EXPLOSION AND FIRE RISK ANALYSES OF MARITIME FUEL CELL ROOMS WITH HYDROGEN

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ABSTRACT

A methodology for explosion and fire risk analyses in enclosed rooms is presented. The objectives of this analysis are to accurately predict the risks associated with hydrogen leaks in maritime applications and to use the approach to provide decision support regarding design and risk-prevention and risk-mitigating measures. The methodology uses CFD tools and simpler consequence models for ventilation, dispersion and explosion scenarios, as well as updated frequency for leaks and ignition. Risk is then efficiently calculated with a Monte Carlo routine capturing the transient behavior of the leak. This makes it possible to efficiently obtain effects of sensitivities and design options maintaining safety and reducing costs.

1.0 INTRODUCTION

The regulative framework in maritime demands that new technologies are proven to be as reliable, safe and user friendly as the technologies currently employed. Cost efficient methods to handle the safety and regulatory challenges related to introduction of hydrogen and fuel cells in the maritime sector are therefore needed if these technologies are to be adopted in this sector.

At present, several initiatives are working to introduce hydrogen and fuel cells in ship applications. The motivation varies, but typically a key driver is to reduce greenhouse gas emissions and local pollution. In some instances, hydrogen is a possible contributor to increase energy security, and it is also suitable for storage of surplus intermittent renewable power. Hydrogen used as a fuel in fuel cells can offer a solution for zero emission transport at sea given that the hydrogen production follows a carbon neutral pathway.

Replacing fossil fuels with hydrogen is not currently commercially attractive for most ship owners unless public or private incentives are provided. Land-side infrastructure will need to be developed in parallel with the ship project. Compared to traditional fossil fuels, hydrogen might increase the required fuel on board storage volume. This will however depend on the basis for comparison and varies between application scenarios. In instances where zero or low emission solutions are required, hydrogen fuel cell solutions might provide longer operational range than e.g. pure battery powered solutions. Therefore, several projects evaluate the feasibility of battery – hydrogen – fuel cell – hybrid solutions. Introducing hydrogen and fuel cells in shipping means introduction of new technology for the marine environment. Hydrogen as fuel has several advantages in addition to being a long term sustainable solution: Compared to fossil fuels, hydrogen fuel cells significantly reduce noise and vibration, and with less movable parts they are expected to require less maintenance.

The properties of hydrogen compared to fossil fuels are quite different. Introducing hydrogen as a fuel also introduces possible safety related challenges. Therefore, systematic and structured safety analyses will be required. A key issue is to ensure that such analyses consider the real properties of hydrogen and how hydrogen interacts with its surroundings, including containment materials. Existing competence and experience from other applications areas (e.g. cars, buses, rail and trucks) and with similar fuels (e.g. compressed or liquid natural gas when considering liquid hydrogen) can provide useful input. There are also regulatory gaps that need special attention. Due to the regulatory gaps, there is a need for an overreaching approach that covers the whole development of a maritime hydrogen fuel cell project. Technology Qualification [1] is such an approach, and it was originally developed specifically for introduction of novel technologies and/or known technologies in new environments. The DNV GL Recommended Practice on Technology Qualification [1] describes the usual steps required to carry out this process. It was originally developed for offshore technologies, but has also been successfully applied in other areas. One recent example is the development of large maritime Li-Ion battery systems. The methods for explosion and fire risk analyses described in this paper are examples of analyses that fit into a typical Technology Qualification Process.

1.1 Maritime Regulations

A maritime fuel cell system must satisfy regulatory requirements for on-board power generation systems. In the case of hydrogen as fuel, fuel specific requirements regarding arrangement and design of the fuel handling components, piping, materials and storage will need to be defined [2].

The IGF Code [3], provides requirements for ships using gases and other low flashpoint fuels and it is therefore applicable for hydrogen. The IGF Code came into force on January 1st 2017, and is a mandatory instrument applicable for all ships using such fuels. Requirements for fuel cells will constitute a new Part E of the IGF Code (under development). These will not cover the fuel storage and fuel supply system. Until relevant regulative amendments are finally approved and have come into force, the IGF Code Part A requires applications making use of hydrogen and fuel cells to be covered by the alternative design approach in accordance with SOLAS Regulation II-1/55. This approach is required to demonstrate an equivalent level of safety compared to conventional oil fueled machinery. The IGF Code Part A gives requirements both to conduct a risk assessment of the alternative design and to evaluate explosion consequences.

DNV GL have issued Classification rules [4] for fuel cells installations (Pt.6, Ch.2, Sec.3), and low flashpoint liquid fuels (methanol and ethanol) (Pt.6, Ch.2, Sec.6). Classification rules for gas fueled ships (Pt.6, Ch.2, Sec.5) cover all types of gases in principle, with detailed provisions for hydrogen being planned. Until detailed requirements are in place, approval of ships with hydrogen fuel cells installation will be handled on a case by case basis.

1.2 Previous work on hydrogen safety

Relevant experience with Hazard Identification (HAZID) and Hazard and Operability (HAZOP) studies as well as detailed risk analyses for hydrogen applications exist, but most of these studies have been undertaken for land based applications. A previous paper explored hydrogen risk modeling using a Bayesian network [5]. It used input and results from a traditional Quantitative Risk Assessment (QRA) case study undertaken as part of DNV GL’s engagement in the HyApproval project [6]. The first main step in a QRA process is to undertake a Hazard Identification. This is done to define the risk scenarios to be assessed in further detail in the QRA.

