INTRODUCTION TO HYDROGEN SAFETY ENGINEERING

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ABSTRACT

The viability and public acceptance of the hydrogen and fuel cell (HFC) systems and infrastructure depends on their robust safety engineering design, education and training of the workforce, regulators and other stakeholders in the state-of-the-art in the field. This can be provided only through building up and maturity of the hydrogen safety engineering (HSE) profession. HSE is defined as an application of scientific and engineering principles to the protection of life, property and environment from adverse effects of incidents/accidents involving hydrogen. This paper describes a design framework and overviews a structure and contents of technical sub-systems for carrying out HSE. The approach is similar to British standard BS7974 for application of fire safety engineering to the design of buildings and expanded to reflect on specific for hydrogen safety related phenomena, including but not limited to high pressure under-expanded leaks and dispersion, spontaneous ignition of sudden hydrogen releases to air, deflagrations and detonations, etc. The HSE process includes three main steps. Firstly, a qualitative design review is undertaken by a team that can incorporate owner, hydrogen safety engineer, architect, representatives of authorities having jurisdiction, e.g. fire services, and other stakeholders. The team defines accident scenarios, suggests trial safety designs, and formulates acceptance criteria. Secondly, a quantitative safety analysis of selected scenarios and trial designs is carried out by qualified hydrogen safety engineer(s) using the state-of-the-art knowledge in hydrogen safety science and engineering and validated models and tools. Finally, the performance of a HFC system and/or infrastructure under the trial safety designs is assessed against predefined by the team acceptance criteria. This performance-based methodology offers the flexibility to assess trial safety designs using separately or simultaneously three approaches: deterministic, comparative or combined probabilistic/deterministic.

1 INTRODUCTION

The hydrogen economy is developing under the pressure of various factors such as scarcity of fossil fuels, political agreements on climate change, the limitation of world industry “addiction” to oil due to an exponential increase of crude oil prices, the rise of energy consumption in developing countries, etc. [1] and [2]. Hydrogen advantages as an energy carrier are well known: its combustion produces no carbon dioxide emission, it releases more energy per unit mass compared to other fuels, and it can be produced from renewable energy sources like wind, tide, solar, and hydro resources [1].

From a safety point of view, hydrogen is not more dangerous or safer compared to other fuels [3]. Hydrogen leak is difficult to detect as it is a colourless, odourless and tasteless gas; when burning in clean atmosphere hydrogen has an invisible flame, and it is more prone to deflagration-to-detonation transition compared to other gases [4], etc. However, at the same time the main hydrogen safety asset, i.e. its buoyancy, confers the ability to rapidly flow out of an incident/accident scene, and mix with the ambient air to a safe level [4] and [5].

Hydrogen safety awareness and practical experience have been gained in the process industries like petrochemical, food, electronic, metallurgical processing, fuel in space applications, etc. In these industrial applications hydrogen was consumed at a site of production. Nowadays, hydrogen is out of chemical plants and is available to public through different demonstration projects. Hydrogen-fuelled buses and cars are on the road and refuelling stations are operating in different countries around the globe [5]. There is a clear need for a new safety culture to deal with HFC systems and use of infrastructure that must be underpinned by systematic education and training at different levels from school to safety professionals. Safety solutions will define a level of competitiveness of particular HFC technology, system, or infrastructure.

Quality of hydrogen safety provisions directly depends on availability of performance-based methodology rather than a group of prescriptive codes and standards to carry out HSE of relevant systems and infrastructure. This methodology should be complemented by up to date Regulations, Codes and Standards (RCS), highly educated and trained engineers and technicians, and the state-of-the-art tools for safety engineering design. The World's first higher education course in hydrogen safety, i.e. MSc in Hydrogen Safety Engineering [6], is established in January 2007 and undergoes continuous development to include latest research findings, update of RCS, and innovative engineering solutions and advanced safety strategies. There are more educational and training activities within the educational committee of the International Association for Hydrogen Safety (http://www.hysafe.org/IAHySafe), including the International Short Courses and Advanced Research Workshop series "Progress in Hydrogen Safety" (http://hysafer.ulster.ac.uk/phs/).

Since 2004 the essential progress in de-fragmentation of research, closing of knowledge gaps, development of contemporary models and validated tools, contribution to RCS, and dissemination of the state-of-the-art in hydrogen safety was achieved through the efforts of the European Network of Excellence "Safety of hydrogen as an energy carrier" (NoE HySafe) funded by the European Commission. In 2009 an international hydrogen safety research community established the International Association for Hydrogen Safety (IA HySafe) that is formed on and took over from the NoE HySafe. Despite the progress in hydrogen safety science, engineering, and technology during last decade an overarching performance-based methodology to carry out HSE is still absent.

Risk-informed and quantitative risk assessment approaches, which require statistical data, can only compliment not substitute professional safety engineering design of HFC systems and infrastructure. It is natural that emerging technologies can hardly be characterised by representative statistical data of faults, incidents, etc. This makes practical application of probabilistic methods in hydrogen safety engineering less valuable at the moment. Besides, risk-informed methods are not always easy to understand by engineers and/or regulators. There are still debates in hydrogen safety community on aspects and interpretations of risk-informed approaches and uncertainty of their predictions. At the same time, the public is keen to know that all possible has been done to make HFC applications safe rather than be simply satisfied that the probability of personal fatality is 10^{-4} or 10^{-6} or 10^{-8}. The same is valid for court proceedings. There is another implication of a potential disbalance between deterministic engineering efforts and probabilistic/risk-informed assessments, i.e. resources can be diverted away from creative engineering and real problem solution to acceptance of generalised level of risk which uncertainty is questionable.

There is currently an overestimation to some extent of expectations and a role of RCS in safety design of HFC systems in authors' opinion. Codes and standards by definition are at least three years old to current level of knowledge in the field. They are naturally quite narrowed by a particular topic and cannot account ahead for all possible situations to be resolved, especially for new and developing technologies. They are written and reflect interests of mainly industry rather than all stakeholders. Safety information is thus "naturally" fragmented throughout the growing with time number of standards. It is why a separate overarching safety oriented standard, giving the methodology to carry out HSE and systemise/maintain available knowledge in the field, is needed to underpin the safe use of hydrogen and fuel cells in low-carbon economy.

The aim of this paper is to introduce the subject, scope, design framework including main procedures and sub-systems of the hydrogen safety engineering (HSE) defined here as an application of scientific and engineering principles to the protection of life, property and environment from adverse effects of incidents/accidents involving hydrogen. The paper presents ideas underpinning a draft for development of a performance-based standard for carrying out hydrogen safety engineering which is to be developed and submitted to one of the standard development organisations.

2 THE GENESIS OF HYDROGEN SAFETY ENGINEERING

2.1 The hydrogen economy and public safety

HFC technologies, systems, and infrastructure are currently at the stage of demonstration projects and early markets before their commercialisation after 2015. The hydrogen economy requires overcoming the lack of infrastructure [7]. New technologies improve units of hydrogen production as well as transportation and delivery networks at the end of which there will be the public [8]. Sometimes, implementation of new technologies and design of infrastructure involve the use of hydrogen under circumstances that are not yet addressed by research [9]. Technical staff at maintenance workshops, refuelling stations, and emergency services should be educated and trained to deal with hydrogen systems at pressures up to 1000 bar and temperatures down to -253°C (liquefied hydrogen) in the open and confined space like tunnels, car parks, etc. Regulators and approvers should be provided by the state-of-the-art knowledge and guidance to assist in the safe implementation of HFC technologies within the built environment. A number of professional hydrogen safety engineers required to underpin the emerging industry is expected to grow. Safety engineers and technicians, including those who have handled hydrogen in different industries for several decades, need to undergo retraining through continuous professional development courses to acquire the last knowledge and engineering skills for use of hydrogen in a public domain. Indeed, emerging HFC systems and infrastructure "*will create in a close future entirely new environment of hydrogen usage, which is not covered by industrial experience or through existing codes and recommended practice*" [3].

