Institution: Ulster University

Unit of Assessment: Architecture, Built Environment and Planning (13)

Title of case study: Supporting the Inherently Safer Deployment of Hydrogen Systems and Infrastructure by informing Regulations, Codes and Standards (RCS): HySAFER-RCS

Period when the underpinning research was undertaken: January 2000 to December 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Prof Vladimir Molkov	Professor of Fire Safety Science	1999 – present
Dr Dmitriy Makarov	Reader in Hydrogen Production and Storage	2000 – present
Dr Sile Brennan	Senior Lecturer in Hydrogen Safety	2007 – present
Dr Volodymyr Shentsov	Lecturer in Hydrogen Safety	2014 – present
Dr Sergii Kashkarov	Research Associate in Safety Engineering	2016 – present
Dr Donatella Cirrone	Research Associate in Safety Engineering	2018 – present

Period when the claimed impact occurred: August 2013 to December 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Hydrogen Safety Engineering and Research (HySAFER) Centre's research addressed key knowledge gaps and technological bottlenecks in the safety of hydrogen technologies. The research has informed science-based Regulations, Codes and Standards (RCS), supporting deployment of technologies by providing the technical requirements to achieve safety. The impact is the adoption of Ulster research into international RCS. Specifically, HySAFER research has:

I1: Informed International RCS through activities of Working Groups (WGs) of UN GTR#13/IWG/SGS, CEN/CENELEC/JTC6 and ISO/TC197.

I2: Supported deployment of hydrogen technologies through provision of safety guidance: European Guidelines on Fuel Cell Indoor Installation and Use; European Model Evaluation Protocol; and the European Emergency Response Guide.

I3: Provided novel engineering tools of the e-laboratory in Hydrogen Safety for stakeholders.

I4: Devised design of innovative fire test protocol, invented breakthrough safety technology.

I5: Impacted European funding priorities.

2. Underpinning research

HySAFER studies described in the seminal work by Molkov (2012, **R2**), have been built upon research which began in 2000 and 30 externally funded projects in the area of hydrogen safety (e.g. **G1** 2012-15**, G2** 2013-18). These include but are not limited to: the similarity law (Molkov, **R2**), the pressure peaking phenomenon (PPP) (Brennan/Molkov/Makarov/Shentsov), correlations for vented deflagrations including non-uniform and localised mixtures (Molkov/Makarov), dimensionless jet-flame length correlation (Molkov, **R2**), hydrogen inventory limit for a warehouse-like space (Makarov/Molkov) and passive ventilation theory (Molkov/Shentsov, **R1**).

Key knowledge gaps have been addressed including a contemporary computational fluid dynamics (CFD) model for dynamics of blast wave and fireball after hydrogen tank rupture in a fire in the open atmosphere, most recently published (Molkov/Cirrone/Shentsov/Makarov, **R6**), a reduced model (Makarov/Shentsov/Molkov) and a CFD model for the PPP for jet fires (Brennan/Hussein/Makarov/Shentsov/Molkov, **R5**). Considerable work has been completed to understand the behaviour of a high-pressure tank in a fire; this has included a conjugate heat transfer CFD model and theoretical blast wave decay theory. The study on thermally protected tanks is completed (Makarov/Kashkarov/Molkov, **R4**). The *significance* and *reach* of the HySAFER research is in breakthrough safety strategies and innovative engineering solutions, e.g. explosion free in a fire composite tank without thermally activated pressure relief device (TPRD) as per EU patent application No.18706224.5 dated 05/09/19, which are utilised by stakeholders globally.

External grants (Section 3) amalgamating research, education/training, and outreach activities underpin the significance, rigour and originality of the research to inform international RCS (**I1**).