Availability of relevant incident and accident information is important when quantifying risk. Several initiatives to develop such data sources have been undertaken, one example is the HIAD [7] that was developed in HySafe [8]. Another, is the site h2tools.org that aims to share lessons learned related to the use of hydrogen. It is known that hydrogen-related incident experiences have been collected in hydrogen projects, but such information is not commonly available. Therefore, the availability of relevant statistical and hydrogen specific incident and accident information is limited. Whenever possible such information should be utilized, and it might in some instances be possible to obtain some supplementary relevant input directly from vendors, but such data obviously need to be utilized with care. When sufficient statistical data for hydrogen is not available, the solution is typically to use data for hydrocarbon incidents. This represents a source of inaccuracy for any risk assessment, and it is therefore recommended to undertake sensitivity studies to explore the effect of this known uncertainty.

1.3 Explosion Risk Analyses on other objects

Explosion Risk Assessments (ERAs) are required by Norwegian authorities for oil and gas installations [9], and have typically been performed in a probabilistic manner with the use of Computational Fluid Dynamics (CFD) simulations for the consequence assessment. The ERA provides detailed input for the design of the installation to meet a certain safety risk acceptance criteria. This includes design of walls, decks, pressurized or safety critical equipment, safety systems, fire and gas detectors etc. The approach employed systematically in the oil and gas industry has further been applied in the maritime industry to a limited degree: Explosion analyses with CFD have been performed due to safety concerns when e.g. LNG or Li-ion batteries are introduced as an alternative to conventional fuel providing power for propulsion. Maritime authorities typically require that an equivalent level of safety as in a conventional ship can be demonstrated [10] in such cases. The Norwegian Maritime Authority (NMA) requires an explosion analysis to be performed for a ship specific battery space, to demonstrate that the battery space is designed handle the explosion that may occur in a severe battery failure scenario and considering the associated gas generation and composition [11]. DNV GL has applied CFD simulations in multiple analyses to effectively provide such supporting information.

2.0 DETERMINISTIC ANALYSIS AND CONSEQUENCE MODELING

Modelling of consequences is an essential part of a risk analysis and essential to obtain realistic representation of possible accidental scenarios. Consequence models can be used to show the impact of a worst case or a worst credible scenario in a deterministic analysis without considering the frequencies, or be used in a probabilistic analysis where frequencies and probabilities are also included. A possible approach is to start with a deterministic analysis with the worst-case consequences. If this is shown to not cause unacceptable consequences (e.g. escalation) of the event, then the deterministic assessment is sufficient. If the analysis indicates unacceptable consequences, a probabilistic approach can be used to determine if the resulting event frequency is below a certain acceptance level. The probabilistic approach is described in Section 4.0. If only a deterministic approach is used, the identification of a worst credible event (WCE) can be very difficult, and will require in-depth knowledge of possible failure mechanisms and scenarios. The WCE is often also decisive for the design and operation of safety systems. The probabilistic approach is also uncertain; however it provides a much more complete description of the risk.

Several types of consequence models with different level of resolution and accuracy exist [12]. This section focuses on the CFD consequence models and how they are used in a maritime setting. The special features with hydrogen that need to be included in the modeling and design of maritime rooms and safety systems is considered. The expected accuracy and areas of uncertainty is further discussed together with suggested areas of improvements.

2.1 Computational Fluid Dynamics (CFD)

CFD models provide a realistic 3D representation of fluid flow phenomena during an accident and are therefore popular and useful in risk analyses and for design of rooms and safety systems. CFD tools like FLACS (from Gexcon) and KFX (from Computit) have included properties of hydrogen and have been tested with real hydrogen and similar gases for a range of experiments. Such comparisons give an indication of the level of accuracy that can be expected for the different flow phenomena [13]. A database of experiments with hydrogen exists (SUSANA) which can be used to validate models [14,15]. It is essential that the CFD model is validated for hydrogen, and that the user is aware of where uncertainties exist. Dispersion and ventilation CFD models are in reasonably good agreement with experiments on the gross features of the flow and regarding overall integral values such as ventilation rates in a room, and the combustible gas cloud size. Local gas concentration values or velocities are associated with larger uncertainties since flow patterns tend to be shifted slightly compared to experiments. The main sources of errors are the grid resolution, and the turbulence models. Two-equation turbulence models are most popular (e.g. the k-ε model), and such models are a compromise to fit a wide range of types of flows. Therefore, local uncertainty exists even if the grid is fine enough. Ventilation and dispersion codes are usually consistent so that they converge to a constant solution when the grid is refined. A grid resolution study is therefore recommended to eliminate the grid error. Human errors also exist when a model is used. Therefore, a validation exercise against available similar experiments should be performed by the modeler before using them on new situations. This way the modeler can change only the needed parameters, reducing the chance of making mistakes.

To use the CFD code for *optimization* of ventilation system, room design, and gas detector location, and to understand how hydrogen clouds disperse in a complex room, it can be recommended to perform dedicated experiments with hydrogen leaks and ventilation in full scale models of the actual maritime room. Experiments can then be used in combination with CFD codes to first verify the CFD code and second, run the CFD code with a larger number of variations and sensitivities until an optimal design and ventilation is obtained.