It becomes crucial to ensure safety of public as its perception of hydrogen as a safe constituent of future energy systems is essential "*if a hydrogen economy is to replace the existing fossil fuel-based economy*" [10]. It is important that the perception of hazards and risks for hydrogen applications should not exceed that of current fuels. However, unfortunately "*very little has been done to educate people about the properties and safety of hydrogen, even though public acceptance or lack thereof, will in the end make or break the hydrogen future*" [11]. Therefore, as it would be impractical to train general customers to professional level, educational programmes in hydrogen safety should be developed and primarily target experts already involved in hydrogen economy [9]. Teaching of hydrogen safety engineering and its implementation into day-by-day engineering practice requires clear understanding of what HSE processes and constituent parts are.

2.2 The emerging profession of hydrogen safety engineering

The Workgroup on Cross Cutting Issues of the European HFC Technology Platform [12] indicated that educational and training efforts are key instrument in lifting barriers imposed by the safety of hydrogen. This Workgroup has estimated that during the FP7 period (2007-2013), the educated staff needed may amount to 500 new graduates from postgraduate studies on an annual basis in all of Europe. In a study of the European e-Academy of Hydrogen Safety performed within the NoE HySafe, it was estimated that the subset of these necessary graduates specialising in hydrogen safety would amount to 100 on an annual basis [9].

The higher education of researchers and engineers is a key to surmount challenges of hydrogen safety. The development of an International Curriculum on Hydrogen Safety Engineering (www.hysafe.org/Curriculum) was the first step in the establishment of the profession undertaken by the European e-Academy of Hydrogen Safety in collaboration with partners around the globe. About 70 renowned international experts contributed to the draft for development of the Curriculum [9]. The Curriculum has been already implemented into the World's first postgraduate course at the University of Ulster and continuous professional development course at Warsaw University of Technology.

The main contributor to the establishment of the profession through a closing of knowledge gaps and educational/training programmes is the international hydrogen safety community coordinated by IA HySafe.

The HSE discipline is developing on the experience and lessons learnt by fire safety engineering, which is today a well-established profession focused mainly on building fires. An important step in the establishment of fire safety engineering as a profession was a model curriculum for under and postgraduate courses published in 1995 [13]. Unfortunately, graduates of fire safety engineering courses are not able currently to tackle specific problems of hydrogen safety such as high pressure leaks and dispersion, spontaneous ignition and thermal effects of under-expanded jet fires, pressure loads of hydrogen-air deflagrations/detonations and blast waves, etc. However, there are common problems, knowledge and experience which HSE can utilise to some extent, such as fire resistance of structures and life safety, emergency services intervention, etc.

Fire safety was originally regulated by prescriptive codes, aiming to protect societies from adverse effects of fires in traditional buildings with low hazard occupancies [14]. But for more complex buildings, the prescriptive approach didn't meet the needs of designers or approval bodies. Those prescriptive codes didn't offer flexibility for innovation, they didn't necessarily provide optimum solution for a particular project, they provided requirements without statement of objectives, they might lag many years behind modern design practice and their use unable to anticipate all eventualities [15] and [16]. In the late 1980s, a project led by the Warren Centre in Australia made a significant contribution by proposing fundamental improvements to fire safety. The purpose was to define a basis for a new generation of RCS. Among the numerous recommendations of the Warren Centre Report [17], some are directly applied to hydrogen safety systems: design for fire safety should be treated as "*an engineering responsibility rather than as a matter for detailed regulatory control*"; designers should develop a greater understanding of fire phenomena and human behaviour and adopt appropriate engineering techniques in their design of fire safety systems; fire engineering design courses and training strategies should be developed and implemented, up to and including postgraduate level, etc. This report led to a worldwide attention towards fire safety engineering. The methodology highlighted by this approach was dedicated to measure design's performance using different tools, e.g. simple engineering calculations and contemporary computer-based models. There was an intention to implement non-complex documents [15] in performance-based fire safety regulations to provide greater flexibility when designing and evaluating a project, and to promote innovation in building design, materials, products, and fire protection systems [14]. This approach nevertheless requires education of professionals and the validation of tools and methods used for quantification [15]. The developments in hydrogen safety engineering are greatly inspired by and based on the developments of fire safety engineering, including performance-based RCS, educational programmes and freely available contemporary CFD (Computational Fluid Dynamics) tools like Fire Dynamics Simulator (http://fire.nist.gov/fds/). The framework for fire safety engineering is described by Deakin and Cooke [18]. Some of their statements can be directly transferred to define the HSE framework:

- **Provide a systematic approach.** The process used to undertake HSE and evaluate the performance of a design, should be clearly defined and explained. The framework will set the basis of the methodology that should be applicable for a HSE study.
- **Define acceptance criteria.** The performance of a design is evaluated by comparison with deterministic, comparative or probabilistic criteria.
- **Simplify the problem.** The HSE process is separated into analysis of Technical Sub-Systems (TSS) that can be used individually to address specific issues or together to address all of the safety aspects of a hydrogen system.
- **Illustrate interactions.** The complexity of phenomena and interactions between elements of hydrogen system, people and the built environment in a case of incident requires a simplified approach by underlining interactions between different TSS.
- **Ensure adequate consideration of all those factors relevant to any aspect of the design.** In order to identify all significant variables in a quantification process, it is essential to list relevant scenarios. Doing this, it is possible for each scenario to inventory critical factors from hydrogen system/infrastructure such as parameters of accident scenario including occupancy, etc.
- **Insist on clear presentation and comment on calculation methods and data sources.** As the application of HSE might be subject to review and approval, it is essential that findings, calculations and assumptions, are presented in a report that can be clearly and readily understood.

2.3 The subject and scope of hydrogen safety engineering

HSE is defined as the application of scientific and engineering principles to the protection of life, property and environment from adverse effects of incidents/accidents involving hydrogen. Terminology of HSE used in this paper is given in alphabetical order in Appendix 1. These definitions help in understanding of further content of the paper.

The HSE can be applied to existing and new hydrogen systems, including but not limited to stationary, e.g. combined heat and power systems, or portable, e.g. mobile phone and computers, applications for indoor and outdoor use, hydrogen transportation and refuelling infrastructure, power generation, hydrogen production and distribution units, storage, infrastructures such as garages, parking, tunnels, pipelines networks, etc. A hydrogen system could be defined as an equipment dealing with hydrogen e.g. storage, production, delivery, distribution, consumption, etc. Hydrogen should remain contained within hydrogen system from its production/delivery to its final use.

3 THE DESIGN FRAMEWORK, SUB-SYSTEMS AND PROCEDURES

HSE comprises a design framework and technical sub-systems both explaining how to apply scientific and engineering principles to safety design of a HFC system and/or infrastructure.

3.1 The design framework outline

The described in this section HSE design framework is inspired by British Standard BS 7974 [19] and relevant Published Documents, which 55 organisations contributed to [20]. The Draft for Development (DD) of the future standard with a tentative title “Application of hydrogen safety engineering principles to the design of hydrogen systems” is outlined below. The DD will include a number of documents to describe the design framework and HSE procedures, details of TSS, and a document to describe procedures for the probabilistic risk assessment. A series of documents describing each TSS will contain the state-of-the-art information and guidance on how to undertake a quantitative safety analysis by selected validated engineering tools.

The design framework document will:

- Describe the philosophy of HSE;
- Provide means of establishing acceptable levels of hydrogen safety economically and without imposing unnecessary constraints;
- Provide guidance on the design and assessment of hydrogen safety measures;
- Give a structured approach to measure the performance compared to defined design objectives;
- Be used to create and evaluate trial design without compromising safety;
- Recognise that alternative and complementary hydrogen safety strategies can be used to achieve defined objectives;
- Identify requirements for further research.

Three main steps or procedures of HSE are (see Fig.1):

- Qualitative design review (QDR);
- Quantitative analysis;
- Assessment against criteria.

These steps are the same as in fire safety engineering [16] and [19]. The main procedures are described in detail further in sections 4 to 6.