Hazard distances from hydrogen systems have cost implications arising from land values. Before Ulster work, no validated models existed to estimate hazard distances from a fireball and blast wave following rupture of storage vessels at pressures up to 100 Megapascals (MPa) in a fire. It was demonstrated for the first time in 2015 (Molkov/Kashkarov) and confirmed recently by detailed numerical study (Molkov/Cirrone/Shentsov/Makarov, **R6**) that the assessment of hazard distances must account for contribution of hydrogen combustion at contact surface to the blast wave strength. This research paved the way to understanding of a slow decay of blast wave and unacceptably high velocity of fireball propagation, which led to the HyTunnel-CS funding (**G5** 2019-22). Research on IP-protected breakthrough safety technology on explosion free in a fire TPRD-less tanks (**G2** 2013-18**, G3** 2017-19) with industrial partners Hexagon-Lincoln (USA), Sherwin-Williams (UK), Pro-Science (Germany), Optimum CT (USA) and Authorised Testing (USA) solved the problem of devastating consequences after tank rupture in a fire (including blast wave, fireball, projectiles). The use of two composites in the load-bearing wall with properties defined by Intellectual Property allows the hydrogen-impermeable liner to melt and start release of hydrogen in a form of microleaks through the wall before tank rupture. This multi-disciplinary inter-sectoral study highlighted the importance of the revealed tank failure mechanism in fire and led to the breakthrough leak-no-burst safety technology for hydrogen storage composite tanks for onboard and stationary applications (**I4**). Three different series of prototypes of TPRD-less tanks were successfully manufactured and tested in the USA. At the same time the influence of specific heat release rate on fire resistance rating and test reproducibility in different laboratories was discovered, underlining the need for change in the fire test protocol of the Global technical regulation on hydrogen and fuel cell vehicles (GTR#13) (**I1**).

Ulster with Maryland (USA) developed passive ventilation theory, enhancing safety by correcting previous faulty engineering methodology which either underestimated hydrogen concentration in air twice for lean mixtures or overestimated twice for rich mixtures (Molkov/Shentsov, **R1**).

Previous research demonstrated that structural integrity can be compromised by PPP (Brennan/Molkov, **R2**). Recently the PPP for experimental ignited releases has been investigated theoretically and numerically, and highlighted safety concerns in high-pressure storage previously considered “safe”. The numerical study (Brennan/ Shentsov/ Makarov/Molkov, **R5**) gave insights into the phenomenon. Recommendations to improve the technology have been realised by OEMs, e.g. Daimler and Toyota reduced their TPRD diameter to 2mm. The requirement to address the PPP is implemented in ISO standards (**I1**), and an engineering tool of e-Laboratory to predict overpressure during an ignited release was developed (**G4** 2017-2021).

Localised vented deflagrations and their mitigation techniques were not studied until recently (Makarov/Molkov**, R3**). The theoretical model was developed and validated against HSE (UK) and KIT (Germany) experiments. The study revealed that only a fast-burning fraction of non-uniform flammable mixture contributes to the maximum vented deflagration overpressure. Ulster’s unique CFD deflagration model is used by industry and academia in Canada, Greece, Japan, Poland, and UK (Shell) (**I3**) informing safe design of Fuel Cell and Hydrogen (FCH) systems and infrastructure. A thermodynamic model for deflagration overpressure in closed space such as a warehouse was developed and validated which shows that hydrogen inventory in an enclosure without vents should not exceed the amount that, when divided by the enclosure volume, gives an average volumetric concentration below 0.3% by volume (Makarov/Molkov, **R3**), i.e. far below the lower flammability limit of 4% by volume.

3. References to the research

The quality of the underpinning research is evidenced through the publication of scientific papers in leading peer-reviewed journals and the only monograph in hydrogen safety engineering in the world. Six of many publications by the research group are:

R1: Molkov, V, Shentsov, V and Quintiere, J (2014) Passive ventilation of a sustained gaseous release in an enclosure with one vent. *International Journal of Hydrogen Energy*, 39, pp. 8158-8168. 10.1016/j.ijhydene.2014.03.069.