Explosion models are typically more uncertain than dispersion models due to use of semi-empirical sub-grid models to represent the rapid deflagration on a relatively coarse grid. Validation blind tests have shown that CFD codes can give one order of magnitude higher or lower values than the explosion pressure measured [13]. The CFD models contain a sub grid model that holds a large part of the energy in an explosion and this causes the solution to be dependent on the grid size to a larger degree than a dispersion model. CFD codes for explosion are therefore not always consistent and the solution changes even when the grid is refined. It is therefore essential that the user follows the code's gridding instructions carefully. If no gridding instructions are provided for hydrogen explosions, the code owners should be contacted for such information.

The effects of explosion mitigating measures, such as relief panels and deluge on gas detection, can be modeled with some CFD tools (e.g. FLACS); however, there is a lack of validation tests that show that the CFD tools can be used for *optimization* of such measures for hydrogen explosions. Hence, experiments where explosion relief panels and water deluge are investigated in real maritime rooms can be recommended. This will provide fabrication data for relief panels, such as size, weight and release pressure, that need to be used to effectively reduce the pressure. Deluge experiments indicate the beneficial effects [16] and similar experiments can be recommended for real engine room configurations. Deluge has shown to give large pressure relief for the extreme high pressures and if the explosion risk is high, deluge may be the last measure that can reduce the low frequency, high consequence events sufficiently.

2.2 Ventilation

Ventilation in a room is governed by fans connected to an air supply and extraction system. When hydrogen leaks are possible, the ventilation system is essential to get the gas diluted and removed from the room. It is the ventilation system that sets up the air flow in the room and therefore it is important to model the inlet and outlet nozzles as realistically as possible with the correct location, direction and release speed and rate. The ventilation simulations can further be used to check that all parts of the room are well ventilated and that there are no dead zones or recirculating flow zones where gas clouds can build up. The ventilation simulations can be used actively to test different fan and nozzle configurations to design the best ventilation system for a hydrogen leak. As described in section 2.3, a specially designed ventilation system may be needed for hydrogen.

2.3 Dispersion

Dispersion of a hydrogen gas leak in a room can have large influence on the flammable cloud size and therefore the explosion and fire risk [16]. A CFD simulation of gas dispersion from a leak should start with a fully converged velocity field from a ventilation simulation. This way the buildup of the gas cloud as a function of time from the leak starts will be simulated. Ventilation and dispersion simulations are often performed after each other, where first the flow pattern seen from the ventilation simulations can be used to guide where to locate the leak. If the leak is in an area with dead or recirculating flow, then a larger cloud can form (provided the leak rate is small). Hence, to be on the conservative side, simulated leaks should be in areas with slow flow in combination with possible leak sources. Designers can also avoid leak sources (piping and valves) in areas with slow air movements.

It is primarily the amount of hydrogen that leaks and the ventilation air flow that governs the cloud size. The flammable cloud size can be classified into three main types depending on the amount of gas coming out, and the ventilation strength.

Lean jet clouds are clouds that have concentrations mainly below Lower Explosion Level (LEL) due to a small leak rate/short leak duration, combined with a good/strong ventilation flow. The jet that forms from the leak will always have a high hydrogen concentration in the core, so that a certain part of the jet will be flammable. However, in the jet the mixing is good due to the jet speed itself, and, if the leak rate is small, this flammable core is too small to cause critical explosion pressures if ignited. The strategy for minimizing the explosion risk in a fuel cell room should be to ensure that only a lean jet cloud can form. This can be achieved by limiting the amount of gas that can leak, combined with a ventilation system that gives a high enough air flow in the room. The aim of the CFD ventilation and dispersion simulations is to show that this is achieved.

It is noted that a large hydrogen jet release can produce a large turbulent jet in which concentrations are in the flammable range. If this is ignited, then a possible high explosion pressure can result if the jet is long enough. Hydrogen jet fire tests performed only for demonstration have produced a pressure wave that can be felt, although tests were not large enough to cause any damage. This phenomenon can occur due to turbulence in the jet which causes a high acceleration and flame speed, and it is believed that a possible deflagration and even deflagration to detonation transition (DDT) can occur if the run-up distance in the jet is long enough. This can happen for a large hydrogen jet in the open air without obstacles present. It can therefore be important to assess the flammable cloud size in large hydrogen jets. Experiments with hydrogen indicate that lengths are quite long, more than 10 m with obstacles, before DDT can happen [17].