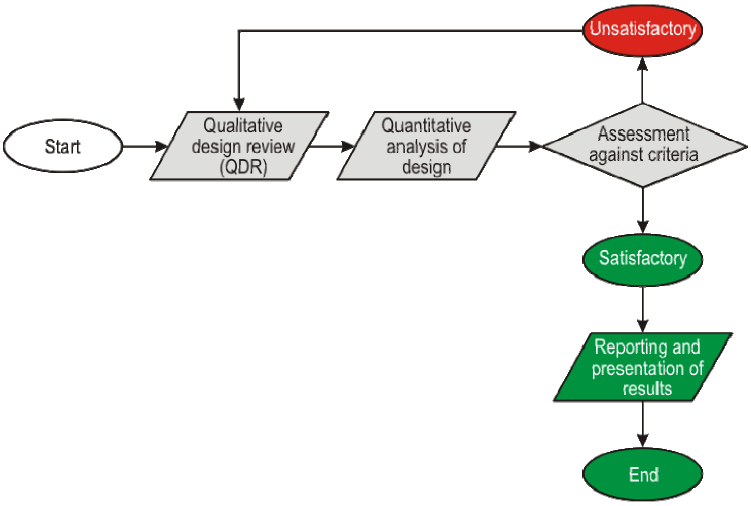

Figure 1. Hydrogen safety engineering procedures.

The HSE design has to demonstrate the compliance with regulatory requirements and be completed by a fully documented Report on Hydrogen Safety Engineering that can be readily assessed by the approvals bodies. Representatives of the approvals bodies should be involved in the process at the QDR stage to facilitate the final permitting.

3.2 Technical Sub-Systems: definition and content

To simplify the evaluation of a HSE design, the quantification process is broken down into several TSS. The following requirements should be accounted for when developing individual TSS:

- TSS should together, as reasonably as possible, cover all possible aspects of hydrogen safety;
- TSS should be balanced between their uniqueness or capacity to be used individually, and their complementarities and synergies with other TSS;
- TSS should be a selection of the state-of-the-art in the particular field of hydrogen safety science and engineering, validated engineering tools, including empirical and semi-empirical correlations and contemporary tools such as CFD models and codes;
- TSS should be flexible to allow update of existing or use of new appropriate and validated methods, reflecting recent progress in hydrogen safety.

The suggested TSS titles and the outline of their technical contents are as follows:

TSS1: Initiation of release and dispersion.

It will include information on potential sources and scenarios of hydrogen leaks [21]; the effect of hydrogen on different materials, e.g. embrittlement or permeation [22]; methods to calculate flow parameters at the real nozzle exit, including parameters of highly under-expanded jets, e.g. mass flow rate, density, temperature, etc., for different storage pressures and leak diameters, including a correction due to friction and minor losses [23]. The original under-expanded jet theory and the similarity law, validated recently for both expanded and under-expanded jets, will be used to calculate concentration decay in a single round and plane jet [24] and [25] using only hydrogen density at a real nozzle exit and a real leak diameter. Methods to calculate hydrogen dispersion from different leaks, including permeation [26], in an enclosure and requirements to natural ventilation [27] will be included in TSS1 to tackle dispersion of permeated hydrogen and larger leaks. The correlation to account for an effect of buoyancy on safety distance in case of downward and horizontal jets will be presented. Pressure peaking effect for non-reacting release in vented enclosure, characteristic for hydrogen only, will be explained and a nomogram to calculate overpressure in enclosure with known volume, vent area and mass flow rate of hydrogen release, will be presented. The methodology to calculate dynamics of blowdown from a storage vessel through orifice of known size will be given. Best practices, e.g. recommendation to reduce mass flow rate in piping to technological limit or use of a restrictor to limit mass flow rate during accidental release, etc.

TSS2: Ignitions.

It will provide information on different ignition mechanisms, including a “diffusion” mechanism of spontaneous ignition of hydrogen during sudden release; flammability limits for upward, downward and lateral flame propagation and their dependence on pressure, temperature [28], and diluents concentration [29]; minimum ignition energy for initiation of deflagrative flame propagation and direct initiation of detonation of hydrogen-air and hydrogen-oxygen mixtures [30] and [31]; the autoignition temperature and its dependence on hydrogen concentration, pressure and temperature [32] and [33]; the size of maximum experimental safe gap [34], etc.

TSS3: Deflagrations and detonations.

It will provide information on how to assess hydrogen explosion hazards, calculate pressure effects of hydrogen explosions, i.e. overpressure and impulse of unconfined deflagrations and detonations using Sach’s variables [35]; calculate shock propagation velocity and pressure in reflected shock. It will describe how to assess the potential of hydrogen-air mixture to undergo deflagration-to-detonation transition (DDT) [36], discuss the overpressure generated by delayed ignition of high pressure releases [37], etc.

TSS4: Fires.

It will provide guidance on how to estimate severity of different types of fires from micro-flames [38] to high mass flow rate jet fires (correlation for jet flame length e.g. [24], radiative heat fluxes [39] and air temperature in downstream currents [40], etc.) will be provided. The data on how to evaluate the potential for lift-off, blow-out and blow-off of hydrogen jet fires will be given [41], [42] and [43]. The simple engineering nomogram for flame length and flame width determination [24] will be included, etc. This nomogram is validated against experimental data and accounts for pressure limit of flame existence at small size orifices using experimental results presented by different research groups [39], [40], [43], [44], [45], [46], [47], [48] and 49]. Fire resistance of hydrogen system elements will be characterised where it is possible, including onboard storage, etc.

TSS5: Impact on people, structures, and environment.

It will outline issues relevant to life safety and evacuation strategy and will propose guidance on how to estimate consequences of a hydrogen incident on life, property and the built and natural environment depending on the severity of an accident and potential targets (customers, member of public, first responders, buildings, windows, walls, etc.). Consequences will be estimated with regard to:

- Radiant fluxes [50], [51], [52] and [53];
- Hot air currents from jet fires [54];
- Direct (blast load) and indirect effects (body translation, missiles) of explosions [51], [54], [53] and [55];
- Oxygen depletion [30] and [5] in relation to asphyxiation, etc.

The life safety and evacuation strategy could be defined based on the information contained in [56].

TSS6: Mitigation techniques.

It will provide guidance on the use of different detection and mitigation techniques and strategies, and how to evaluate and take into account their impact on prevention of hydrogen incident/accident and/or mitigation of its adverse effects. The impact of barriers on the development of reacting [57] and non-reacting hydrogen jets [58], and on the reduction of overpressure generated by jet explosion [57], can be evaluated by comparison with experimental data and numerical simulations. Available and validated tools for hydrogen engineering, like the vent sizing technique for mitigation of deflagration in confined spaces [59], will be gathered and introduced. Requirements to natural and forced ventilation to tackle indoor hydrogen releases will be described. The role of pressure relief devices will be discussed in this TSS.

TSS7: Emergency services intervention.

It will provide relevant for emergency services information on hydrogen behaviour during releases and combustion and guidance on control strategies and tactics during the initial response phase of the incident [60], the evaluation of the rate of build up of resources of the emergency services [61], no harm distances, etc.

In addition to outlined TSS documents, a supplementary document on probabilistic risk analysis for hydrogen systems will be prepared by a group of international experts similar to the approach of BS 7974-7 [62]. This document will give information on various techniques to conduct a probabilistic risk analysis from simple statistical analysis, logic trees (fault trees and event trees) to complex analysis (reliability analysis, partial safety factors, etc.) similar to described in [62]. Ideally, this risk-informed document should also include information on risk acceptance criteria and provide statistical data on frequencies of leak of various sizes for different components, probability of failure of mitigation and detection systems, probability of ignition, etc.

3.3 Example of interactions between QDR and TSS

Selected TSSs are interlinked as one would provide numerical outputs that could feed other TSSs as inputs. Table 1 draws these likely and potential interactions by identifying the possible outputs and inputs of QDR and each TSS. It has to be underlined that the table does not represent the interactions within a TSS. Depending on the objectives of particular HSE study, it is possible, with a minimum of inputs, to use only one TSS. For example, the sole use of TSS1 makes possible the evaluation of hydrogen dispersion from free jets with knowledge of only reservoir pressure and leak diameter. If leak flow parameters are known or assumed, fire hazard can be assessed by using only the TSS4.

Table 1. Illustration of likely and potential interactions between QDR and/or TSS.

