ESTABLISHING THE STATE OF THE ART FOR THE DEFINITION OF SAFETY DISTANCES FOR HYDROGEN REFUELLING STATIONS

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ABSTRACT

Hydrogen is widely considered a clean source of energy from the viewpoint of reduction in carbon dioxide emissions, as a countermeasure against global warming and air pollution. Various efforts have been made to develop hydrogen as a viable energy carrier, including the implementation of fuel cell vehicles (FCVs) and hydrogen refuelling stations (HRSs). A good network of hydrogen refuelling stations is essential for operating FCVs, and several hydrogen refuelling stations have been constructed and are in operation worldwide [1]. However, despite the potential benefits of hydrogen, its flammability creates significant safety concerns. Furthermore, even though the energy density of hydrogen is lower than that of gasoline and there is no carbon present, which means the amount of radiant heat flux released during combustion is relatively small, hydrogen must be handled at high pressure in order to make the cruising range of a fuel cell vehicle (FCV) equal to that of gasoline-powered vehicles. Therefore, it is essential to properly evaluate these safety concerns and take reasonable and effective countermeasures.

Approximately 50 accidents and incidents involving HRSs have been reported globally [2]. Sakamoto et al. [2] analysed accidents and incidents at HRSs in Japan and the USA to identify the safety issues. Most types of accidents and incidents are small leakages of hydrogen, but some have led to serious consequences, such as fire and explosion. Recently, there was a serious incident in Norway at Kjørbo, where a strong explosion was observed [3] – indeed this was within a short time of two other serious incidents in the USA and South Korea showing that the frequency of such incidents may be higher as deployments increase. Use of hydrogen forklifts (and the associated refuelling infrastructure) is another challenge to consider.

Hydrogen refuelling stations are often installed in urban areas facing roads and are readily accessible to everyone. Therefore, a key measure to approve the hydrogen refuelling stations is safety distances between the hydrogen infrastructure and the surrounding structures such as office buildings or residential dwellings. Whilst a lot of work has been carried out on safety distances (see e.g. [4-6), the accident scenario assumptions and safety distances varied widely in those studies. As a result, no consensus has yet emerged on the safety distances to be used and efforts are still needed to bridge the gap between international standards and local regulations (see e.g. [7-8]).

The paper analyses this issue and provides guidance on the way forward.

1.0 INTRODUCTION

The possibility of using hydrogen as an energy carrier has increasingly caught interest of both public and government policy makers in recent times primarily due to the growth in global awareness about the impact of greenhouse gases and also the finite nature of fossil fuel reserves. Hydrogen is widely considered a clean source of energy from the viewpoint of reduction in carbon dioxide emissions, as a countermeasure against global warming and air pollution, and this makes the deployment of hydrogen in combination with renewable energy sources and possibly nuclear energy an interesting alternative.

Various efforts have been made to develop hydrogen as a viable energy carrier, including the implementation of fuel cell vehicles (FCVs) and hydrogen refuelling stations (HRSs). A good network of hydrogen refuelling stations is essential for operating FCVs, and several hydrogen refuelling stations have been constructed and are in operation worldwide [1].

However, despite the potential benefits of using hydrogen as an energy carrier, the safety of hydrogen during production, and in particular application remains a significant concern. The hazards from hydrogen primarily stem from its wide flammability range (4 – 75% in air), low ignition energy, extremely fast burning rate (order of magnitude larger compared to natural gas), and the considerable amount of energy released when it burns or explodes. Hydrogen is also quite different from natural gas in certain other ways, some of which actually help to reduce the risk of using the gas. Hydrogen is much lighter than air (factor of 8 lighter compared to natural gas) and therefore, has very strong buoyancy that will quickly remove the gas in an unconfined situation. However, much lower energies are needed to ignite hydrogen and mitigation methods traditionally used for natural gas seldom work in case of H_2.

