Institution: University of Ulster

Unit of Assessment: 16 Architecture, Built Environment and Planning

Title of case study: Advancing Safety of Hydrogen and Fuel Cell Technologies: HySAFETY

1. Summary of the impact (indicative maximum 100 words)

The adoption of hydrogen and fuel cell systems provides one solution to fossil fuel depletion, security of energy supplies and sustainability concerns. However, safety is a key technological barrier to the hydrogen economy. The technological impact of this case study is the adoption of research outcomes, from work undertaken by the Hydrogen Safety Engineering and Research centre (HySAFER), Built Environment Research Institute into international regulations, codes, and standards (namely Commission Regulation (EU) No.406/2010, and the international ISO/TR15916), and development of novel safety strategies, guidance, protocols, and engineering solutions supported by significant external research funding.

2. Underpinning research (indicative maximum 500 words)

Hydrogen safety is a multi-disciplinary research area with numerous knowledge gaps concerning releases, dispersion, ignitions, fires, deflagrations, detonations, effects on materials, and mitigation techniques. Research at the University of Ulster, utilising facilities developed under EPSRC/JIF funding (grant 3a), dates from work into modelling and large eddy simulation (LES) of industrial scale deflagrations i.e. "explosions". Molkov and Makarov (staff since 1999 and 2000 respectively), first showed that vented deflagration overpressure is an indirect function of flow turbulence and combustion instabilities (ref 3.1). They collaborated with Shell (2006) discovering the phenomenon of coherent deflagrations (ref 3.2), explaining the physical reason for deflagration severity in low strength equipment and buildings. Partnership with industry (Tamanini/FM Global/USA) and academia (Dobashi/University of Tokyo/Japan) (grant 3b) provided the limits for vent cover inertia, ensuring there is no reduction in the effectiveness of deflagration mitigation when venting and informing EU guidance as outlined in Section 4.

HySAFER (Molkov/Makarov) became a partner in the European Network of Excellence "Safety of hydrogen as an energy carrier" (2004) (grant 3c) expanding the scope of the group's research to other physical phenomena underpinning hydrogen safety. A significant number of research grants followed (Section 3) facilitating outputs and informing guidance and technology development.

Hydrogen can permeate (similar to "seepage") through the walls of a storage vessel. In an enclosed space such as a garage this permeation and dispersion may result in a flammable atmosphere unless regulated. Research in HySAFER by Saffers (researcher 2008-2011, lecturer 2011-2012), Makarov and Molkov in 2010 demonstrated the maximum rate of permeation of hydrogen from an onboard storage tank is sufficiently low, such that there is no flammable mixture formed, even on the tank surface. Together with partners Volvo (Sweden), CEA (France) and NSRCD (Greece) a safe permeation rate limit of 6.0 Ncm^3 of hydrogen per hour per litre of container internal volume was established (ref 3.3). This rate limit was adopted into European Regulation No.406/2010 as outlined in Section 4 (sources 5.1 and 5.2).

The release of hydrogen in the form of a jet is the start of most accidents and is usually followed by jet fire and/or explosion. The ability to predict the behaviour of unignited and ignited jets (fires) is fundamental for calculating separation distances. Typically hydrogen releases occur from high pressure meaning the jet is "under-expanded", thus it is important to understand how an under-expanded jet behaves. In 2008 Molkov, Makarov and Bragin (researcher/lecturer 2006-2012) developed an original "under-expanded jet theory" which accounted for flow losses and hydrogen's non-ideal behaviour at high pressures. This theory enabled conditions at the jet exit to be calculated. In 2010, Molkov and Saffers validated the similarity law for concentration decay in under-expanded jets. This meant the similarity law could be used as a means of calculating separation distances for unignited jets. Hydrogen's buoyancy impacts on separation distances as a horizontal jet will begin to rise as it loses momentum. Thus separation distances can be significantly reduced using the correlation for momentum-to-buoyancy-controlled flow transition in non-reacting/reacting jets. Initial work on jet fires was reflected in the HYPER guidance (grant 3d) and the novel jet flame length correlation developed by Molkov/Saffers has become the cornerstone for hydrogen safety engineering (refs 3.3 and 3.4).

Pressure relief devices (PRD) are mandatory for hydrogen onboard storage, they enable a gas tank to empty in the event of fire, preventing catastrophic failure. HySAFER has developed innovative designs to reduce the jet length from a PRD as demonstrated by the underpinning work on under-expanded plane jet behaviour (ref 3.5).

In 2010 Brennan (researcher 2007-2008, lecturer since 2008), Molkov and Makarov discovered the pressure peaking phenomenon for unignited indoor releases of hydrogen, and drastically changed the requirements for engineering calculations of ventilation system parameters. The research demonstrated that a release indoors can lead to overpressures capable of compromising the integrity of a structure (ref 3.6) and thus pressure peaking phenomenon should be accounted for in design. In addition, this work and that on PRDs highlighted the need for improved ventilation systems, PRD design, and increased fire resistance of hydrogen storage tanks (grants 3e, 3f and 3g).