Qualitative Design Review	TSS1: Initiation of release and dispersion	TSS2: Ignitions	TSS3: Deflagrations and detonations	TSS4: Fires	TSS5: Impact on people, structures and environment	TSS6: Mitigation techniques	TSS7: Emergency services intervention	**Parameters**
●	●	●	●	●	●	●	●	Site layout
●	●	●	●	●	●	●	●	Building and structure characteristics
●	●	●	●	●	○	●	○	Hydrogen system characteristics
●	●	●	○	●	○	●	○	Leak parameters
●	●	○	●	●	○	○	○	Exit flow parameters
○	●	○	○	●	●	●	○	Dynamic of hydrogen blow-down
○	●	●	○	●	●	●	○	Flammable envelop of non-reacting releases
○	●	○	○	○	●	●	○	Pressure dynamic of non-reacting release in enclosure
○	●	●	●	○	●	●	○	Accumulation
○	●	●	○	○	○	●	○	Potential for ignition
○	●	●	○	○	○	●	○	Initial flame propagation
○	●	●	●	○	●	●	○	Jet explosion
○	○	○	○	○	●	●	○	Deflagration
○	○	○	○	○	●	●	○	Detonation
○	○	○	●	○	●	●	○	Physical explosion of storage
○	●	○	○	●	●	●	○	Jet flame length
○	○	○	○	●	●	●	○	Radiative heat flux
○	○	○	○	●	●	●	○	Convective heat flux
●	○	○	●	●	●	●	○	Impact on life safety
●	○	○	●	●	●	●	○	Impact on property
●	○	○	●	●	●	●	○	Impact on the environment
○	○	○	○	○	●	●	○	Evacuation strategy
○	●	○	○	○	○	●	○	Ventilation system
○	●	○	●	●	○	●	○	Impact of barriers
○	○	○	●	○	○	●	○	Venting of deflagration
○	●	●	○	○	○	●	○	Time to detection
○	○	○	○	○	○	●	●	Time of emergency services intervention
○	○	○	○	○	●	○	●	Intervention strategy
○	○	○	○	○	●	●	●	On site accident control equipment

Note: ● - likely interactions, ○ - potential interactions.

For example, in TSS1 “Initiation of release and dispersion”, one can use storage pressure and leak diameter from QDR to calculate a leak parameters as an output. The flammable envelope size is an output that will serve as a foundation for separation distance with regards to the geometry and layout of the hydrogen system and whether it should be mitigated or not.

The leak parameters and dispersion of hydrogen will serve as an input to the TSS2 “Ignitions”, to assess the location of flammable mixture and evaluate the possibility of its ignition.

In TSS3 “Deflagrations and detonations” an input on size hydrogen-air mixture from TSS1 or TSS6, when considering vents, forced ventilation, etc., will be used to assess the maximum pressure effects and a potential for DDT. If an ignition occurs, the severity of deflagrations and detonations in terms of overpressure and impulse will be the main output of TSS3.

In TSS4 “Fires” a mass flow rate, an output from TSS1, can indicate if a sustained micro-flame is possible. The conservative estimate of an under-expanded jet flame length can today be easily determined by a storage pressure and a leak orifice diameter (outputs from QDR) using the simple engineering nomogram [24] reproduced in Fig.2. Blue arrows in Fig.2 demonstrate three steps in use of the nomogram: step 1 – choose an actual nozzle diameter (3 mm in the example) and draw horizontal line until intersection with a relevant pressure line (350 bar in the example), 2 - draw vertical line until intersection with the line at the top part of the nomogram, 3 – draw final horizontal line to determine the flame length (5 m) and width (0.85 m). The estimate of the flame length is based on the best fit line of the correlation for flame length The ratio of the maximum visible hydrogen flame width to hydrogen flame length is accepted as 0.17 [47]. To be conservative the flame length determined by the nomogram can be increased by 50%. Finally, with the jet flame length, the axial and radial radiative heat flux and flow temperature downstream the jet can be calculated and serve as an input to other TSS.

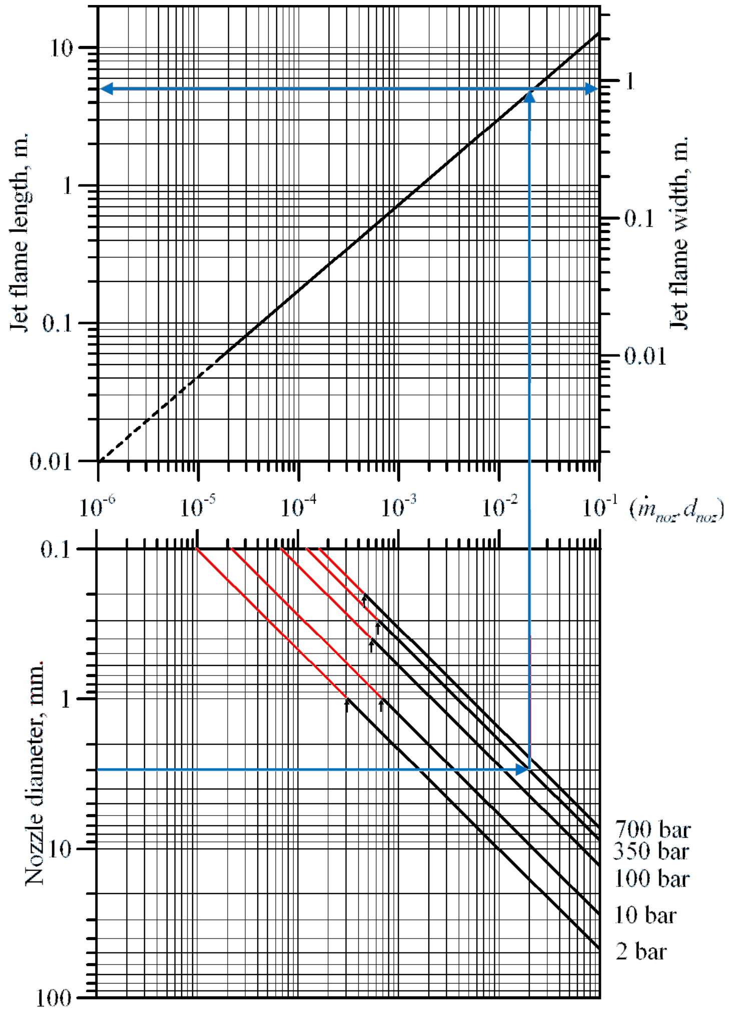

Figure 2: The nomogram for determination of hydrogen jet flame length and width [24].

In TSS5 “Impact on people, structures, and environment”, the output from QDR on building design and occupancy will serve as an input to development of the evacuation strategy. The severity of non-reacting release, jet fires and explosions, coming as output from TSS1, TSS3 and TSS4, or, when mitigation measures are applied, from TSS6, will be used to estimate the consequences for customers, staff, member of public, first responders, buildings, structural elements, environment, etc.

TSS6 “Mitigation techniques” can be used to formulate detection and mitigation strategies and techniques based on the severity of thermal and pressure effects initiated by unscheduled releases calculated in TSS1, TSS3 and TSS4. The impact of barriers on the characteristics of non-reacting hydrogen jets and jet fires, e.g. overpressure generated by jet explosion, can be used as an output of TSS6 and input to TSS5. In confined space the hydrogen-air mixture composition, output of TSS1, and the enclosure dimension, output of QDR, are inputs to TSS6 to calculate a sufficient vent area or estimate overpressure of vented deflagration. Similarly, data from QDR and TSS1 are needed to estimate whether natural ventilation is sufficient or forced ventilation system to be installed.

In spite of indubitable progress in hydrogen safety in the last decade, there are still numerous gaps of knowledge and a need in science intensive tools based on contemporary theories and validated against a series of experiments [63]. Knowledge gaps includes but not limited to: effect of the wind on outdoor releases in areas with complex surroundings such as in urban streets, and indoor releases in enclosures with natural ventilation; structure and hydrogen concentration decay in plane and circular jets as compared to round jets; interaction of multiple jets; cold jets in humid air; concentration profiles in downward and impinging jets; under-ventilated hydrogen fires and phenomena of self-extinction and re-ignition in enclosures; impinging jet fires and heat transfer to structural elements, storage vessels and communication infrastructure; predictive simulations of blow-off, lift-off, and blow-out phenomena; flames from plane jets (cracks); simulation of microflames; reproduction of coherent deflagrations phenomenon in vented enclosures, including sub-grid scale modelling of Rayleigh-Taylor instability; deflagration-to-detonation transition models for large-scale explosions, including effect of inertia of vent cover on DDT; partially premixed flames, in particular triple flames in hydrogen-air layers and their pressure effects in enclosed space, etc.