Furthermore, even though the energy density of hydrogen is lower than that of gasoline, which means the amount of radiant heat flux released during combustion is relatively small, hydrogen must be handled at high pressure in order to make the cruising range of a fuel cell vehicle (FCV) equal to that of gasoline-powered vehicles. Also, hydrogen burns with a high-temperature and high-radiation but invisible flame, making it difficult to detect. Another way of increasing hydrogen's energy density is to use it in a liquified form (LH_2). This has different safety challenges as once a loss of containment incident happens and LH_2 is released, it could be extremely dangerous. This is because the storage temperature of liquid hydrogen is 20 K, but the liquid will undergo a rapid phase change, and then transform into the gas cloud because of great temperature difference, which can then disperse to form a flammable and explosive cloud, especially in an unsteady atmospheric environment.

Also, owing to its small molecular size, hydrogen can damage the material of construction of storage containers, piping, valves, and other equipment through the mechanism of embrittlement which can lead to leakage.

Another key issue with hydrogen is its propensity for transition to detonation (possible in concentrations ranging from 10 – 60% in air) which can cause far more damaging consequences than a deflagration. It is also much more challenging to 'arrest' hydrogen flames and explosions, particularly in closed environments. Therefore, it is essential to properly evaluate these safety concerns and take reasonable and effective countermeasures.

Approximately 50 accidents and incidents involving HRSs have been reported globally [2]. Sakamoto et al. [2] analysed accidents and incidents at HRSs in Japan and the USA to identify the safety issues. Most types of accidents and incidents are small leakages of hydrogen, but some have led to serious consequences, such as fire and explosion. Recently, there was a serious incident in Norway at Kjørbo, where a strong explosion was observed [3] – indeed this was within a short time of two other serious incidents in the USA and South Korea showing that the frequency of such incidents may be higher as deployments increase. Use of hydrogen forklifts (and the associated refuelling infrastructure) is another challenge to consider. These recent Hydrogen Refuelling Station (HRS) accidents confirm the need for improved design of these facilities to further facilitate the commercialization of a Hydrogen economy.

Furthermore, hydrogen refuelling stations are often installed in urban areas facing roads and are readily accessible to everyone. Therefore, a key measure to approve the hydrogen refuelling stations is safety distances between the hydrogen infrastructure and the surrounding structures such as office buildings or residential dwellings. Hydrogen safety distances (also referred to in the literature as separation distances) can be defined as the minimum distances separating specific targets (e.g., people, structures, or equipment) from the consequences of potential accidents related to the operation of a hydrogen facility such as a refuelling station. Safety distances are also used to reduce the potential that a minor accident at one portion of a facility propagates to another part of the facility thus exacerbating the resulting consequences. It should be noted that whilst specified safety distances may not provide protection against all potential accidents, they generally should address likely events initiated by a hazard located on the facility and by external hazards. The latter case implies that safety distances can be two-way measures that protect adjacent structures from the hazards of the facility and also protect the facility against the hazards from adjoining facilities. Properly designated safety distances will result in acceptable levels of risk to both the public and workers from potential accidents at a hydrogen facility.

Whilst a lot of work has been carried out on safety distances (see e.g. [4-6), the accident scenario assumptions and safety distances varied widely in those studies. As a result, no consensus has yet emerged on the safety distances to be used and efforts are still needed to bridge the gap between international standards and local regulations (see e.g. [7-8]).

The paper analyses this issue and provides guidance on the way forward.

2.0 CURRENT STATUS

Codes and standards applicable to hydrogen facilities such as refuelling stations are currently developed by a various standards and code development organizations (SDOs / CDOs) including the National Fire Protection Association (NFPA), American Society of Mechanical Engineers (ASME), Compressed Gas Association (CGA), Underwriters Laboratories (UL), European Industrial Gases Association (EIGA), Society of Automotive Engineers (SAE), International Organization for Standardization (ISO), and the International Code Council (ICC), among others. When such codes and standards are adopted by governmental authorities, they become regulations, and compliance with them is widely accepted as evidence of a safe design.