Ideally mixed clouds are the second cloud type and have gas concentrations in the flammable range, including downstream in the jet, in the passive flow regime where there is enough gas from the leak to form a flammable cloud. This can create the largest flammable cloud size and it can *in theory* fill the entire room with explosive gas if there is no or little ventilation. The ventilation rate and location of air nozzles have an essential influence on the flammable cloud size for this cloud type. The hydrogen clouds are flammable in a large range of concentrations (from 4.0 to 75%) and can therefore be ideally mixed for a large range of leak rates and ventilation rates. The leak rate and the ventilation rate cause opposite effects on the mixing and cloud size as follows: Increasing leak rate causes a richer cloud and increasing the ventilation rate causes a leaner cloud. Therefore, when the leak rate is below a certain level, it is best to increase the ventilation rate. When the leak rate has exceeded a critical level, increasing the ventilation rate can make the flammable cloud larger. Factors that influence this are mainly the ventilation rate and patterns in the room, and the amount of hydrogen leaked. A strategy to reduce the explosion risk is therefore to ensure that the combination of leak rate and leak duration is below a certain number (by fuel pipe dimensions, internal pressure and Emergency Shut Down (ESD) volumes) combined with a ventilation rate that is high enough to dilute the cloud to a lean jet cloud type. Design of a system that can result in an ideally mixed gas cloud should be avoided, and if the amount of hydrogen is large enough to create an ideally mixed cloud, CFD simulations can be used to design a safe ventilation system or vent panel system.

The third cloud type is *rich clouds. These* occurs when the leak rate is large and the ventilation rate is small so that most of the mixture of hydrogen and air is above Upper Flammability Limit (UFL). A leak growing to become a rich cloud, will always pass through an ideally mixed cloud type. Similarly, a rich cloud that is diluted with air will also become flammable at some point, meaning it will always pass through an ideally mixed cloud type. Therefore, the rich cloud types should also be avoided unless inert gas is used instead of air.

Due to the dual effect of ventilation on cloud size, it is important to consider a representative number of gas leak cases and ventilation rates when performing the gas dispersion simulations. The dispersion simulations should primarily be performed to show that the flammable clouds that can occur are below a critical size. If the cloud size is too large, the leak source should be reduced and/or the ventilation rate should be increased respectively, until the clouds are found to be within a manageable size.

Many combinations of leak locations and ventilation nozzle configuration exist, and the CFD cases need to be selected carefully to be able to represent possible scenarios. Typical input to a risk analysis is the ventilation nozzle configuration, ventilation rates and layout of the fuel cell room. This system design can be called the base case design. Then the possible leak source locations and associated gas jet directions need to be decided. One possible strategy is to select several possible leak locations associated with possible leaks from the fuel supply piping and the fuel cells. Such input could be provided based on a HAZID/QRA. The number of cases should be sufficient to cover the natural variation in cloud sizes arising from the relevant input parameters. These include the initial leak rate, leak profile, leak duration, jet direction and leak location, which all need to be varied across the possible combinations. Expert judgements can contribute to select relevant scenarios that can create large clouds. However, it is often more efficient to run a larger number of CFD cases rather than to rely on judgements. A well-balanced number of cases that is affordable to run and gives the correct picture of clouds is ideal. These cases are suitable for the first assessment of the base case design and configurations. Thereafter, an iterative optimization process can start and be conducted in close cooperation with designers. The CFD analyst can show results from dispersion simulations and explain where gas builds up and indicate reasons why it happens (e.g. large leak rates, or poor ventilation in parts of the room). The designers and the analyst can then cooperate and suggest improvements to the gas detector layout, ESD and/or ventilation system. The improved design can be iteratively modeled until a well-working system is obtained, resulting in an inherently safe design which does not increase construction costs. In some cases, smart design solutions can be found where construction and operation costs are even reduced.

2.4 Explosion

Explosions in an enclosed room will build up pressure due to the expansion that occurs when hydrogen is burning. The resulting pressure follows a simple relation where the pressure increase is proportional to the amount of flammable gas in the room. If the room is filled with 100% stoichiometric air/hydrogen mixture, the explosion pressure in the room will be approximately 8 barg [18]. The burning of hydrogen occurs relatively fast and high pressures are typically reached within 0.2 to 0.5 seconds for typical room sizes. Therefore, venting openings need to respond quickly and be large enough to relieve the pressure within a short time span.

Note the difference between hydrogen explosions in fully enclosed rooms and explosions in open areas with jet turbulence or turbulence created by obstacles. These are two different mechanisms causing explosion pressures. The former is the most critical phenomenon in an enclosed room or box as this can cause an overpressure of 8 barg independent on the dimensions of the box. The latter mechanism needs a certain run-up distance to create a high explosion pressure.

When the room is fully enclosed, CFD explosion simulations are not necessary due to the simple linear relation between pressure and cloud size. The cloud size can first be calculated based on the amount of hydrogen that can leak and dispersion simulations. Then an explosion worst-case pressure can be calculated. If the cloud fills e.g. 1/8 of the room volume, the explosion pressure is approximately 1 barg. Structural assessments should be considered to decide the strength of the room and if venting panels or other measures are needed.

An explosion Dimensioning Accidental Load (DAL) needs to be established for the fuel cell room. To show that the room is sufficiently solid, the explosion risk analysis needs to demonstrate that the DAL pressure is below the design (tolerance) pressure of the walls and decks of the room. Sufficient margins should also be in place to account for uncertainties in the input data and models.

If the explosion DAL pressure can be higher than the actual design pressure, measures such as venting panels need to be installed. Venting panels need to open towards a safe location since there could be a subsequent fire with smoke and heat escaping. The location of the fuel cell room needs therefore to be preferably located on the upper part of the ship, bordering to aft or to the sides. The vent panels can then open towards the sea (if it is high enough above the waterline) or upwards.