There is a demand in validated tools able to simulate in reasonable time dispersion of hydrogen in enclosure with natural and forced ventilation; spontaneous ignition in pressure relief devices and transition to sustained jet fire; impinging reacting and non-reacting under-expanded jets; vented deflagrations at low-strength equipment and enclosures, etc.

4 QUALITATIVE DESIGN REVIEW (QDR)

QDR is a qualitative process based on the experience and knowledge of a team. It allows its members to think of the possible ways a hydrogen incident/accident might be initiated and establish a range of strategies to maintain acceptable level of safety and risk. Ideally, QDR has to be carried out early in the design process and in a systematic way, so that any substantial findings and relevant items can be incorporated into the design of HFC application or infrastructure before the working drawings are developed. In practice however, the QDR process is likely to involve some iteration as the design process moves from a broad concept to greater detail.

4.1 Personnel involved in QDR

The formation of the QDR team depends on the nature and size of the project and on the extent of the analysis to be conducted. It should always include qualified hydrogen safety engineer(s) who will carry out the quantified analysis. The participation of architect, structural engineer, fluid mechanics engineer and a member of operational management ensures that all aspects of the design can be investigated in the context of the hydrogen safety objectives and that the impact of proposed solutions on other aspects of the design, are fully appreciated. A non-exhaustive list of other personnel that has to be involved in QDR includes: owner, representative of approval bodies, representative of insurers, emergency services, and owners of any occupancy in the vicinity of the hydrogen system and/or infrastructure.

4.2 Review of technical characteristics, site layout and management

4.2.1 Hydrogen system characteristics

The hydrogen system should be usually described by using Piping and Instrumentation Diagram (PID) representing the piping systems (diameter, length, materials, and pressure), the position and type of valves, the location of hydrogen vents, detection and mitigation systems, instrumentation connections, etc. The technical characteristics of components such as compressors, storages, fuel cells, dispenser, etc. should also be described.

To ensure the commercial and technical viability of the hydrogen system, the operational management should provide their requirements, e.g. operational pressure, hydrogen production and/or consumption/delivery rate. It is also important to estimate the required hydrogen storage inventory, as this parameter will be used to classify the hydrogen system under land use planning legislation. For instance in the UK, the NIHHS [64] requires the operators to provide a pre-construction safety report to Health and Safety Executive before a new construction can begin for storage above 2 tonnes. Above 5 tonnes of hydrogen stored, the COMAH Regulations [65] applies and impose conditions to the operators; storages above 50 tonnes require further restrictions.

4.2.2 Site layout, building and structures characteristics

The site and surroundings should be described by reference to schematic drawings or models. On the site itself, buildings and structures are likely to be built around or near the hydrogen system, e.g. protection against adverse weather, systems to prevent of intrusion, commercial building, etc. Information would be then required on the presence of dwellings, shops, barriers, canopy, type of materials used for walls and pavement, presence of electric cables, fire fighting equipments, bollard to prevent collisions, lightening protection equipment, etc. All the relevant available information about the use of these buildings and structure, their anticipated contents, the possible environmental influences, occupant's characterisation, should be reviewed.

In addition, information should be provided on the location of the facility, the accessibility by road or by other means, the type of buildings, structures and occupancy (industry, leisure, habitation, etc.) at the boundaries of the property, any known information on land use planning that might affect in the future the characteristics of buildings and structures beyond lot lines, any unusual factor that might influence the HSE project.

4.2.3 Management

The following factors should also be taken into account when assessing the likely nature and extent of management in an infrastructure: knowledge of ownership; staffing and level of hydrogen safety training; security; control over work, e.g. repairs to structure; the frequency of maintenance and testing of detection and mitigation technologies; liaison with the emergency services; contingency planning; degraded system planning; management of risk; and the continuity in the compliance with RCS. There is a greater confidence on management procedures when answers to these questions are positive.

4.3 Establishment of safety objectives

Safety objectives should be defined during the QDR. They should be appropriate to the particular aspect(s) of the design under consideration, as HSE may be used either to develop a complete hydrogen safety strategy or to consider one aspect of the design. The main hydrogen safety objectives are life safety, loss control and environmental protection.

4.3.1 Life safety

A hydrogen system can represent a hazard for occupants, first responders and members of the public. The main life safety objectives may include provisions to ensure that:

a) The occupants are able to leave the facility in reasonable safety or consequences to occupants are acceptably low;
b) First responders are able to operate in reasonable safety;
c) Collapse or falling debris does not endanger people, including fire-fighters, who are likely to be near the facility.

The HSE process should address all likely exposures to life threatening conditions like oxygen depletion, radiant heat flux, air temperature, overpressure, cryogenic temperatures, etc.

4.3.2 Loss prevention

As the effects of a hydrogen accident on the continuing viability of a business can be substantial, consideration should be given to reduce the damage to designated structures and valuable contents. This should guarantee the business capability, the preservation of the corporate image and reduce the potential for large financial losses.

4.3.3 Environmental protection

When estimating potential hazards to other facilities, constructions, flora and fauna in the vicinity of a hydrogen system and infrastructure, consideration should be given to the limitation of:

a) The severity of accident on adjacent facilities, especially in urban area or when hydrogen is handled in large industrial complex with a potential of "domino effect" [66];
b) The release of hydrogen into the built environment/nature to limit adverse effects of asphyxiation and cold burns on fauna and flora.

4.4 Identification of hazards and associated phenomena

A systematic review of the hydrogen system and its close environment should be conducted to establish the sources of potential hazards, taking account of the following factors: circumstances of production, transport and use of hydrogen; conditions of storage (volume, pressure, temperature, tank's material, location, etc.); potential for ignition (e.g. electric, electrostatic, hot surface, potential for spontaneous ignition of sudden release, risk of mixing with oxidiser, etc.); architectural characteristics (dimensions, location, structure, confinement, degree of congestion, potential for accumulation, materials of construction, etc.); presence of other combustible contents; nature of other activities within and beyond the infrastructure/facility; possible sources and frequency of leak; any unusual factors, etc.

Several methodologies can be used to identify hazards (simple checklist, HAZOP, FMEA, etc.) depending on the level of detail required. The potentially hazardous phenomena, e.g. formation of flammable cloud, jet fire, deflagration, etc., arising from an incident/accident should be reviewed qualitatively by the QDR team. In order to control hazards and consequences the QDR team should suggest possible trial safety designs providing safety at acceptable level in their opinion, which should be checked at the quantitative stage by hydrogen safety engineer.

To identify potential system failures or foreseeable faulty events that might have a significant influence on the outcome of the HSE study, it is necessary to conduct an assessment of "what-if events" [16]. Examples of "what-if events" could include: full bore rupture of pressurised hydrogen pipe, unscheduled mixing of hydrogen with oxidizer within the system, e.g. electrolyser, failure of detection and/or mitigation system, failure of emergency shutdown valves to go in safe position, blockage of emergency exits during the accident, management fails to implement hydrogen safety system training and maintenance procedures, etc. In a probabilistic study the likelihood and consequences of such event will generally be quantified. In addition, for deterministic studies the QDR team should judge the significance of "what-if events" by considering whether:

a) Consequences are tolerable or not worse than in a code compliant design; or
b) Additional protection measures are essential to provide a degree of redundancy.

4.5 Trial safety designs

To achieve an acceptable level of safety, the initial design could be amended or additional protection measures could be provided. To do so, the QDR team should establish one or more trial safety designs taking into consideration selected accident scenario(s). The different designs could satisfy the same safety objectives and should be compared with each other in terms of cost-effectiveness and practicability. At first glance, it is essential that trial designs should limit hazards by implementing prevention measures and ensuring the reduction of severity and frequency of consequences. Although HSE provides a degree of freedom, it is also necessary to fully respect relevant regulations when defining trial designs. A first step would be to base an initial trial design on the recommendations of established codes, including prescriptive, if possible [16]. Then other designs could follow the principles developed by Möller and Hansson [67]:

- Inherently safe design: the aim is to minimise the source of harm from identified hazards and limit the impact of consequences;
- Procedural safeguards: this is in relation with the respect of safety codes and standards and quality assurance together with the training and behaviour control of staff. In the HSE approach this will mainly concern the safety management of the premise;
- Safe fail: the system should fail safely (for example, valves of any hydrogen system should automatically go to the safe position in the event of a power failure as recommended by [68]);
- Safety reserves: they are used to ensure the strength of construction.