However, there are several barriers for harmonisation of these codes and standards across the globe. These include, but are not limited to:

- Limited government influence on codes and standards
- Competition among SDOs and CDOs
- Large number of local government jurisdictions
- Inadequate representation of a certain SDO / CDO at international forums
- International competitiveness
- Conflicts between domestic and international standards
- Lack of consensus on codes and Standards
- Lack of Sustained Industry Support at International Technical Committees
- Competition in Sales of Published Standards
- Jurisdictional Legacy Issues
- Insufficient Technical Data to Revise Standards

Various codes and standards have been developed to support the design of HRSs such as the NFPA 2, Hydrogen technologies code by National Fire Protection Association [9] and SAE J2601 standard by Society of Automotive Engineering [10] as well as the ISO IS 19880-1 [11].

A review has been carried out on the studies that have been performed in this area. The search method used the following main threads:

- Conversation and un-structured interviews with authors' professional networks to determine known relevant standards, guidance, papers and established practice that is regularly used;
- Bibliography searches to identify relevant freely available standards, or reference text books regularly used within the community;
- Paper searches on the International Hydrogen Safety Conference Sites for the years 2005 to 2019;
- Review of the Fire and Blast Information Group (FABIG) repository
- Paper searches on Elsevier/Sciencedirect using the following search terms

The items were reviewed at a high level to ensure their relevance and to identify common themes arising from the assessment.

Due to the barriers described above, the separation or safety distances can vary from one code or standard to another and it is unclear how they should be used in a global setting. Whilst a lot of work has been carried out on safety distances (see e.g. [4-6), the accident scenario assumptions and safety distances varied widely in those studies. As a result, no consensus has yet emerged on the safety distances to be used and efforts are still needed to bridge the gap between international standards and local regulations (see e.g. [7-8]).This can create a problem for the approval of hydrogen refuelling stations and other related infrastructure [9-10].

Further, there is often additional discrepancy in how safety distances may be specified. For instance, in some cases, the safety distance values may be constant whilst in other cases they could be a function of the hydrogen storage pressure. The latter is much more realistic and a blanket specification of safety distances should be avoided.

For instance, LaChance [12] provides an example of separation distances based on one possible consequence of a hydrogen leakage event: the radiant heat flux from an ignited hydrogen jet. It was shown that the required safety distances required to limit the exposure of a person to a radiant heat flux of 1.6 kW/m^2, which is generally accepted as a level that will not result in harm to an individual even for long exposures, are significantly affected by the pressure of the hydrogen gas and the leak diameter. This suggests that the gas storage pressure is an important parameter that should be considered when specifying safety distances and that the selection of a specified leak size and orientation is critical in determining the separation distances.

3.0 DETERMINISTIC VS RISK-BASED APPROACH

In many situations, even this 'deterministic' approach is not robust enough as it may lead to 'incorrect' safety measures to be specified or inappropriate (either too large or insufficient) safety distances to be chosen. A discussion on why such an approach is much more consistent and robust is given below (for a non-hydrogen application, but it is equally relevant). Let us consider an offshore module which is open on three sides. The weather deck as well as the cellar deck is plated and the design question is whether the mezzanine deck should be plated or grated, see Figure 1.

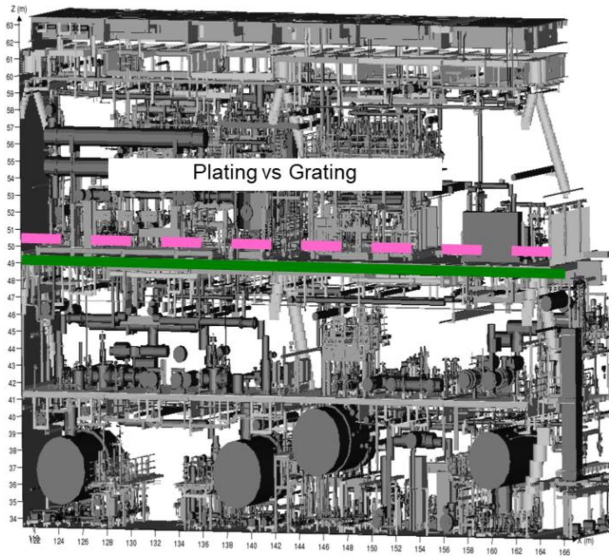

Figure 1. An offshore module open on three sides

Based on physical considerations, the effect of choosing a grated or plated deck will affect each of the following:

- Ventilation will be improved
- Flow pattern will be altered in the case of a release, and may lead to the 'ingress' of any gas cloud formed into the neighbouring deck area for a grated deck
- Explosion load will be higher for a plated deck as venting of explosion overpressure will be

limited by the plated deck

Due to all these considerations, the study is quite complex and it is not straightforward to ascertain the effect on explosion risk for this design choice.

On a deterministic level, one may simply consider the explosion overpressure as a function of cloud size and compare it for the two configurations. The result of this comparison may appear as, see Figure 2a. It is evident that the explosion loads are higher for a ‘plated deck’ configuration, especially for larger cloud sizes. However, this deterministic analysis does not provide the full story as we have no estimate of what the ‘chances’ are of generating the different gas cloud sizes. This can be done using a probabilistic assessment taking into account the leak frequency and the ignition probability. Due to the considerations described above, it is seen here that the frequency of larger cloud sizes is considerably larger for the ‘grated deck’ configuration, see Figure 2b. A full picture of the risk-based explosion load can be obtained by combining the two sets of data in Figures 2a and 2b. This is presented in Figure 2c. This shows that the ‘grated deck’ configuration leads to significantly higher dimensioning load. For this installation, it is shown that the effect of increased cloud size was far more significant than the other effects (improved ventilation, improved pressure relief). It should be noted that conclusions of this type are usually geometry/installation specific and cannot be generalized. For instance, if the area is well ventilated (for example due to the process area being located in area with more wind) the relative effect of the grating would be significantly lower.

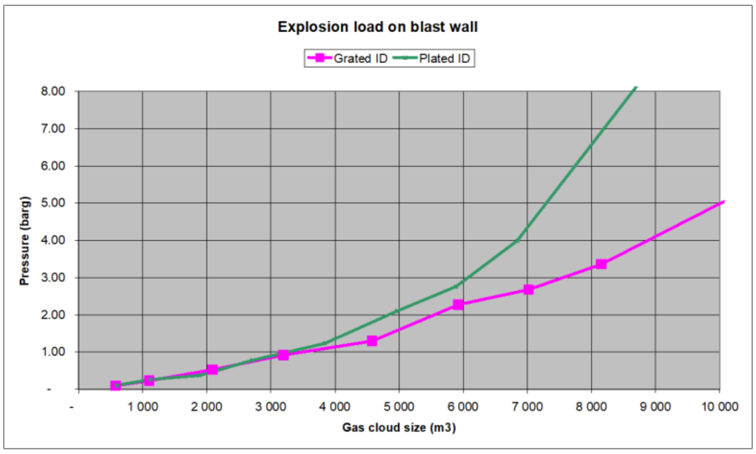

Figure 2a. Explosion load as a function of cloud size for the two deck configurations for the offshore module considered