Explosion simulations with CFD models are recommended to guide the size, weight and opening pressures of explosion relief panels. Since such panels need to open quickly, the inertia and mass of panels are also important parameters that decide the real relief capacity. Such panels are widely used in offshore process modules. Due to the inertia of the panel, the explosion pressure in the room is only partly reduced. The CFD model can then be used to set the release pressure (pressure when panels will start to open), the size and the mass of the panel. When a possible design is found using CFD models, the panels need to be certified and preferably tested to show that they are constructed per the specifications.

Explosion pressures can also be reduced by suppression agents such as water deluge or inert gas. The pressure reduction effects of water deluge can be significant for strong explosions [19] and this method is used in high-risk explosion areas offshore. Water deluge is then initiated at gas detection at the earliest time when the leak is confirmed. It is important to start the deluge early enough to be able to supress the build-up of a large cloud with the potential to cause an explosion. However, if water is released too early, it can slow down the escape time and cause unwanted water in the room. Therefore, the deluge is often set to start after 3-5 gas detectors have detected gas, thus minimising the chance of deluge being initiated in error. A small *increase* in explosion pressure is further observed from experiments for small gas clouds due to the added turbulence from water droplets. This increase is small compared to the reduction obtained for larger gas clouds; hence if there is a risk of larger gas clouds, the effect of deluge on gas detection is positive overall. Due to the complex effects of water deluge, it is recommended to run CFD simulations with water deluge together with an explosion risk analysis. The present explosion risk analysis can be performed to show the effect on the explosion risk and recommendations can be given based on such quantitative risk analyses.

Release of inert gas during a leak can also be a possible mitigating measure. This can mainly be in narrow enclosures and hoods where there is no space for personnel. CFD dispersion simulations can be performed to assess the rates and amount of inert gas needed. Gas needs to be vented to a safe location, and the inert gas release needs to last long enough until the gas concentration is sufficiently below the flammability limit.

2.5 Fire

Hydrogen can burn giving a very high flame temperature, the flames are nearly invisible, and at the same time the radiation from a hydrogen fire is lower than from a typical hydrocarbon fire. These differences should be considered in a risk analysis. Personnel operating hydrogen systems need to be aware of the risk of invisible flames. The fire impact on structures can be severe due to the high temperature. In the risk analysis, the fire extent and duration is considered to determine the risk of escalation of fire to a neighbouring area. Effect of water deluge is not accounted for in risk analyses for offshore oil and gas installations due to the possibility of clogging of water nozzles or failure of fire detection, etc. In this case, the main barrier against fire escalation will be passive fire protection (PFP) on the walls and decks. A CFD fire analysis can be used to decide if and where PFP is needed. First, the fire design scenario needs to be established. This is the same scenario that is used in the gas dispersion cases and it is assumed that the leak is ignited immediately. The effect of fire detection, and ESD times, and segment volumes and pressures is used to find the fire duration. Here, the hole size and the initial leak rate can give several different fire durations, and it is usually an intermediate hole size that creates the worst fire with the longest duration of a certain size. Typically, 2-3 different fire sizes can be simulated and the impact over time on a structure element can be found. If the impact on the structure is significant enough, the wall and deck need to be covered with PFP. The distance to possible leak locations can also be decisive for PFP needed.

Testing of PFP in hydrogen fires is not common and it may be necessary to run PFP tests due to the different fire properties.

The effect of deluge on a hydrogen fire should be considered carefully. It is not desirable to extinguish the fire if it is in an enclosed room since it can then result in an explosion instead. Deluge therefore needs to be carefully designed, providing enough water to cool the surroundings, without extinguishing the fire. Testing, guided by CFD models of deluge and fires, is recommended to obtain a robust deluge strategy.

2.6 Structure response

Structural response to explosion and fires should also be considered as a part of the risk analyses.

The purpose of the structural response calculations is to demonstrate that the loads from the consequence calculations do not cause a rupture of the walls and an escalation of the incident. Usually the resistance of actual wall and deck design is found and this is compared with the explosion and fire loads from the risk analysis. Separate structural response analyses are applied for explosions and fires. DNV GL Recommended Practices [20,21] are available that can be used for linear and non-linear calculations of the response of walls and plated structures to explosions and fires.

The explosion pressure load inside a small room will act on all walls and decks at nearly the same time with a uniform pressure build-up, like an even pressure increase in a balloon. The pressure increase time is still relatively fast, typically 0.2-0.5 seconds and the rise time can be considered in a dynamic response calculation if the response time of the walls are of the same order as the explosion rise time. More detailed structural response calculations can also be performed with finite element calculations in case the simplified calculations indicate that the strength of the wall or deck is close to the design explosion pressure.

Fire response calculations can also be performed with either simplified or advanced methods. Design fire loads that are obtained from risk analysis should be represented primarily by a heat flux and a duration. Since hydrogen flames are hotter and less radiative than hydrocarbon flames, the fire loads on the structure will be governed by convective heat transfer and not radiative. Heat loads for hydrocarbon fires can therefore not be applied. In the absence of hydrogen standards for heat loads, it is possible to simulate fires with CFD models and obtain the convective heat loads. The convective heat has a strong dependence on the flow velocity in the jet and the distance from the source may therefore be important. The impact area of the fire load is an important input to the structural response calculations; hence the fire design scenario needs to be carefully defined with a leak rate as a function of time and a duration. When the fire impact, with associated duration and size, is established as a part of the risk analysis, the structural response calculations can identify the expected time to heat-up and initiate collapse of a wall or deck. If the wall design is considered unable to withstand the design fire, passive fire protection (PFP) needs to be applied. If the risk analysis identifies the need for large amounts of PFP, a PFP optimization routine can be performed where the actual size and location of the fire is considered together with detailed structural response analyses. Such analyses can be recommended to avoid the hidden risk caused by possible corrosion under PFP materials.