The application of these principles to the development of trial designs of hydrogen systems could be done in the following order [69]:

- Eliminate occurrence of severe accident by inherently safe design or by appropriate safety management;
- Limit hydrogen inventory;
- Limit the number of hydrogen sources;
- Promote hydrogen dilution;
- Suppress ignition sources;
- Avoid conditions for flame acceleration (no high hydrogen concentration; no confinement; no congestion);
- Avoid conditions for detonation (no high hydrogen concentration; limit cloud size);
- Limit consequences of explosion by strong construction.

4.6 Acceptance criteria and methods of analysis

The QDR team has to establish the criteria against which the performance of a design can be judged. Three main methods can be used: deterministic, comparative, and probabilistic. The QDR team can, depending of trial designs, define acceptance criteria following all three methods.

4.6.1 Deterministic studies

The objective of a deterministic study is to analyse the performance of trial safety design(s) selected by QDR team for chosen scenarios with models based on physical, chemical, thermodynamic and human behavioural relationships, derived from scientific theories and empirical correlations [16]. Among advantages of the deterministic approach are [16]: provides a simple yes/no result; widely used for life safety evaluation; use of well validated calculation procedures available; considerable data available. Disadvantages of deterministic studies include [16]: dependence on initial assumptions; provides no direct measure of costs and benefits; limited benefit for loss control purposes compared with a probabilistic approach.

a) Life safety criteria

The deterministic life safety criteria are based on physiological response to severity of impact and can be defined for life threatening, injury and incapacitation from evacuating. The criteria can be specifically chosen for the population under consideration, as it can be members of staff, occupants evacuating the facility, member of the public or first responders with personal protective equipments. They can be used in the process assessment against criteria by comparison with an output of the quantitative analysis.

Firstly, it is important to note that regarding the health hazard properties of hydrogen molecule itself, it appears to be non-toxic [30] and not classified as a carcinogen [70]. Nevertheless, attention should be paid to the level of hydrogen concentration in relation to asphyxiation. Tables with details of physiological response to oxygen depletion can be found in [5] and [30].

Hydrogen fires are a source of hazard due to heating of entrained surrounding air that can lead to hard breathing to rapid unbearable pain [54]. Also the radiant heat flux generated is absorbed by a person's skin causing pain, non-lethal and fatal burns [5]. The gravity would depend on several factors, such as the source strength, the distance from the source, the view angle between hydrogen fire and radiated object, the level of clothing, the exposure time and atmospheric conditions (especially amount of water vapour) [5], [30], [54] and [71]. For calculation purposes it is possible to use the scale of threshold of pain for clothed persons given by Kaiser [50], or simple equation or Probit function that can be found in [51], [52] and [53].

Deflagrations and detonations generate direct and indirect physiological impact on human [5]. A Probit function [72] can be used to calculate the probability of fatality by using overpressure. To encompass other harmful effects of blast wave [72] and [73], such as impulse, pressure-impulse diagram can be found in [51] and [53]. Probit functions can also provide an estimate of the indirect impact of explosions like missiles effect and the whole body translation [51], [54] and [55].

Liquefied hydrogen has extremely low temperatures [74] and cryogenic burns can result from contact between unprotected parts of the body and cold fluids or surfaces [30] and [74]. A sudden release of liquid hydrogen can result in hypothermia in case of prolonged exposure [5] and [30] while prolonged inhalation of cold vapour or gas may damage lungs [5].

b) Loss prevention and environmental protection criteria

Considering hydrogen systems, we can distinguish between the system/infrastructure itself, its content and the environment. The level of accident severity can impact the built environment objects and nature to different degree. If damaged, their value should not only be considered "*as a direct financial replacement cost, but also as a loss of an asset and productive time*" [19]. Also, the time necessary to replace damaged components can result in business disruption or deviation of customers towards competitors. Consideration should be given to reducing the escalating effects of objects, events and layouts on damages. Attention should also be paid to the value and importance of the property in and around a facility.

Acceptance criteria may include the definition of value for: number of specific valuable objects that are acceptable to damage; maximum zone of direct damage due to hydrogen release, fire and/or explosion; maximum zone of extinguishing water damage; maximum time periods for recovery from an accident. Damages caused by hydrogen accident can be evaluated by taking into account critical values that causes irreversible damages (overpressure, impulse, radiative heat flux, etc.). These acceptance criteria should be adequately chosen by the QDR team and hydrogen safety engineer, depending on particularities of a case.

4.6.2 Comparative studies

In some projects, recommendations of prescriptive codes and standards when they are available might provide the near optimum solution for a safe design. If the hydrogen system is regulations and codes compliant, a full HSE study may not be necessary. For comparative type of study, the acceptance criteria may simply be defined in terms of compliance with existing code requirements.

Current applicable prescriptive solutions can be found in various standards. However, standards are not mandatory except if they are referred to in Regulations and unlike HSE, standards don't include state-of-the-art of knowledge in hydrogen safety. Some standards are appropriate to the design of hydrogen refuelling station equipped with an electrolyser: separation distances from liquefied or gaseous compressed hydrogen [75], [76] and [77], design of hydrogen vents [76] and [78], design of oxygen and inert gas vents [78] and design of canopy above refuelling dispensers with or without storage and compressor mounted at the top [76] and [79].

However, a design under consideration can sometimes be innovative and recommendations of prescriptive code might not be directly applicable. In that case, it is possible that the design presents limited departures from prescriptive code and a comparative study can be conducted. The objective of such study is to demonstrate that the hydrogen system, as designed, presents at least the same level of safety performance and is as effective and reliable as a similar type of system designed in accordance with prescriptive codes and standards. This type of approach can be often made without calculation and requires less extensive analysis than deterministic or probabilistic studies that use absolute criteria.

Nevertheless, particular intentions and objectives of these prescriptive solutions should be known, and assumptions and methods of calculations used to define these design criteria must be clearly understood by hydrogen safety engineers. Then alternative designs may be developed to address the specific underlying objectives identified.

Another comparative study approach could consist in transposing existing prescriptive recommendations for alternative fuel such as CNG/LPG to hydrogen systems when reasonable with taking into account difference in physical and chemical properties.

The advantages of the comparative method of analysis [16]: relatively quick; consistent with established prescriptive codes; not usually dependent on initial assumptions; may be used where definitive design data are not available; explicit safety factors are not required; allows the use of probabilistic risk assessment without the need for absolute acceptance criteria. The disadvantages are [16]: generally only suitable for one or two significant departures or several minor deviations from prescriptive codes; might incorporate the weaknesses of the prescriptive codes.

4.6.3 Probabilistic studies

The objective of a probabilistic study is usually to show that the risk of a given event occurring is acceptable or tolerably small. The modern definition of risk is provided by ISO/IEC Guide 73:2002 [80] stating that it is the "*combination of the probability of an event and its consequence*" while safety is defined as the *"freedom from unacceptable risk"*. This means that safety is a societal category and cannot be numerically defined while risk is a technical measure that can be calculated [81]. Society, in consequence, establishes acceptable levels of risk or risk acceptance criteria. The use of risk acceptance criteria is a key element required to develop risk-informed codes and standards [81]. Their primary concern is the potential for people's injury or death. Such criteria be established for all the category of people exposed to the consequences of facility-related accidents (mainly occupants, staff, public, first responders). But a major difficulty comes from the current absence of mandatory risk acceptance criteria specific to hydrogen systems [81], [82], [83] and [84] that could severely hinder the reliability of results of the probabilistic risk assessment.

Nevertheless some risk-informed separation distances have been implemented in recent hydrogen standards (NFPA 2 and 55) and were based on a guideline of 2E-5 fatalities/year as chosen by NFPA 2 Working Group [85].

The advantages of the probabilistic approach [16]: provides comparison between dissimilar safety systems; provides a numerical value of risk; can quantify the probability of unlikely events with severe consequences; can quantify the risk associated with failure of one or more elements of safety system; provides data for cost-benefit analysis. The disadvantages are [16]: limited or absent statistical data; time consuming and thus expensive analysis.