R2: Molkov, V (2012) Fundamentals of Hydrogen Safety Engineering I and II, www.bookboon.com, ISBN 978-87-403-0226-4 and ISBN 978-87-403-0279-0.

R3: Makarov, D, Hooker, P, Kuznetsov, M and Molkov, V (2018) Deflagrations of localised homogeneous and inhomogeneous hydrogen-air mixtures in enclosures. *International Journal of Hydrogen Energy*, 43 (20), pp. 9848-9869. 10.1016/j.ijhydene.2018.03.159.

R4: Kim, Y, Makarov, D, Kashkarov, S, Joseph, P and Molkov, V (2017) Modelling heat transfer in an intumescent paint and its effect on fire resistance of on-board hydrogen storage. *International Journal of Hydrogen Energy,* 2 (11), pp. 7297-7303.

10.1016/j.ijhydene.2016.02.157.

R5: Brennan, S, Hussein, HG, Makarov, D, Shentsov V and Molkov, V (2019) Pressure Effects of an Ignited Release from Onboard Storage in a Garage with a Single Vent. *International Journal of Hydrogen Energy*, 44 (17), pp. 8927-8934. 10.1016/j.ijhydene.2018.07.130.

R6: Molkov, V, Cirrone DMC, Shentsov V, Dery W, Kim W and Makarov, D (2020) Dynamics of blast wave and fireball after hydrogen tank rupture in a fire in the open atmosphere. *International Journal of Hydrogen Energy,* In Press. 10.1016/j.ijhydene.2020.10.211.

The research underpinning this case study is the result of extensive funding. Over the course of the REF period around GBP3,000,000 was awarded to the HySAFER team. Five of twenty grants from Research Councils (EPSRC), H2020 and The Regional Economic Development Agency for Northern Ireland (Invest NI) performed in 2014-2020, which have contributed to the impact, are listed below. HyTunnel-CS, whilst still ongoing, has already impacted upon standard bodies (**I1**).

G1: Molkov, Brennan and Makarov
HyIndoor: Pre-normative research on safe indoor use of fuel cells and hydrogen systems
CEC-FP 7-FCH-JU
02/01/2012 - 01/01/2015
GBP276,924

G2: Molkov, Makarov, Shentsov and Kashkarov
EPSRC Supergen Challenge: Integrated safety strategies for onboard hydrogen storage systems
EPSRC
15/10/2013 - 31/12/2020
GBP970,514

G3: Molkov, Makarov and Kashkarov
Composite tank prototype for onboard hydrogen storage based on novel Ulster's leak-no-burst safety technology
Invest NI: Proof of Concept
01/04/2017 - 01/12/2020
GBP105,980

G4: Molkov, Makarov and Shentsov
NET-Tools: Novel Education and Training Tools based on digital applications related to Hydrogen and Fuel Cell Technology
CEC-H2020-JTI-FCH
01/03/2017 - 30/11/2020
GBP227,138

G5: Makarov, Molkov, Cirrone, Shentsov and Kashkarov
HyTunnel-CS: Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces
CEC-H2020-FCH
01/03/19 - 28/02/22
GBP338,910

4. Details of the impact

The significance of the research is through informing RCS including UN ECE GTR#13, ISO and EU standards and pan-European guidance documents. The research also underpinned the development of the e-Laboratory of Hydrogen Safety, composed mainly of Ulster’s models/tools, impacted upon funding priorities in hydrogen safety research.