3.0 RISK ANALYSIS METHOD

The computer model Express was developed for calculation of explosion risk in oil and gas process modules/areas [22,23]. In the present work, this model is applied for hydrogen explosion and fire risk calculations in an enclosed fuel cell room. The model includes consequence models for a transient gas leak including the shutdown of the ESD segment, leak rate calculations, gas dispersion modelling, gas detection, ignition, as well as explosion pressure models. The mathematical models are developed as explicit formulae, also called response surfaces, and are implemented in a Monte Carlo simulation routine. An essential input to the generation of response surfaces is results from CFD ventilation, dispersion and explosion simulations. By this approach, the same gas dispersion model is applied to find the detection time, ignition probability and the size of the gas cloud at ignition, as opposed to other stand-alone, individual models where each model has separate assumptions about gas dispersion. By using CFD results from the actual room, generic formulations are avoided, and the need to make conservative assumptions regarding the cloud size is reduced.

The response surface models originally developed for natural gas applications will in principle also work for hydrogen, provided the correct adjustments are made to account for the different properties of hydrogen. All consequence models (response surfaces) are adjusted to fit the CFD simulations, hence, the Express model can be used as it is just by running CFD simulations with hydrogen gas. The leak frequency and ignition models are further adjusted to account for hydrogen.

Due to its general consequence model and the inclusion of explosion mitigation efforts in the models, Express is ideal to determine the most effective explosion mitigation strategy. The following effects may be investigated:

- Air ventilation. The effect of room ventilation rates and nozzle configuration may be obtained through modelling of the changes in ventilation system and the resulting cloud size.
- Room size and confinement. The effect of the room size or covers over fuel cells may be obtained through changes in the gas cloud size and explosion pressure from CFD. If the room or enclosure is fully enclosed, a linear correlation between pressure and gas filling fraction can be used omitting the need for explosion CFD simulations.
- Protection systems. Gas detection, ESD, depressurization (if relevant), and shutdown of ignition sources may be modelled in detail with the transient gas dispersion model. The effects of changed philosophy or settings may be found by simple parameter changes in Express or by running new CFD simulations.
- Explosion vent panels. The effect of venting panels can be implemented from CFD simulations with different panel configurations. Similarly, the effect of explosion suppression agents can be investigated.

The Explosion Risk Analysis method in Express will produce a pressure exceedance curve where the frequency vs pressure can be compared for several different effects described above (see Figure 1). In this context, when several effects are investigated, a prioritization among the measures can be made on an equal basis. This way well-founded and quantified decision support can be provided. Risk drivers are also identified and the method can be used actively to improve explosion and fire risk.

4.0 VENTILATION AND DISPERSION EXAMPLE

An example of ventilation and gas dispersion was modelled for a virtual, hypothetical fuel cell room to demonstrate gas cloud build-up during a leak. The CFD tool FLACS v10.4 developed by Gexcon was used for the simulations. The room modelled was 7x5x3 m^3 in the *x*, *y*, *z* directions, respectively. The fuel cell system was represented by four rows of five stacks, equally distributed, placed on the room’s floor. A pipeline network was added on top of the stacks for different pipeline sizes. It is noted that this is not an authentic room configuration, it is merely an imagined room that is used to show possible effects of ventilation and dispersion.

It was assumed that the air circulation is driven by eight ventilation nozzles, four located at the bottom for air entrance and four at the top for air suction. Inlet was placed low and outlet was high so the airflow followed the natural buoyant flow of a possible small hydrogen leak. The high location of outlet nozzles, flush with the ceiling, is essential to avoid pockets of hydrogen collecting in the ceiling. The nozzles were assumed to be located on opposite sides of the room to attempt to provide a unified flow through the room with minimum re-circulation. The ventilation rate was modelled assuming 30 air changes per hour (ACH) in the room. Due to the turbulent air flow patterns created, no uniform flow was observed in the CFD simulations. The air flow velocity was almost stagnant in most of the room except near the nozzles.

The dispersion simulations were conducted with an example scenario with considering a full rupture of a 20 mm diameter tubing. A HAZID/QRA would in most cases be used as input when defining credible leak scenarios. This was not part of this work, and what is most likely a conservative scenario was selected for illustration. The hydrogen mass flow rate modelled is a *constant* 0.05 kg/s with a direction towards the wall where the air inlets are located. This scenario can be regarded as conservative and possibly worst case since it involves full rupture of the fuel pipe. The case considered also assumes failure in the ESD system with a continuous release of hydrogen from the reservoir. With the closure of ESD valves and a lower pressure in the pipe, the leak rate would quickly be reduced, however, this effect is not included in the simulation. Note that the purpose of this example is to describe the method, and the results should not be used in a risk analysis directly. If the pipe was connected to a single fuel cell, the amount of hydrogen that could leak out after the ESD valves are closed is usually very limited and subject to variation between different fuel cells. A quick and reliable gas detection and shutdown system is therefore essential to limit the amount of gas escaping. Figure 2 shows the explosive and flammable cloud volumes that develop during the first 20 s of the leak. A large explosive cloud is formed already after 5-10 seconds due to the large leak rate. Figure 3 illustrates the hydrogen flammable gas cloud dispersion in the room.