4.7 Establishment of scenarios for analysis

4.7.1 Choice of scenarios

It is the role of QDR team, based upon their experience and knowledge, to establish the scenarios that require analysis and the ones that don't need to be considered. Indeed, to evaluate the performance of a trial hydrogen safety design, an infinite number of possible scenarios can be applied. And as it is not possible to quantify them all due to the limited availability of data and resources, scenarios should be restricted to the most significant or worst-credible ones. Furthermore, scenarios with a very low probability of occurrence should not be analyzed unless their outcome is potentially catastrophic and a simple remedy is available. Finally, it is usual to identify a number of worst-case scenarios for supplementary evaluation.

4.7.2 Description of scenarios

The description of scenario(s) should be appropriate for the quantification process and based upon assumption and experience of the QDR team members. This could include the following: hydrogen inventory (pressure, volume, etc.); leak parameters (nozzle size, location, orientation, shape, phase, duration, etc.); potential for dispersion and accumulation (confinement, obstacles, natural and forced ventilation, etc.); ignition (location, strength, time of ignition, etc); performance/failure of detection/mitigation or fire suppression systems considered in the "what-if" approach; severity of external source of hazard (intensity, duration, etc), etc.

The scenarios should also be chosen in order to meet the safety objectives and primarily life safety objectives. So, considering exposition to instantaneous or cumulative untenable conditions, it is important to review the occupancy in relation to occupant's initial position compared to the possible immediate hazardous area; the factors most likely to influence human behaviour and movement during evacuation. Additional considerations on occupancy should also be taken with regards to: occupant's number and their familiarity with the premises; their alertness and mobility. Furthermore, attention should be paid to means of escape, design parameters such as travel distance, escape routes, number and position of exits and exit widths.

4.8 Document outputs of QDR

The QDR team should provide a set of qualitative outputs to be used in the quantitative analysis: results of the architectural review; hydrogen safety objectives; significant hazards and associated phenomena; specifications of the scenarios for analysis; one or more trial designs; acceptance criteria and suggested methods of analysis.

Following QDR the team should decide which trial design(s) is likely to be optimum. The team should then decide whether quantitative analysis is necessary to demonstrate that the design meets the hydrogen safety objective(s).

5 QUANTITATIVE ANALYSIS

Following QDR a quantitative analysis may be carried out using TSS where various aspects of the analysis can be quantified by a deterministic study or a probabilistic study. The quantification process is preceded by the QDR for two main reasons: to ensure that the problem is fully understood and that the analysis addresses the relevant aspects of the hydrogen safety system; and to simplify the problem and minimise the calculation effort required.

The reduction of calculation effort is made by the QDR team when establishing which potential threats are significant and require quantification. In addition, the QDR team should identify appropriate methods of analysis among: simple engineering calculations; CFD simulations; simple probabilistic study; full probabilistic study.

A deterministic study using comparative criteria will generally require fewer data and resources than a probabilistic approach and is likely to be the simplest method of achieving an acceptable design. A full probabilistic study is only likely to be justified when a substantially new approach to hydrogen system design or hydrogen safety practice is being adopted. The analysis may be a combination of some deterministic and some probabilistic elements.

5.1 Use of Technical Sub-Systems

To perform a full HSE analysis it is necessary to use several TSS. However, various types of HSE studies with specific hazards, accident scenarios and trial safety designs may require different calculation approaches. For each project it is then necessary to: establish required numerical outputs; consequently identify the TSS that will be used in the quantitative process; dress the list of useful interactions between these TSS; set up relevant calculation procedures.

Calculations to be performed within each TSS will use inputs pre-determined in the QDR and inputs from other TSS. Yet care should be taken when assigning values to these inputs. Indeed, a conservative approach would require using worst-credible conditions and probably safety factors for defining these variables. However, considering a series of unlikely events in the development of a scenario would lead to an over-conservative design and increase of the HSE study cost. On the other hand, the use of average values does not provide a design with an acceptable level of safety. To perform a successful quantitative analysis it is necessary to rationalize the problem qualitatively during the QDR stage. Attention may then be focused on the quantitative interpretation of the design and, in particular, the uncertainties that the quantification may involve.

5.2 Deterministic procedures

Deterministic procedures quantify the development of an incident/accident involving hydrogen, its severity and associated consequences. Deterministic techniques will be described in detail in TSSs. Inputs and outputs to/from TSS may be used to carry out a time-based analysis of the hydrogen safety system performance.

In many cases, the use of nomograms, hand calculations or simple computer models will provide adequate accuracy. The empirical, semi-empirical and theoretical correlations and relationships validated against experimental data will be implemented in different TSS. Caution should be taken to use tools within limits of their applicability. In adopting any engineering tool or modelling technique the user should ensure that: it has adequate predictive capability; it is appropriate to the scenario under consideration; simple engineering tools have been adequately assessed and contemporary CFD tools were thoroughly verified/validated and the governing equations and validations are published in peer reviewed journals.

Provided the modelling techniques and/or tools are appropriately chosen, deterministic studies have to account for uncertainties in initial and boundary conditions. For example, this can be done by assuming the worst-credible initial conditions. However, if this approach is not satisfactory, sources of uncertainties might be addressed in a sensitivity analysis to check the robustness of the results and to investigate the criticality of each input parameters. In particular, the following uncertainties might be considered:

Uncertainties of input parameters. The most significant uncertainties are probably in the initial assumptions. A sensitivity analysis can help to determine the level of accuracy required of these input data. Such analysis may be conducted by investigating the response of the output parameters to changes in the individual input parameters. When modelling for life safety, the initial inputs that are most likely to impact on the outcome are: storage pressure, capacity and leak diameter (QDR, TSS1).

Uncertainties due to QDR simplifications. QDR aims at defining simplifications and assumptions to facilitate a full HSE analysis. Yet a single element of hydrogen safety system or assumption might be critical to the outcome of the study. The QDR team should then test the criticality of "what-if events". For example, the QDR team might have assumed that leaks would quickly activate the emergency shut down while an alternative scenario would assume a failure and the release of the total hydrogen inventory. The comparison of outcomes from the quantitative process would enlighten the criticality of the failure under consideration. Further consideration could be given to provide a degree of redundancy in the design (addition of valves, detectors, etc.) or to carry out a specific probabilistic study to investigate the reliability of such particular mitigation system.

Uncertainties due to modelling or use of engineering tools. When there is a doubt about the reliability of calculation technique employed, the outcome can be compared against another tool, e.g. one based on different modelling approach. Any significant discrepancies may be accounted for by choosing the most conservative of the results or by introducing an appropriate safety factor.

5.3 Probabilistic procedures

The probabilistic approach is different from the use of TSS and should be treated as a particular methodology to be presented in the separated dedicated document. Probabilistic risk assessment study aims at estimating the likelihood of a particular unwanted event occurring. This can be achieved by the use of statistical data on the frequency of leaks and reliability of mitigations technologies, combined with a deterministic evaluation of the consequences of possible hydrogen incident/accident [19].

By assigning probabilities of failure to hydrogen safety system elements and frequency to unwanted events, it is possible to assess the likelihood of a particular set of consequences. This can be used as a basis to: estimate the frequency of high-consequence events (e.g. multiple fatalities); evaluate the potential of failure of complex safety systems; compare the effectiveness of safety systems; establish the most cost-effective design.

Full probabilistic study can be very time consuming and expensive method of analysis [62] in HSE. In addition, a risk analysis for hydrogen systems "*can be severely limited by data availability*" [62] as "*a key input into a quantitative risk analysis, which is the data required to quantify the frequency of potential accident scenarios*" [83], is hardly available. Indeed, practically in all accident scenarios, an initiation event is unwanted release of hydrogen. Despite the existence of databases gathering such events little data are available on hydrogen-specific component leakages [81], [83] and [86]. Furthermore, the number of operating hours represented in these databases makes the analysis of data "*difficult if not impossible*" [83].

Yet methods to calculate risk-informed separation distances for HFC systems have been proposed [86] and [87]. The Hierarchical Bayesian approach used in the NFPA 55 is based on generic leakage frequency as a function of leak size (i.e., small leaks, large leaks, and ruptures) covering different industries. Leak size of 3% of pipe cross-section area was chosen in NFPA 55 (Edition 2010) for calculation of separation distances [85]. But only limited hydrogen-specific data were used in this analysis, and consequently "*more hydrogen data is needed to provide more robust leakage frequencies*" [85].