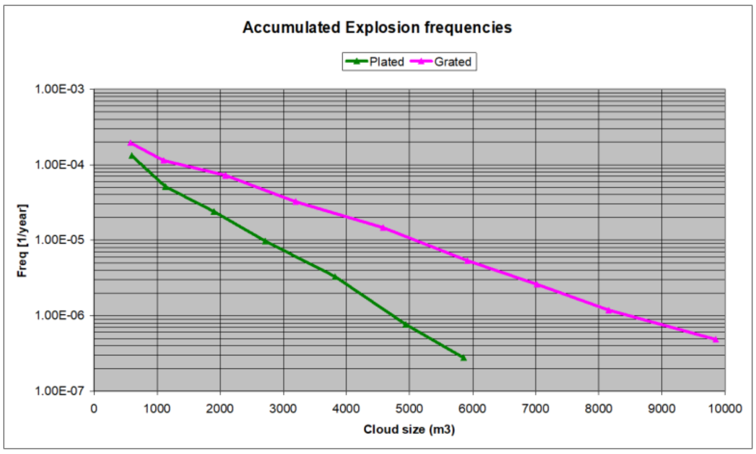

Figure 2b. Frequency of generating a certain cloud size for the two deck configurations for the offshore module considered

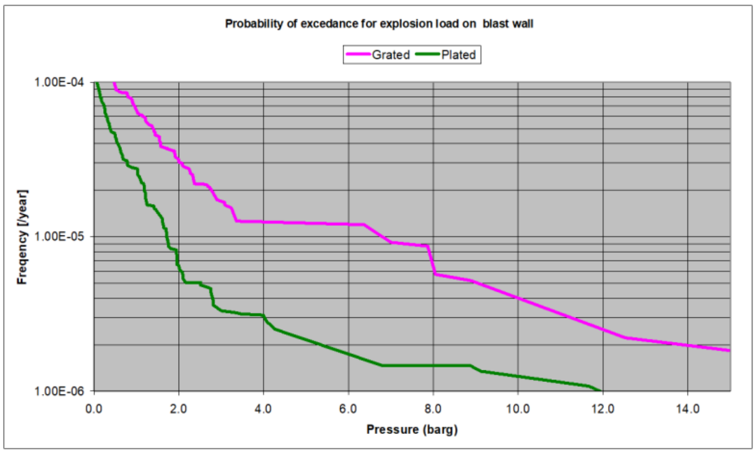

Figure 2c. Overpressure exceedance curve for the two deck configurations for the offshore module considered

Therefore, an alternative approach to establish safety distances for a hydrogen facility involves the use of the estimated risk associated with the operation of the facility. The risk from the operation of a facility is the product of the frequency and consequences of all credible accidents and can be estimated using a quantitative risk assessment (QRA). Credible scenarios should be selected and modelled using appropriate tools and utilized to establish the safety distances. In this risk-informed approach, the estimated risk for the facility is compared to an acceptable risk level to provide a basis for eliminating low risk scenarios from consideration in the determination of safety distances. A consequence of this approach is that the established safety distances will present some residual level of risk that must be acceptable by affected stake holders (i.e., the public, regulators, and facility operators). That level of risk is determined by the selected consequence measures and risk threshold used in the risk-informed evaluation. An additional benefit from the risk-based analysis is that key risk drivers are identified and potential accident prevention and mitigation strategies to them can be identified and possibly specified as requirements in the codes and standards.

Based on this risk-based approach, the following steps could be considered to produce an estimate of safety distances for a hydrogen facility such as an HRS:

1. Select key system characteristics or parameters that fundamentally determine actual risk impact.
2. Based on these characteristics or parameters, divide the system into categories with a roughly similar risk impact, and to which a single set of safety distance requirements can therefore apply. Category limits should be defined considering the different families of equipment actually used (e.g., 35 MPa vs. 70 MPa fuelling systems, where pressure is an identified risk factor)
3. Use the appropriate risk criteria.
4. Populate the safety distance data and evaluate the result against the following criteria:
   a) the safety distances need to achieve their objective with regards to the total risk
   b) integrating all the forms of escalation that should be considered, not only the phenomena covered by the formula selected for application in the risk model

The safety distance figures need to evolve consistently and regularly as the total risk changes. Adjustment to the definition of the categories or to the evaluation of the distance may be required to achieve these objectives through an iterative process. Risk based approaches such as those presented in [12] and [13] are therefore preferred.