3. References to the research (indicative maximum of six references)

The quality of the underpinning research is evidenced through the publication of scientific papers in peer reviewed journals; a number of the key publications by the research group are listed below. A leading definitive text on Hydrogen Safety Engineering by Molkov in two parts is referred to, as these volumes incorporate key research findings by the HySAFER group.

3.1 Molkov, V, Dobashi, R, Suzuki, M and Hirano, T (1999) Modelling of Vented Hydrogen-Air Deflagrations and Correlations for Vent Sizing, *Journal of Loss Prevention in the Process Industries*, Vol.12, pp.147-156. http://www.sciencedirect.com/science/article/pii/S0950423098000497

3.2 Molkov, V, Makarov D and Puttock, J (2006) The nature and large eddy simulation of coherent deflagrations in a vented enclosure-atmosphere system, *Journal of Loss Prevention in the Process Industries*, 19, (2-3), pp.121-129. http://dx.doi.org/10.1016/j.jlp.2005.05.006

3.3 Molkov, V (2012) Fundamentals of Hydrogen Safety Engineering I, www.bookboon.com, ISBN 978-87-403-0226-4.

3.4 Molkov, V (2012) Fundamentals of Hydrogen Safety Engineering II, www.bookboon.com, ISBN 978-87-403-0279-0.

3.5 Makarov, D and Molkov, V (2013) Plane hydrogen jets, *International Journal of Hydrogen Energy*, 38, pp. 8068-8083. http://dx.doi.org/10.1016/j.ijhydene.2013.03.017

3.6 Brennan, S and Molkov, V (2013) Safety assessment of unignited hydrogen discharge from onboard storage in garages with low levels of natural ventilation, *International Journal of Hydrogen Energy*, 38, pp. 8159-8166. http://dx.doi.org/10.1016/j.ijhydene.2012.08.036

The research underpinning this case study is the result of extensive funding. Selected grants awarded to the HySAFER team which have contributed to the impact are listed below; the first grant (3a) was significant in that it financed the research facility.

3a Boyce, Molkov and Nadjai
Fire safety engineering research facility
EPSRC/JIF
01/12/2000 – 30/11/2003
£5,506,589

3b Molkov
Vented Gaseous Deflagrations in Enclosures with Inertial Vent Covers
EPSRC/Fast Stream
16/08/2001 – 15/08/2003
£62,072

3c Molkov, Makarov and Novozhilov
HySafe: Safety of hydrogen as an energy carrier
CEC - FP6 Sustainable Energy NOE
01/03/2004 – 28/02/2009
£183,973

3d Molkov, Dahoe and Makarov
HYPER: Installation permitting guidance for hydrogen and fuel cells stationary applications
CEC - FP6 Sustainable Energy STREP
01/11/2006 – 31/01/2009

£98,703

3e Molkov, Brennan and Makarov
H2FC: Integrating European Infrastructure to support science and development of hydrogen and fuel cell technologies
CEC FP7 Infrastructure
01/11/2011 to 31/10/2015
£460,899

3f Molkov, Brennan and Makarov
HyIndoor : Pre-normative research on safe indoor use of fuel cells and hydrogen systems
CEC FP7 Fuel Cell Hydrogen – JU
02/01/2012 to 01/01/2015
£276,924

3g Molkov and Makarov
Hydrogen and Fuel Cell Supergen Hub
EPSRC – Supergen Hydrogen & Fuel Cell Hub
01/05/2012 to 30/04/2017
£186,453

4. Details of the impact (indicative maximum 750 words)

The *significance* of the underpinning research carried out at HySAFER has been through informing International Regulations, Codes and Standards and developing guidance documents with a *reach* across a range of stakeholders. More specific examples of these are detailed below. The work has contributed directly to inherently safer technological design.

Research collaboration between HySAFER and Volvo/CEA/NSRCD described in Section 2 has resulted in justification of the hydrogen permeation rate limit of 6.0 Ncm^3/h/L. This significant published research finding was first presented to the EC and UN ECE in 2009-2010 and was subsequently adopted into section 4.2.12.3 of the European Regulation on type approval of hydrogen-powered vehicles (sources 5.1 and 5.2). Likewise, HySAFER's permeation research, discussed in Section 2, was included in the UN ECE Draft Global Technical Regulation (GTR) for Hydrogen Fuel Cell Vehicles (source 5.1). The *significance* of the European Regulation stems from its EU wide legally binding status and the first to be hydrogen specific. This regulation facilitates and enables the wider introduction of hydrogen vehicles thereby impacting on the automotive industry in Europe and having global *reach* as vehicles must satisfy this European Law. The UN Global Technical Regulations provide a framework for the global automotive industry, consumers and their associations.