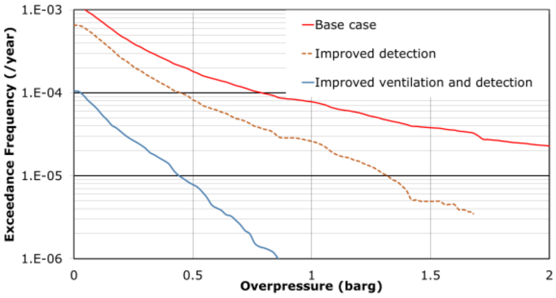

Figure 1. Hypothetical pressure exceedance curve used in sensitivity analysis. Different measures can be compared on an equal basis. High-consequence-low-frequency events can also be compared. The wall design pressure is often associated with an acceptance frequency based on this curve. Note the log scale on the y-axis.

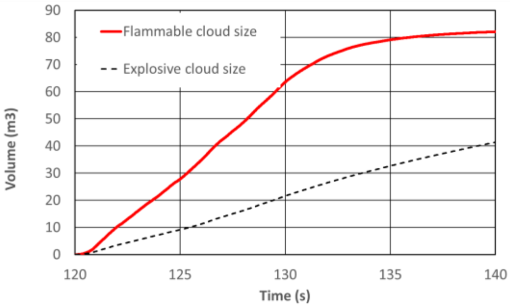

Figure 2. Cloud size development. The flammable cloud volume is the volume of the concentration between Lower and Upper Flammability Limit (LEL and UEL). Explosive cloud is the stoichiometric equivalent cloud size defined and calculated in FLACS (Q8). This cloud belongs to the ideally mixed cloud type in Section 2.3. The leak starts at t = 120s.

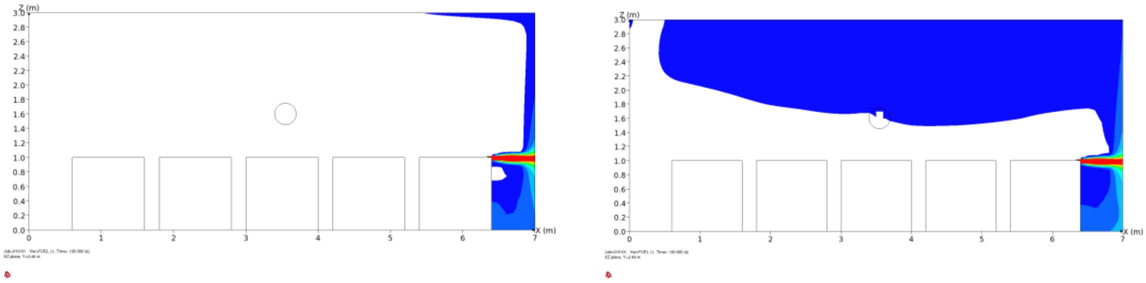

Figure 3. Hydrogen flammable gas cloud dispersion in the engine room after 5s (left) and 10s. XZ cut plan. Red is above UEL, dark blue is LEL concentration.

The simulations demonstrated that the gas cloud grows rapidly inside the room due to the high leak rate. The ventilation rate is low compared to the leak rate and cannot dilute the hydrogen. For such large leak rates, the ventilation rate needed to dilute the gas would be so high that it is not practical.

Therefore, for such scenario, the duration of the leak must be limited to a few seconds. If the leak lasted 8 seconds, it would create an explosive cloud of 13 m^3. This can at most produce an explosion pressure of 1 barg applying the linear relation between cloud and pressure. A probabilistic analysis can be performed to show the frequency of such leak, and it can be used to judge if further mitigating measures such as vent panels and deluge on gas detection need to be implemented.

5.0 CONCLUSIONS

A well-established fire and explosion risk analysis method has been adopted for a maritime fuel cell room. The effect of hydrogen in the enclosed room is the novelty explored. An accidental hydrogen leak scenario was considered, and fire and explosion consequences analysed. Gaseous hydrogen in an enclosed space can theoretically cause up to 8 barg pressure due to the expansion caused by combustion of the gas. Measures that contribute to preventing this scenario are therefore essential to control risk. Successful and fast detection of a leak can initiate system shutdown and closure of the fuel supply by closing ESD valves. This is important to minimize the amount of gas leaked. Further, efficient ventilation can reduce the risk of flammable cloud build-up and ignition. Both the initial leak rate and the duration of the leak are needed to calculate the flammable cloud size. With a given flammable cloud size, the worst case or Design Accidental Load (DAL) pressure can be calculated. Using a probabilistic approach, a DAL pressure can be found that is at an acceptable frequency. This pressure needs to be below the design pressure of the room including a safety margin. A structural response analysis can be run to determine the strength of the room. If the frequency of an explosion that causes escalation out of the room is unacceptable, risk controlling measures such as venting panels and water deluge on gas detection need to be considered. Similarly, for fire risk analyses, first a design fire is defined by a probabilistically-obtained or a credible heat load and a duration. Second, it needs to be shown that the structure can withstand this heat load by a fire response analysis. If escalation can occur, Passive Fire Protection coating may be needed.