This has led to the development of tools such as HyRAM (see e.g. [14]). HyRAM is a comprehensive methodology and accompanying software toolkit for assessing the safety of hydrogen fueling and storage infrastructure. It can be used to perform quantitative risk assessment (QRA) with integrated consequence analysis and/or run deterministic consequence models in stand-alone fashion. The HyRAM software toolkit provides a consistent, documented methodology for QRA with integrated reduced-order physical models that have been validated for use in hydrogen systems.

It should however be noted that there are still some differences in safety distance approaches, even if only risk-based approaches are considered (see e.g. [7]). Therefore, each analysis should be carried out at its own merits using the system geometry and data and the most appropriate analysis techniques.

4.0 ASSESSMENT METHODOLOGIES AND EXAMPLES

In recent years, CFD has been increasingly used to perform quantitative risk assessments, especially in the oil and gas industry, involving ventilation, dispersion and explosion calculations. Based on predicted consequences of a range of potential accident scenarios a risk level is predicted. In the authors' view, this is indeed the correct approach as CFD analysis is able to capture the inherent physics and the complex interactions between the HRS geometry, fluid flow and combustion and help us obtain robust results such as those presented in Section 3.0.

However, hydrogen risk is handled very differently at the present time. CFD is used only occasionally, and mainly for worst-case evaluations. We must accept that it is not realistic to perform an extensive risk assessment similar to what is done for large petrochemical installations for most applications. On the other hand, simplified methods may have a questionable validity for hydrogen. Therefore, a comprehensive procedure for risk assessment of hydrogen applications considering its most important objects should be used and this in turn should form the basis for defining risk-based safety distances. Various levels of treatment, ranging from analysing the worst-case scenario to a comprehensive study including ventilation, dispersion and explosion, to evaluate the probability for unacceptable events is considered.

However, we need to be very careful before applying a CFD tool to carry out such risk assessments. The tool needs to be well validated against a range of relevant experiments. Empirical methods and guidelines can also be acceptable to replace certain calculations, provided these are consistently conservative compared to the validated CFD-tool. Another requirement for carrying out accurate risk assessments is the need to model numerous scenarios. Therefore, the CFD tool must enable efficient definition of scenarios and have moderate calculation times. Based on CFD calculations, a typical risk assessment procedure (for hydrogen explosions) can be summarized as follows [15]:

Step 1: Worst-case assessment (3-5 calculations)

- Explode the worst credible scenario (full stoichiometric cloud?); evaluate the consequences
- If the consequences are unacceptable, evaluate modifications of design or mitigation methods (or go to Step 2)

Step 2: "Realistic worst-case" assessment (20-30 calculations)

- Simulate releases with ventilation and estimate worst-case "realistic" flammable cloud
- Explode this scenario and evaluate the consequences
- If the consequences are unacceptable, evaluate modifications of design or mitigation methods (or go to Step 3)

Step 3: Probabilistic risk assessment (100-200 calculations)

- Simulate a range of releases and ventilation conditions, and establish cloud size distribution
- Simulate explosions with the various cloud sizes, and evaluate risk versus acceptance criteria
- Evaluate how risk can be reduced by modifications or mitigation

The possibility of a deflagration to detonation transition (DDT) should also be considered and included in all the steps in an appropriate manner.

A similar approach can also be established for fires but here simpler tools can be more applicable.

Once an appropriate consequence level is established (based on comparison with risk acceptance criteria), this can be used to determine the distance at which the consequence is acceptable (for instance a certain pressure or radiation threshold). This can then form the basis for defining appropriate safety distances.

One of the authors has previously studied releases from 700 bar hydrogen cars and 350 bar hydrogen buses for two different tunnel layouts (500 m long) and a range of longitudinal ventilation conditions using the risk-based approach [16], see Figure 3.

The study suggested that for hydrogen vehicles a typical worst-case risk assessment approach assuming the full gas inventory being mixed homogeneously at stoichiometry could lead to severe explosion loads. However, a more extensive study with more realistic release scenarios reduced the predicted hazard significantly. As a final step of the risk assessment approach, a probabilistic QRA study is performed in which probabilities are assigned to different scenarios, time dependent ignition modelling is applied, and an overpressure exceedance curve is established. This led to a moderate risk level, which could be used to define appropriate safety distances.