HySAFER is actively involved in the development and review of standards for ISO/TC 197 Hydrogen Technologies and participates in the International Energy Agency (IEA) Hydrogen Implementing Agreement (HIA) Task 31 Hydrogen Safety. HySAFER's research, presented to ISO/TC 197 (source 5.3), on the pressure peaking phenomenon and fire resistance of storage tanks with a PRD has been incorporated into the recently revised ISO/TR 15916 "Basic considerations for the safety of hydrogen systems" (sources 5.3 and 5.4). This reference document is widely used by the hydrogen and fuel cell industry with a global *reach.* Its *significance* is in setting the benchmark for safety of hydrogen systems.

As described in Section 2, HySAFER's expertise originally stemmed from work on deflagrations, in particular venting of deflagrations and the development of a vent sizing methodology. This vent sizing methodology and an engineering nomogram to estimate separation distances for high pressure releases and jet fires has been included in The European Installation Permitting Guidance for Hydrogen and Fuel Cell Stationary Applications (source 5.5). The *significance* of this guidance, developed in 2009 by a European and North American Consortium to address industry needs, is in providing a compendium of information with a *reach* across a variety of stakeholders including use by the hydrogen and fuel cell industry. The document was subsequently adopted by the Health and Safety Executive for application in the UK (sources 5.5, 5.6 and 5.7).

The European hydrogen industry (New Energy World Industry Grouping, http://www.new-ig.eu/members) formulates requirements for industry-driven safety research in Europe through the Fuel Cell and Hydrogen Joint Undertaking (FCH JU). The international experts group, including Molkov, published the Reference Report on CFD Gap Analysis (http://publications.jrc.ec.europa.eu/repository/handle/111111111/15294) based on research carried out at HySAFER with *significance* in terms of influencing the European Commission's funding priorities and specifically the FCH JU Annual Implementation Plan 2012 and related funding call January, 2012 (source 5.8).

The physical separation distance from hydrogen systems can be comparatively large with practical and cost implications arising from land values. The *significance* of safety devices such as PRDs as part of hydrogen systems is in providing a mechanism to reduce separation distances and hence cost. Research at Ulster into improved fire resistance of hydrogen storage tanks and PRDs that reduce flame length by an order of magnitude has led to a patent application (source 5.9). A discussion document on hydrogen safety devices issued by the UK Health and Safety Executive's Health and Safety Laboratory (source 5.7) incorporates the PRD work at HySAFER. Industrial gas company Air Liquide has been using HySAFER's research, specifically vented deflagration methodology, flame length correlation and the nomogram for pressure peaking to inform their internal design and industrial guidance (source 5.10).

The *significance* of research at HySAFER has been its use by industry to improve product design, enabling the development of inherently safer technologies. In this context, research on releases and fires has provided the framework for assessing safety distances and developing safer commercial designs. A key example that illustrates industry relevance was a design study (2011) for a home refueller for 700 bar hydrogen-powered vehicles. This ITM Power led project for the US Department of Energy used HySAFER's modelling approach for unignited jets. Furthermore, a safety strategy developed at HySAFER was adopted by ITM Power with direct impact on their product development. Specifically the results for hydrogen release within confined spaces were used to modify their control system and hardware solutions to predict the behaviour of an unplanned release and the design of a safety case. This facilitated ITM Power's certification and compliance activities ensuring that the company produces safe, reliable products for the growing hydrogen economy with a potential *reach* across different economic sectors (source 5.6).

5. Sources to corroborate the impact (indicative maximum of 10 references)

Electronic copies of all sources including web links can be provided.

5.1 Corroborating statement 1 – Research Engineer, Volvo Group Trucks Technology.
5.2 Commission Regulation (EU) No 406/2010 of 26 April 2010 implementing Regulation (EC) No 79/2009 of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles. Section 4.2.12.3, page 86. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:122:FULL:EN:PDF
5.3 Corroborating statement 2 - President, International Association of Hydrogen Safety.
5.4 ISO/TR 15916. Basic considerations for the safety of hydrogen systems. ISO Technical Committee 197 Hydrogen Technologies. (4.1.3.5, 4.2.5, 5.2.3.2, 6.3.1, 6.4.2, 7.2.1, 7.5.11, E.94 reference 13 p 60).
5.5 Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version, Health and Safety Executive 2009 http://www.hse.gov.uk/research/rrpdf/rr715.pdf p33 utilises research from HySAFER's input into the HYPER Installation Permitting Guidance, which was used as the basis of this UK guidance (http://www.hyperproject.eu/)
5.6 Corroborating statement 3 - Technologist, ITM Power Plc.
5.7 Corroborating contact 4 - Head of Explosion Safety Unit, Health & Safety Laboratory.
5.8 Fuel Cells and Hydrogen Joint Undertaking, Annual Implementation Plan 2012, European Commission, (Section 3.3.5 & page 95) http://www.fch-ju.eu/sites/default/files/FCH%20JU%20Annual%20Implementation%20Plan%202012%20-%20final.pdf
5.9 Patent Application WO 2012/143740 A2, International Application Number PCT/GB2012/050895 "Gas Storage" (International Filing Date 23 April 2012).
5.10 Corroborating statement 5 - R&D Project Coordinator, Air Liquide.