BASELINING THE BODY OF KNOWLEDGE FOR HYDROGEN SHOCK INTERACTIONS AND DEBRIS ESCALATION

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ABSTRACT

The differences in behaviour of hydrogen, when compared to natural gas, under deflagration and detonation scenarios are well known. The authors currently work in the area of fire and explosion analysis and have identified what they feel are potential gaps in the current Body of Knowledge (BOK) available to the sector. This is especially related to the behaviour around secondary shock formation and interactions with surrounding structures, especially with 'open' structures such as steel frameworks typically seen in an offshore environment, and practicable methods for determining debris formation and propagation.

Whilst the defence sector has extensive knowledge in these areas, this is primarily in the area of high explosives where the level of shocks observed is stronger than those resulting from a hydrogen detonation. This information would need to be reviewed and assessed to ensure it is appropriate for application in the hydrogen sector.

Therefore, with a focus on practicality, the authors have undertaken a two-phase approach. The first phase involves carrying out a through literature search and discussions within our professional networks in order to ascertain whether there is a gap in the BOK. If good research, guidance and tools to support this area of assessment already exist, the authors have attempted to collate and consolidate this into a form that can be made more easily available to the community. Secondly, if there is indeed a gap in the BOK, the authors have attempted to ensure that all relevant information is collated to act as a reference and provide a consistent baseline for future research and development activities.

1.0 INTRODUCTION

This paper presents the current state of the authors' background research, subsequent discussion and observations, as well as the initial conclusions based on the existing information reviewed.

This work has been conducted from a 'practitioners' point of view as opposed to a pure research project. We have therefore tried to consider the available information in the context of typical 'real world' deployments at different scales, with the associated socio-economic constraints for typical projects. The authors have tried to apply a 'Pareto Principle' to the information gathering process, based on the assumption that if information takes an excessive amount of time to locate and understand it is unlikely to be located or used. It is hoped that this work will assist future reviewers by reducing the necessary effort to identify and reference relevant standards, guidance and information in the future.

The authors will continue this body of work in parallel to their ongoing consultancy work and engagement with the system safety engineering community working on hydrogen deployments.

2.0 METHODOLOGY

The intent of this work is to provide, or at least start the process, of baselining the current Body of Knowledge (BoK) available to support the safety assessment of hydrogen from two distinct aspects:

- Secondary shock formation in the event of a hydrogen Deflagration to Detonation Transition (DDT)

- Practicable methods for determination of debris formation and propagation

The aim is to determine:

- Is there a gap in the BoK relating to hydrogen aspects

- What the available baseline of information is

The search method used the following main threads:

- Conversation and un-structured interviews with authors' professional networks to determine known relevant standards, guidance, papers and established practice that is regularly used;

- Bibliography searches to identify relevant freely available standards, or reference text books regularly used within the community;

- Paper searches on the International Hydrogen Safety Conference Sites for the years 2005 to 2019;

- Review of the Fire and Blast Information Group (FABIG) website

- Paper searches on Elsevier/Sciencedirect using the following search terms: hydrogen, shocks, debris

The items were reviewed at a high level to ensure their relevance and to identify common themes arising from the assessment. The following criteria were used to assess the reviewed information:

- Does it assess shock formation and propagation?

- Does it assess the formation of secondary shocks from structures the initial shock moves over?

- Does it assess the applicability of the assessment to hydrogen shocks?

- Does it assess debris/shrapnel formation?

- Are other relevant phenomena discussed or raised that need to be highlighted?

A 'Pareto Principal' was applied in terms of the effort spent. If standards, guidance, text books or papers are not easily identifiable from this level of search, they would not readily known/accessible to people outside of the experienced academic community but working in the current deployments of hydrogen.

The identified information was then reviewed in the context of the typical deployments the authors are aware of in order to highlight information that was most relevant to this current round of assessment. The relevant information was then recorded, alongside any arising discussion/observations.

Where possible heuristics to qualitatively assess risks associated with secondary shock and debris formation from hydrogen explosions were developed and are presented for further consideration. These will need to be validated.