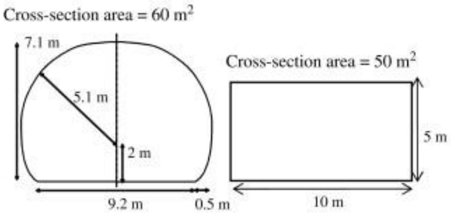

Figure 3. Schematic of the tunnel cross-section

Another study involved a possible dangerous situation in a hydrogen workshop caused by a small release of hydrogen (of the order of 10g), which may get ignited subsequently [17], see Figure 4. The goal is evaluating the risk if this happens in terms of pressure loads. Again, it is seen that the worst-case scenario leads to some unacceptable consequences, especially in case pre-ignition turbulence is considered (which is likely to be present if there is a high-momentum hydrogen release which then gets ignited). The pressure in this case is predicted to be around 500 mbar. Establishing some realistic release scenarios led to significantly smaller than the assumed flammable volume in step 1, and also of much lower average concentration, which meant significantly lower explosion loads. This study was also extended to determine the risk level based on an assumed incident frequency (see Figure 5) and again this measure could be used to establish robust safety distances.

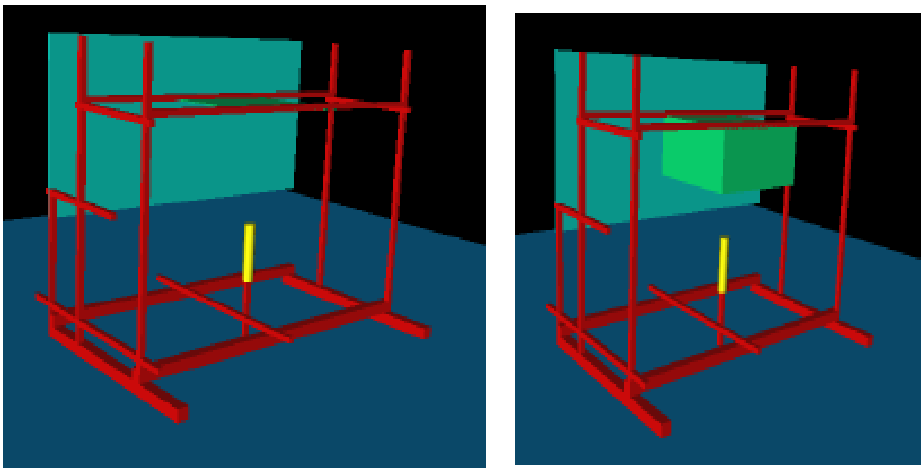

Figure 4. Geometrical configurations of the ‘workshop’ scenario considered, plate only (left) and plate with sidewalls (right).

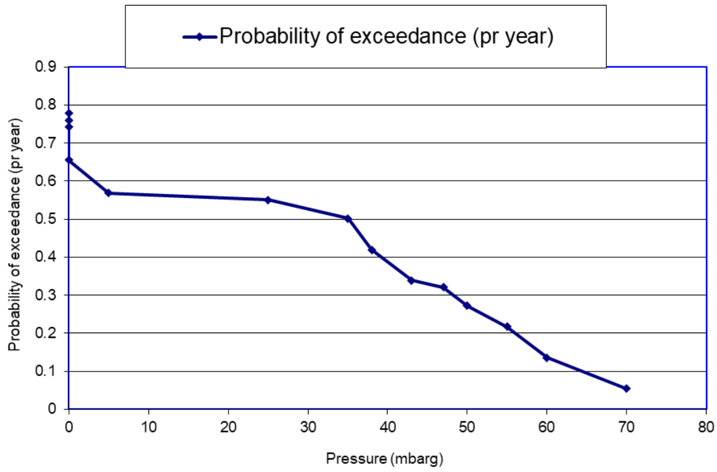

Figure 5. Frequency of a certain explosion load in the 'workshop' based on an accident occurrence rate of 10 incidents per year.