It has to be underlined that the use of probabilistic approach also requires a quantitative analysis using deterministic calculations in order to quantify the consequences of hydrogen incident/accident.

6 ASSESSMENT AGAINST CRITERIA

Following the quantitative analysis, the results should be compared with the acceptance criteria identified during the QDR exercise. Three basic types of approach can be considered: deterministic one shows that on the basis of the initial assumptions a defined set of conditions will not occur; comparative approach shows that the design provides a level of safety equivalent to that in similar systems and/or conforms to prescriptive codes (as an alternative to performance-based HSE); probabilistic approach shows that the risk of a given event occurring is acceptably low.

If none of the trial designs developed by the QDR team satisfies the specified acceptance criteria, QDR and quantification process should be repeated until a hydrogen safety strategy satisfies acceptance criteria and other design requirements. Several options can be considered when re-conducting QDR [19]: development of additional trial designs; adoption of more discriminating design approach, e.g. using deterministic techniques instead of a comparative study or probabilistic instead of deterministic procedures; re-evaluation of design objectives, e.g. if the cost of hydrogen safety measures for property loss prevention outweighs the potential benefits. When a satisfactory solution has been identified, the resulting HSE strategy should be fully documented.

7 REPORTING AND PRESENTATION

The HFC system and/or infrastructure designed by HSE might be a subject to review and approval. As HSE provides a flexible approach using performance-related objectives, it is not possible for approval bodies to simply compare the proposed design against a set of well-defined recommendations. It is hence important that all stakeholders understand assumptions made and findings achieved during carrying out HSE.

7.1 Report on Hydrogen Safety Engineering

The implementation of HSE procedures and results in a fully documented "Report on Hydrogen Safety Engineering" guarantees the hydrogen safety design to be readily assessed by a third party. The Report should set out clearly the basis of the design, the calculation procedures used, any assumptions made during the study, and conclusions achieved. For the understanding by all the stakeholders of the purpose of proposed safety measures, there should be a clear distinction between the protection of life, property and environment.

Depending on particularities and scope of the HSE study, the reporting of the results and findings could contain the following information [16]:

a) Objectives of the study;
b) Full description of the HFC system/infrastructure;
c) Results of the QDR;
d) Quantitative analysis:
    1) Assumptions;
    2) Engineering judgments;
    3) Calculation procedures;
    4) Validation of methodologies;
    5) Sensitivity analysis;
e) Assessment of analysis results against criteria;
f) Conclusions:
    1) Hydrogen safety strategy;
    2) Management requirements;
    3) Any limitations on use;
g) References (e.g. drawings, design documentation, technical literature, etc.).

7.2 Briefing for owner/occupier

Management of hydrogen safety is both critical and integral to the success of a hydrogen system/infrastructure safety design. Provisions of all HSE strategy elements have to be implemented effectively and properly maintained. Indeed, available statistics shows that human errors and management insufficiencies are factors in more than 50% of incidents/accidents involving hydrogen

[68] and [88]. Hence, any specific aspect of the hydrogen safety strategy depending upon a high standard of hydrogen safety management, should be documented in a “Hydrogen Safety Manual” that should be available in each HFC facility for the benefit of internal and external controls. The “Report on Hydrogen Safety Engineering” should be incorporated into this Manual. The general management and operational procedures in the “Hydrogen Safety Manual” should be written with references to the Report. The Manual should contain the technical specifications for all aspects of the facility or infrastructure and should particularly include the hydrogen safety policy statement (e.g. prevention of accidents, creation of separation distances, contingency planning, etc. [89]), the safety management structure, continuing control, audit and maintenance procedures, staff education and training, record

7.3 Audit

In order to maintain the effectiveness of the hydrogen safety strategy, it is essential that regular and effective testing and maintenance procedures are conducted. In a large HFC facility with the public access an independent audit should be carried out periodically. The frequency of such audits should be determined according to the nature and complexity of the system/infrastructure concerned and in relation with the relevant regulations. Audits should ensure that policies adopted by the management of hydrogen safety system are appropriate and being implemented effectively, and that testing of equipment and systems is being carried out.

8 CONCLUSIONS

Hydrogen safety engineering (HSE) is a key to the success of the hydrogen economy. It is the powerful tool for provision of hydrogen safety by qualified engineers in the growing market of HFC systems and infrastructures. The paper outlines the draft for development of a future standard with a tentative title “Application of hydrogen safety engineering for design of hydrogen and fuel cell systems and infrastructure”. HSE provides the methodology and makes it possible to develop inherently safe HFC systems/infrastructure, innovative safety strategies, and breakthrough engineering solutions.

The HSE procedure includes three main steps. Firstly, the qualitative design review (QDR) is performed by a qualified team composed of relevant stakeholders, whose experience and knowledge is used to analyse a HFC system/infrastructure, suggest scenarios and trial safety designs, formulate acceptance criteria. Secondly, the quantitative analysis is carried out using the state-of-the-art knowledge in hydrogen safety science and engineering, and validated contemporary models and tools. Thirdly, the assessment of the trial safety design performance against pre-defined acceptance criteria is undertaken.

The next development of this study is a completion of the state-of-the-art Technical Sub-Systems description comprising validated engineering models and tools which are partially cited in this paper. The essential part of the TSSs development strategy is its ability to adopt new scientific findings and engineering solutions.

The development, dissemination and teaching of the HSE subject at Universities will help to recognised HSE as a new profession and an important cornerstone supporting the safe introduction of hydrogen and fuel cell technologies, systems, and infrastructure to the global market.

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APPENDIX: TERMINOLOGY

Acceptance criteria: term of reference against which the performance of a design is assessed (based on [19]).

Accident: an unforeseen and unplanned event or circumstance [90].

Comparative study: methodology, aiming to demonstrate that a hydrogen technology as designed is as safe as a similar technology designed in accordance with prescriptive codes (based on [19]).

Consequences: expected effects from the realisation of the hazard and severity, usually measured in terms of life safety exposure, property damage and environmental impact [91].

Deterministic study: methodology, based on physical relationships derived from scientific theories and empirical results that, for a given set of initial conditions, will always produce the same outcome [19].

Hazard: chemical or physical condition that has the potential for causing damage to people, property and the environment (based on [19] and [91]).

Hydrogen safety engineering: application of scientific and engineering principles to the protection of life, property and environment from adverse effects of incidents/accidents involving hydrogen (based on [19]).

Hydrogen safety manual: document providing all necessary information for the effective safety management of hydrogen technology, system and infrastructure (based on [19]).

Incident: something dependent on or subordinate to something else of greater or principal importance [90].

Management: person(s) in overall control of the premises whilst people are present, exercising this responsibility either in their own right or by delegation [56].

Methodology: system of methods used in a particular field [90].

Method: way of doing something, especially a systematic way; implies an orderly logical arrangement (usually in steps) [90].

Performance–based hydrogen codes: codes based on the performance of design and the interactions between all the aspects of hydrogen safety (based on [92]).

Prescriptive hydrogen codes: codes prescribing sets of measures to reach the hydrogen safety in hydrogen technologies (based on [92]).

Probabilistic study: the systematic development of numerical estimates of the expected frequency and/or consequence of potential accidents associated with a facility or operation based on engineering evaluation and mathematical techniques [92].

Report of the hydrogen safety engineering study: Report established following a HSE study and gathering all necessary information, calculations, assumptions and findings for assessment by a third party (based on [19]).

Risk: combination of the probability of an event and its consequence [19].

Scenario: set of circumstances, chosen as an example, that defines the development of incident/accident involving hydrogen (based on [19]).

Severity: qualitative or quantitative estimate of the hazard intensity in terms of source intensity, time, and distance [91].

Separation distance: the minimum separation between a hazard source and an object (human, equipment or environment) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident [87].

Tenability: maximum exposure to severity from a hydrogen hazard that can be tolerated without causing incapacitation (based on [19]).

Trial hydrogen safety design: package of hydrogen safety measures which in the context of the technology/system/infrastructure may meet the specified safety objectives (based on [19]).