I1: Informed international science-based RCS

CEN/CENELEC/JTC6 Hydrogen in Energy Systems (WG3 Hydrogen Safety) suggested in June 2020 a New Work Item Proposal "Safe use of hydrogen in built constructions" based on HyIndoor (**G1**) and HyTunnel-CS (**G5**) project outcomes. The importance of Ulster's work is evidenced by the CEN/CENELEC/JTC6 secretariat (**C1**) who confirms they *"have seen the clear impact of the pre-normative research (PNR) work carried out at HySAFER of Ulster University on standard development" … "The PNR outputs of the HySAFER-led project HyTunnel-CS are directly informing standard development".*

International standard ISO 19880-1 "Gaseous hydrogen - Fuelling stations - Part 1: General requirements" uses the HySAFER's term "hazard distance" which is deterministic and can be calculated by Ulster's tools. This standard recommends "thermal shielding" for storage vessels based on the underpinning research at HySAFER on vehicle tanks (**G2** 2013-18**, G3** 2017-19). ISO 19882 "Gaseous hydrogen land vehicle fuel tanks and TPRDs" has drastically changed requirements for ventilation systems. It now requires accounting for the PPP discovered at Ulster. ISO/TR 15916:2015 "Basic considerations for the safety of hydrogen systems" cites the seminal book by Molkov (**R2**) as a key reference. The "*strong*" impact of HySAFER research on ISO standards, and development of inherently safer hydrogen systems, is acknowledged by the Chairperson of ISO/TC197 (**C3**) who notes the *"outstanding research work carried out at HySAFER, in particular on models and tools for assessment of hazard distances, the pressure peaking phenomenon, and safety of storage tanks has been incorporated into publicly accessible safety documentation*". This is echoed by the Chair of Hydrogen Europe RCS Strategy Coordination Group who confirms the impact HySAFER research has had on RCS globally **(C2).**

The GTR#13 (Phase 2) accounts for Ulster's contributions to the fire test protocol. The control of specific heat release rate in a fire source (HRR/A) has led to drastically improved fire test reproducibility. HySAFER research on the significance of HRR/A is publicly accessible through the GTR Informal Working Group, Sub-Group Safety **(C4).** The significance of the GTR#13 stems from its EU-wide legally binding status.

These documents facilitate the safer deployment of hydrogen vehicles and refuelling infrastructure, improve testing procedures, and impact OEMs worldwide. They are used by the hydrogen industry with a global reach and its significance is in setting the benchmark for the safety of hydrogen-powered vehicles.

I2: Industry-relevant guidance

HySAFER has provided technical safety requirements through industry-relevant guidance: European Guidelines on Fuel Cell Indoor Installation and Use; European Model Evaluation Protocol; and European Emergency Response Guide.

Collaboration with Air Liquide (France) and partners within the HyIndoor project (**G1** 2012-2015) resulted in industry-led European Guidelines (**C5**). Ulster's engineering models/tools are presented in the Guidelines including: design of ventilation systems, mitigation of deflagrations in enclosures by limitation of hydrogen inventory, recommendations for vent sizing of enclosures fully and partially filled in by hydrogen-air mixtures, and effect of flow restrictors. The Guidelines' importance is highlighted by a senior scientist at Air Liquide (**C6**) who notes the *"industry-led guidelines have impact upon hydrogen safety engineering worldwide and assist in underpinning the safe deployment of hydrogen infrastructure"*. The significance of the guidance is in providing a compendium of information with a reach across a variety of stakeholders.

Ulster made a substantial technical contribution to the "European Emergency Response Guide (EERG)" led by the French Fire Academy (ENSOSP). It incorporates HySAFER's tools for the prediction of hazard distances of unignited release, flame length, blast wave and fireball. This guide is used by emergency response personnel globally, its value is corroborated by the Lead of Training at ENSOSP (**C7**) who states how "*through HyResponse ENSOSP are recognised as the leading providers of hydrogen safety training for responders in Europe, our unique operational training is complemented by the research-led educational training provided by Ulster University. The current Ulster led HyResponder project is enabling us to maximise the reach and impact of our training and update EERG by new research findings and use of the online e-Laboratory of Hydrogen Safety created mainly on the basis of models developed and validated at HySAFER"*.