5.0 FINAL WORDS

In recent times, the authors have experienced (as a part of various consultancy projects) that the use of such robust risk analysis techniques can lead to accurate safety assessments as well as specification of useful and relatively non-conservative safety distances, thus enabling more of such hydrogen refuelling stations to be built. Therefore, we recommend that such an approach be followed.

In our view, this approach is the most advantageous as it avoids discrepancies in specified safety distance standards which may not represent the scenario under consideration. Further, if risk-based approaches combined with advanced techniques such as validated CFD are followed rigorously, this can be used to satisfy the applicable regulations.

References:

[1] Alazemi J, Andrews J. Automotive hydrogen fuelling stations: An international review. Ren. Sust. Ener. Rev. 48, 483–99, 2015.
[2] Sakamoto J, Sato R, Nakayama J, Kasai N, Shibutani T, Miyake A. Leakage-type based analysis of accidents involving hydrogen fuelling stations in Japan and USA. Int. J. Hyd. Ener. 41(46), 21564–21570, 2016.
[3] Nel investigation into explosion at Kjørbo hydrogen station. Fuel Cells Bull. 2019(7), 7-8, 2019.
[4] Matthijsen AJ, Kooi ES. Safety distances for hydrogen filling stations. Fuel Cells Bull. 2006(11), 12-6, 2006.
[5] Kim E, Lee K, Kim J, Lee Y, Park J, Moon I. Development of Korean hydrogen fuelling station codes through risk analysis. Int. J. Hyd. Ener. 36(20):13122-31, 2011.
[6] Kikukawa S, Yamaga F, Mitsuhashi H. Risk assessment of Hydrogen fuelling stations for 70 MPa FCVs. Int. J. Hyd. Ener. 33(23), 7129-36, 2008.
[7] LaChance JL, Middleton B, Groth KM. Comparison of NFPA and ISO approaches for evaluating separation distances. Int. J. Hyd. Ener. 37(22), 17488-96, 2012.
[8] Pique S, Weinberger B, De-Dianous V, Debray B. Comparative study of regulations, codes and standards and practices on hydrogen fuelling stations. Int. J. Hyd. Ener. 42(11), 7429-39, 2017.
[9] National Fire Protection Association. NFPA 2: Hydrogen technologies code. Quincy Massachusetts. 2020.
[10] Fuel Cell Standards Committee. SAE J2601: Fuelling protocols for light duty gaseous hydrogen surface vehicles [S/OL].

[11] ISO 19880-1:2020 Gaseous hydrogen — Fuelling stations — Part 1: General requirements. International Organization for Standardization
[12] LaChance J. Risk-informed separation distances for hydrogen refuelling stations. Int. J. Hyd. Ener. 34(14), 5838-45, 2009.
[13] Timmer PGJ, Stam G. Risk based safety distances for hydrogen refuelling stations. International Conference of Hydrogen Safety, Hamburg, Germany, 11-13 September 2017.
[14] Groth KM, Hecht ES. HyRAM: A methodology and toolkit for quantitative risk assessment of hydrogen systems. Int. J. Hyd. Ener. 42(11), 7485-93, 2017.
[15] Hansen OR, Middha P. CFD-based risk assessment for hydrogen applications. Process Safety Progress. 27(1), 29-34, 2008.
[16] Middha P, Hansen OR. CFD simulation study to investigate the risk from hydrogen vehicles in tunnels. Int. J. Hyd. Ener. 34(14), 5875-86, 2009.
[17] Middha P, Hansen OR, Grune J, Kotchourko A. CFD calculations of gas leak dispersion and subsequent gas explosions: validation against ignited impinging hydrogen jet experiments. Journal of hazardous materials. 179(1-3), 84-94, 2010.