2.1 Context of methodology

The authors currently work in system safety assurance for hydrogen deployments, and other safety critical sectors, in the UK (and other countries such as Australia). The deployments vary across a range of different applications and are implemented under a range of different economic pressures, degree of safety oversight and potential interactions with 3rd parties / public access to the sites. To help with assessing the information, the authors broadly considered the following different types of hydrogen projects that they are either supporting directly or are aware of being in progress (see Table 1 below):

Table 1. Project Types

Exemplar Project	Size/ Complexity	Degree of Oversight	3rd Party Exposure	Likelihood of Expansion	Offshore
Community power storage	Simple system, providing energy shifting.	< 2 tonnes hazard planning limit	Limited 3rd party access often remote location	No/Maybe	No
Small re-fueller	Simple system, providing energy storage.	< 2 tonnes hazard planning limit	Frequent 3rd party users	Maybe	No
Combined community hub	Multiple distinct systems at single location	< 5 tonnes COMAH limit	Limited 3rd party access often remote location	Yes	Maybe
Integrated local gas grid and hubs	Multiple distinct systems at multiple location	< 50 tonnes COMAH limit	Multiple 3rd parties and systems interfaces	Yes	Maybe
Large SMR with CCS	Large scale complex project, multiple systems, interfaces and locations	> 50 tonnes COMAH limit	Large workforce and potential to impact offsite 3rd parties	Already large scale	Maybe

This is based on the authors current working context of the UK, but it is hoped this provides a consistent baseline for readers to work from.

Many of the smaller projects are being implemented in the UK such as community power projects, private installations on properties such as farms or light industrial estates.

3.0 INFORMATION GATHERED

3.1 Professional networks

Our immediate professional network identified the following publications for the design of structures for blast. They all encourage the use of simplified analysis methods to predict the response of the structure. They guide the engineer towards robust but ductile structural materials, typically steelwork and/or Reinforced Concrete (RC), that absorb the energy of the overpressure wave by plastic deformation. Careful detailing of RC and steelwork structural frames is needed to avoid brittle failure modes. Building structures requiring blast-resistance would tend to avoid the more brittle forms of construction (e.g., unreinforced masonry, glazed elevations). For internal explosions, blow-out panels in walls and/or sacrificial roof spaces are often used to limit the overpressure developing within a confined space. For external explosions shield walls can be useful for protection of existing structures.'

Typical standards and guidance used were:

- ASCE publication Design of Blast Resistant Buildings in Petrochemical Facilities
- TM5-1300 Design of Structures to resist the effects of Accidental Explosions US Department of the Army (1991)
- R3 Impact Assessment Procedure – Magnox/British Energy
- Blast and Ballistic Loading of Structures, by Smith and Hetherington.

3.3 ICHS Conference Papers Review

As anticipated, there are multiple relevant papers from previous ICHS conferences. The following general themes were evident in the papers:

- The majority of relevant papers dealt with either Deflagration to Detonation Transition (DDT) or detonation propagation including sustainment / re-detonation especially around obstacles in the flame flow direction. Whilst these phenomena are related to secondary shocks formation, there does not seem to have been explicit assessment of secondary shocks forming around process pipework and potential constructive or destructive interference between them to create localized overpressure peaks.
- There seems to be little assessment of debris formation although Studer et al [1] and Halim et al [2] do assess deformation of containment materials under internal hydrogen explosion, and Skob et al [3] looks at structural response of structures to hydrogen explosions. The general theme seems to be that debris formation for hydrogen explosions/sudden pressure release is either considered non-credible or is bounded by the thermal and overpressure effects. For example, in Sun et al [4], only thermal and overpressure are considered, but no rationale for that is given. This is consistent with the risk-informed approach to safety distances given in Figure 8 of Dang-Nhu et al [5] which only has thermal harm and overpressure harm considered, but does recognise a general lack of robust data to support Quantified Risk Assessment (QRA). Similarly, Duclos et al [6] have identified missiles under Hazardous Phenomena, but there is no further assessment or rationale for why they are not considered further. Duclos et al [6] discuss the potential for domino failure for which missiles/debris would be obvious candidates. There is an explicit mention of fragment formation (14 kg top half of tank) in Molkov et al [7] during experiments, but it is stated that engineering solutions are being developed to prevent this. Molkov et al [7] also identify a number of missile/debris references including Baker et al [12] the NASA Workbook for predicting pressure wave and fragment effects of exploding propellant tanks and gas storage vessels.
- There is an explicit example of debris resulting in escalation of an accident, as discussed in in Bjerketvedt et al. [8]
- On the whole deflagration and detonation are considered together, such as in Figure 8 of Dang-Nhu et al [5], although of course the severity of the overpressure effects is considered separately. However, this contrasts with the response of physical structures to DDT as illustrated by Royle et al. [9] where the plastic film fragmentation dramatically changes for 100% H_2 ignition.
- There is both simulation and test of shock wave interactions with protective barriers, which highlights the shock diffraction around the end of barriers.

