explosions, or where blast damage occurred, they can be inferred to be delayed ignition. Where they were described only as fires, they are assumed to be early ignitions.

Among the 18 ignited leaks in the dataset, 8 were described as explosions. Using a beta distribution approach, as above, the conditional probability of delayed ignition could be estimated as 0.45 with a confidence interval from 0.27 to 0.63. This may be over-precise because the reports for several of the events are anecdotal. Among the 6 ignited large leaks, 4 were described as explosions, but there is no simple trend with release rate.

For the HFS-2024 model, the conditional delay probability is taken as 50%, i.e. a split between immediate and delayed ignition of 1:1. This is the same as HFS-2023, but different to HyRAM and HYEX, which assume a conditional delay probability of 33%, i.e. a split between immediate and delayed ignition of 2:1.

When combined with the ignition probability model, it gives large differences in explosion probability. For a 2 kg/s leak, the explosion probability from HFS-2024 is  $0.58 \times 0.5 = 29\%$ , whereas HYEX gives 18% and HyRAM 12% (Table 1). The main reason for the difference is that earlier models were based on judgemental adjustment of offshore hydrocarbon ignition probabilities, whereas the present model is based on hydrogen data. Although the relatively large observed explosion probability could result from under-reporting of unignited leaks, it could also be due to the limited use of EX-rated equipment and high confinement in many of the hydrogen installations that have been built.

#### **4.8. Data limitations**

The data collection in this study has several limitations. The most important is that it comprises incident reports collected by the authors from public domain sources. Hence, it omits leaks that have not been reported by HFS operators, leaks that have been reported but not published by regulators or industry bodies, and leak reports that are published but have not come to the attention of the authors.

The selected dataset is dominated by leaks in Japan and the USA, and has only one leak from China and none from Germany and South Korea,

despite these countries all having large HFS populations.

This would not be critical for estimating ignition probabilities if the dataset was a random sample of the leaks that occur. Unfortunately, the reports are not simply incomplete but also biased towards certain types of events. Under-reporting is more likely for unignited leaks. The main aim of HIAD and H2LL is sharing lessons learned, and hence they focus on incidents with clear lessons, which tend to be ignited leaks. Hence there may be a bias in the data tending to over-estimate ignition probabilities.

A second limitation is that extracting relevant incidents from the available databases is not an exact science. The data sources do not clearly identify which incidents occurred at HFS or tube trailer transfer. The KHK database is in Japanese, and the translation into English may have misrepresented some events. The available descriptions are often unclear and require judgement about whether or not they should be included.

Another important limitation is that most of the selected accident reports do not include parameters such as release rate, so assumptions are required to group the release rates.

#### **4.9. Uncertainty in the model**

Probabilities estimated from data samples are inevitably uncertain, reflecting the random variation in incidents and the limited size of the dataset. These uncertainties are quantified in confidence intervals.

Additional uncertainty arises as a consequence of the data limitations above. While it is usually clear whether the release ignited or not, the estimation of release rate is uncertain and allocation into release rate groups is judgemental for many of the incidents.

The fitting of a model to the data is judgemental, as many different models could fit within the confidence intervals, even without considering the additional uncertainties above. The model has a change of slope at 0.5 kg/s, which allows it to pass through the best estimates of all three release rate groups. However, a simpler model without this discontinuity, passing within the confidence ranges, could also have been used.

The choice of release rate as the sole parameter in the model is influenced by the fact

that the previous models used this form. While the dataset supports this, it shows that release quantity or a combination of release rate and duration would also have been good choices.

## 6. Conclusions

This study has collected available data on 168 leaks from hydrogen filling stations and tube trailer transfer at similar facilities, and analysed them to develop an ignition probability model.

The data can be represented by a model (named HFS-2024) expressing ignition probability (P) as a function of the initial release rate (Q in kg/s) as follows:

$$P = \text{Minimum} (1.0; 0.53 Q^{0.14}; 0.75 Q^{0.66})$$

The conditional delay probability is taken as 50%, i.e. a split between immediate and delayed ignition of 1:1.

At present, the model may be somewhat biased towards over-estimating the ignition probability for large release rates. More open reporting of non-ignited incidents would be desirable to correct this. However, the uncertainties are large, and future models based on better data could be much higher or lower.

This study illustrates the need for better data on both ignited and unignited hydrogen leaks, and provides a pathway for updating the model as experience with hydrogen leaks is accumulated.

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