I3: Unique engineering tools

The e-Laboratory of Hydrogen Safety incorporates numerous engineering tools based on Ulster's publications. The e-Laboratory developed within the NET-Tools project beginning in 2017 (**G4**) is freely available online to stakeholders around the globe. Specific examples of how the tools have impact include: prevention of destruction of civil structures through limitation of the PPP, and calculation of hazard distances. The e-Laboratory has been recognised by the EC's Innovation Radar as a Key Innovation, "*addressing the needs of existing markets*" **(C8)**. The e-Laboratory is used across a range of sectors. Industrial gas company Air Liquide uses Ulster's blast wave decay nomograms along with other tools to inform their safe design of hydrogen systems and infrastructure. The PPP and vehicle tank design and safety requirements have been important in influencing safety considerations in applications of electrolyzer manufacturer ITM Power, and the e-Laboratory is being used to maximise the reach and impact of training at ENSOSP (**C7**).

I4: Design of novel test protocols, patented breakthrough safety technologies

HySAFER research demonstrated that the risk of hydrogen-powered vehicles is acceptable on London roads if the onboard tank fire resistance is above 50 minutes or tank rupture in a fire is excluded. Ulster's breakthrough safety technology of explosion free in a fire TPRD-less tank fully excludes tank rupture in a fire and thus eliminates its devastating consequences. The work has been funded through a series of grants from 2017 onwards with examples given in Section 3 (e.g. **G3, G5**). This technology allows the use of hydrogen vehicles in tunnels and underground parking at risk below of that for fossil fuel vehicles. This IP solution is licenced, most recently by US based Optimum Composite Technologies LLC. Optimum specialises in the design, fabrication and production of alternative fuel cylinders and is focused on the development of compressed gas tanks for aftermarket automotive and OEM applications (**C9**).

I5: European funding priorities

The European hydrogen industry (Hydrogen Europe) formulates requirements for industry-driven safety research through the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) calls. The European Hydrogen Safety Panel (EHSP), including Molkov, advises FCH JU and the International Association for Hydrogen Safety (IA HySafe), including Ulster as a founding member and Molkov as Chair of Education Committee, and publishes Reference Reports on Research Priorities that influence the EC's funding priorities. The importance of Ulster's research in informing funding priorities is corroborated by the Chair of EHSP and IA HySafe Executive Committee member (**C10**), who states *"research at HySAFER, particularly on use of hydrogen indoors, CFD protocols and best practices, safety of liquefied hydrogen, and safety of hydrogen in confined spaces have been reflected in our research priority discussions and reports and have been used to inform the FCH JU Multi-Annual Implementation Plan 2016-2019 and related funding calls".*

Overall, the work at HySAFER has contributed directly to the inherently safer engineering of hydrogen and fuel cell systems and infrastructure through tools, innovations, and RCS.

5. Sources to corroborate the impact

- **C1:** Corroborating statement: Secretariat on behalf of CEN/CLC/JTC 6 and NEN.
- **C2:** Corroborating statement: Chair of Hydrogen Europe RCS Strategy Coordination Group
- **C3:** Corroborating statement: Chair ISO TC197.
- **C4:** Portfolio of evidence from UN ECE GTR#13, Informal Working Group, Sub-Group Safety.
- **C5:** European Guidelines on Fuel Cell Indoor Installation and Use.
- **C6:** Corroborating statement: Senior Scientist, Air Liquide. (significance of HyIndoor)
- **C7:** Corroborating statement: Training lead, ENSOSP. (significance of the EERG and e-Lab)
- **C8:** Email evidence: email received from EC on Innovation Radar outlining how the e-Laboratory within NET-Tools has recently been recognised by the European Commission's Innovation Radar as a key innovation, "*addressing the needs of existing markets*".
- **C9:** Licencing agreement with Optimum CT. EU patent application No.18706224.5, 05/09/19.
- **C10:** Corroborating statement: Chair of European Hydrogen Safety Panel of the FCH JU, member of the Executive Committee of the International Association for Hydrogen Safety.