3.2 FABIG

The FABIG repository presents a wealth of information around fire and explosion in the process industry both onshore and off-shore industry. The full review of these could not be completed prior to writing, but one broad theme is that historically a risk-based approach has been adopted to explosion modelling in the offshore sector. These assessments have used Natural Gas (NG) as the primary flammable gas. Therefore, the congestion, confinement, blast protection and blast relief will all have been based around this underlying assumption. As a result, the risk balance arguments used for existing installations would need to be revalidated for hydrogen deployment due to hydrogen's wider flammability and detonation ranges, propensity for flame front acceleration at lower congestion ratios, potential for DDT and resulting different requirements for blast relief design.

3.4 Defence Networks

Within the defence sector, the modelling of shockwaves and the resulting fragmentation in solid structures (such as concrete) is routinely undertaken and well understood. The authors engaged with various contacts within the defence sector to understand whether this work could be used to determine debris formation and propagation after a hydrogen detonation event. The modelling team at BAE Systems Glascoed were consulted regarding how fragmentation might be modelled using the current software available. Although modelling blast waves within structures is standard, it became apparent that modelling blast propagation within more open structures (such as those seen for offshore platforms) was not widely used within the sector. This poses problems for modelling where destructive and constructive shockwave interference might occur and therefore understanding the shock loading different parts of the structure may be exposed to during an event. If this were better understood, it would be possible to alter the input parameters for current software programmes to predict blast propagation through structures and therefore determine debris formation and propagation.

3.5 Other Information

Two other specific papers were identified during this work that were of relevance. These were:

- Telford [10] which discusses the application of the R3 methodology mentioned above. This provides bounding impact assessment methodologies for a number of impact criteria including missiles

- Basco et al [11] which presents a simplified model for assessing the Johnson's number for a number of scenarios including overpressure, shock and missiles/debris.

4.0 DISCUSSION

Although the authors have not completed their search the following general themes and areas of follow up have been identified:

- Secondary shocks due to interactions with piping etc. at installations, and subsequent constructive or destructive interference of those secondary shocks, is not currently assessed explicitly.

- Whilst there appears to be a wide range of standards and guidance around debris/missiles associated with gas explosions, this does not seem to be explicitly assessed in the risk assessment methodologies for hydrogen systems reviewed to date. This may because the community has already reached a conclusion that it is incredible or dominated by thermal and overpressure effects, but this rationale is not currently explicit captured as far as the authors can see. However, debris/missiles would seem to be a potential 'Black Swan' escalation path, and it is credible for Control and Instrumentation (C&I) to be damaged, even if penetration of vessels is not considered credible for hydrogen explosions.

- There appears to be two slightly different risk regimes for hydrogen system incidents/accidents divided by DDT. Below DDT, thermal and overpressure effects are comparable with other flammable gas explosions, but above DDT the potential effects are different not solely due to overpressures and thermal effects but also structural/material dynamic responses. The transition between < DDT and > DDT is not a linear relationship and is dependent on several factors including congestion and constriction.

- The current offshore explosion protection is based on a risk assessed approach based on the parameters for NG. This means that currently installed fire and explosions may not be appropriate for hydrogen explosions, especially where DDT may be likely due to the already accepted degree of congestion and constriction. This is especially of relevance where re-purposing of old Oil & Gas (O&G) infrastructure is being considered.

- Whilst there is extensive modelling capability for fire, explosion and potential debris formation and escalation this may not be appropriate for the smaller scale deployments as they will constrained by both economics of their projects and their own technical competence to identify the need for and understand the outcomes of these assessments. In addition, it is anticipated that many of these small-scale installations may be added to over time if initially successful, and the authors have concerns about the management of change of these developments.

- From the authors experience there are currently in place, and planned, small scale hydrogen deployments where both congestion and constriction will be present at the same time i.e., at the open end of a U-shaped fire walled bay for a storage vessel, where the manifold and instrumentation will be at the open end of the fire wall as demonstrated in Figure 1.

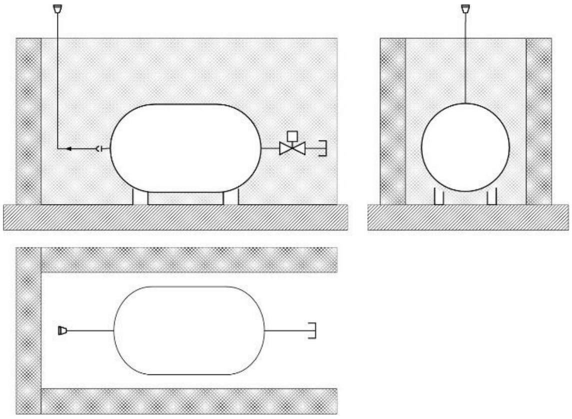

Figure 1. Typical small-scale hydrogen storage schematic with fire wall

The concern here is the configuration could credibly lead to the necessary DDT conditions at the open end of the bay. In addition, if the bay is part of an array with multiple storage vessels, there is the scenario where shock diffraction could result in the adjacent bay having its manifold and associated control & instrumentation impacted as shown in Figure 2.