Risk analyses are suitable to investigate effects of mitigating and preventative measures to arrive at a safe design, and to show that a final design is acceptably safe. Detailed CFD models are well suited to run sensitivities and provide decision support where safety is thus enhanced, and when the methods are used in close cooperation with designers, smart solutions can be found that are both safe and within affordable limits. With the use of this risk based approach, the number of costly design cycles can be reduced so that the maritime industry can adapt more quickly to the use of hydrogen as fuel.

Several areas of improvements are identified that will further provide increased safety and optimized/robust designs. These involve experimental testing of ventilation and dispersion in real fuel cell room configurations, testing of explosion venting panels, deluge and PFP for hydrogen explosions and fires. Tests should be performed in an almost actual full scale fuel cell room where the leak situations are as close as possible to a real leak scenario to avoid scaling effects and non-linear geometry effects. Systematic tests on mitigating measures would provide the results required to be able to validate the effects in a CFD and risk model.

When such validated models are used, optimal designs can be obtained. These results will provide very useful input in the development of prescriptive rules and regulations for maritime use of hydrogen.

6.0 ACKNOWLEDGEMENTS

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7.0 REFERENCES

1. DNV RECOMMENDED PRACTICE DNV-RP-A203, July 2013 (Source http://rules.dnvgl.com/docs/pdf/dnv/codes/docs/2013-07/rp-a203.pdf).
2. Tronstad, T et al. *Study on the use of fuel cells in shipping, Version 0.1*. EMSA European Maritime Safety Agency (2017).
3. IGF Code: International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels, 2016 Edition (K109E) IMO.
4. DNV GL: Rules for Classification, Part 6, Chapter 2, Section 3 Fuel cell Installations – FC, July 2016
5. Haugom, G.P., Friis Hansen, P and Håland, E, Risk modelling of a hydrogen refuelling station using a Bayesian Network, in *International Journal of Hydrogen Energy,* 36(3):2389-2397 · February 2011.
6. Holmefjord, K. and Haugom, G.P., HyApproval Quantitative Risk Assessment of Hydrogen Refuelling Station with on-site production, DNV Report 2006-1409, Rev 4, Final version for HyApproval Deliverable 4.9, 13th July 2007.
7. Galassi, M, C, et al, HIAD – hydrogen incident and accident database, in *International Journal of Hydrogen Energy, Vol 37, Issue 22: 17351-17357*, Nov 2012.
8. The EC Network of Excellence for Hydrogen Safety "HySafe".
9. NORSOK Standard Z-013 Risk and emergency preparedness assessment, Edition 3, October 2010
10. IMO circular 1455 GUIDELINES FOR THE APPROVAL OF ALTERNATIVES AND EQUIVALENTS AS PROVIDED FOR IN VARIOUS IMO INSTRUMENTS.
11. Norwegian Maritime Authority. Guidelines for chemical energy storage - maritime battery systems, Circular – Series V, 18/7/2016.
12. Molkov V.V. Fundamentals of Hydrogen Safety Engineering. 1st Edition, October 2012, eBook (Part 1 and 2) Freely available at http://bookboon.com/
13. Baraldi et. al. Gap Analysis of CFD Modelling of Accidental Hydrogen Release and Combustion, JRC Scientific and Technical Reports, EUR 24399 EN – 2010
14. S. Coldrick et. al. A model evaluation protocol for Computational Fluid Dynamics (CFD) models used in safety analyses for hydrogen and fuel cell technologies. SYMPOSIUM SERIES NO 160 HAZARDS 25 © 2015
15. FABIG Technical Meeting 87 “Ensuring the Adequacy of CFD Modelling in Safety Engineering” Presentations for download at www.fabig.com. 2016.
16. HySEA Newsletter no. 2, 2016. Available at: http://www.gexcon.com/images/uploads/HySEA_NEWSLETTER_02.pdf
17. L.E. Klebanoff et. al. Comparison of the safety-related physical and combustion properties of liquid hydrogen and liquid natural gas in the context of the SF-BREEZE high-speed fuel-cell ferry. Int. j. of hydrogen energy 42 (2017) 757 e774
18. Baker et al. (1983) Explosion Hazards and Evaluation
19. D. Bjerketvedt and M. Bjørkhaug. Experimental Investigation Effect of Water Sprays on Gas Explosions. UK Dept of Energy, Offshore Technology Report OTH 90 316 (1991).
20. DNVGL-RP-C204 DESIGN AGAINST ACCIDENTAL LOADS (2014). Free of charge at www.dnvgl.com.
21. DNVGL-RP-C208 Determination of Structural Capacity by Non-linear FE analysis Methods (2015)
22. A. Huser, M.L. Eknes, T.E. Foyn, S. Selmer-Olsen and H. J. Thevik “EXPRESS – Cost effective explosion risk management” Proc. ERA conf. London Nov. 2000.
23. A. Huser & O. Kvernvold “Explosion risk analysis – Development of a general method for gas dispersion analyses on offshore platforms” Proc. Parallel CFD 2000 Trondheim May 2000.