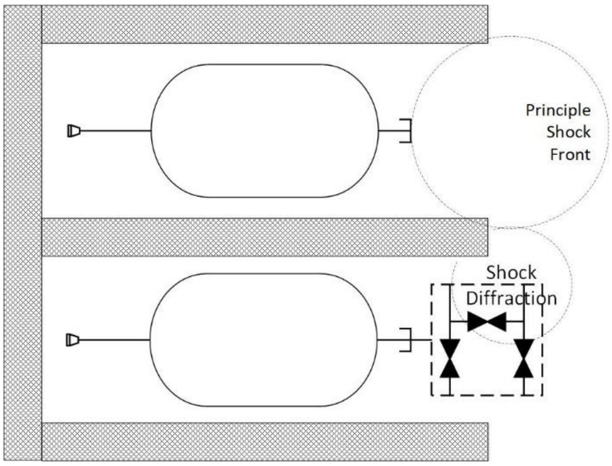

Figure 2. Shock diffraction into adjacent bay end

5 CONCLUSIONS

The authors are planning to continue with the following:

- Continue with the identification of available guidance and standard for debris/missiles, with a focus on publicly available literature, to act as a repository for the community

- Continue with discussions in the defence community around shock modelling especially around secondary shock formation and interactions

- Assess whether the Recommendations below are already covered by information not yet reviewed

The authors are also proposing the following recommendations for consideration by the community:

- A step should be added in the early stages of the risk assessment methodologies, where the potential exacerbating factors for DDT and potential sources of debris/missile formation are considered for the specific system being considered. This stage should be qualitative/deterministic and capture the rationale for whether DDT and/or missile formation is considered credible for that specific installation. Only if they are considered credible should the assessment move to probabilistic/quantified assessment. This is a similar approach that is used within the civil nuclear sector.

- There should be consideration for different severity classifications in the conflagration and DDT regions to account for the different structural responses at the same overpressures, or some way of linking impulse duration to broad categories of structure response

- The R3 method and the approach laid out in Basco et al [11] seem to provide a basis for relatively simple assessment of credible missile/debris scenarios. These could be used as the basis for the initial qualitative/deterministic assessments to determine if debris/missiles should be considered further. These could/should be developed as a set of conservative but valid heuristics that could be applied for small scale projects where they are unlikely to undertake extensive CFD or computer modelling due to both economic and technical constraints.

- The offshore O&G sector will have a non-trivial task to re-assess current fire and explosion protection for hydrogen use on re-purposed assets. There are valid areas for experimentation (if these are not happening) looking at thin-walled steel blast protection response to shock and potential brittle fracture. Also, how fire protection responds to shock (will it stay in place and provide same time period of protection?), as well as the underlying assumptions around escape and evacuation and the protection of escape routes. The current O&G offshore installations accepted congestion and confinement will also have be reviewed in the light of hydrogen's DDT propensity

- For installations where there are multiple storage containers in bays, there should be consideration made of the following configuration to reduce the likelihood of escalation due to shock diffraction and/or debris

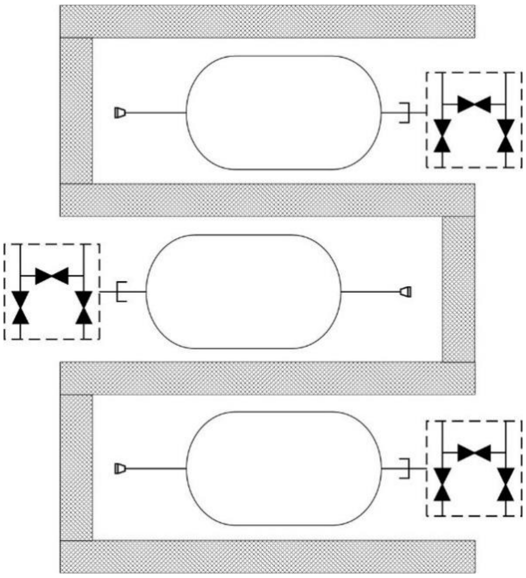

Figure 3. Alternative configuration for adjacent storage bays

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