Institution: London South Bank University

Unit of Assessment: General Engineering

Title of case study: Hydrogen mapping and mitigation using modelling and experimental studies to inform safety case scenarios in nuclear decommissioning operations.

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

This Case Study illustrates how research has had a significant impact on the awareness and management of hydrogen hazards across the UK's pre-eminent nuclear decommissioning and reprocessing organisation, Sellafield Ltd (formerly BNFL). It has enabled Sellafield to:

- Underpin safety cases for nuclear decommissioning operations where mitigation of hydrogen explosions is essential; this is estimated to have saved Sellafield over £550 million;
- Provide 100,000 man-hours of training/CPD on hydrogen hazards to Sellafield staff;
- Access the science relating to hydrogen-air ignition probabilities and options for mitigating potential explosions;
- Expand and update the Hydrogen Technical Guide and associated road map on hydrogen safety with the latest research findings;
- Obtain continued expert advice to the Sellafield Hydrogen Working Party.

In addition, LSBU has, since 2008, benefited from contract research from Sellafield valued at over £1 million.

2. Underpinning research (indicative maximum 500 words)

Professor Philip Nolan (Professor of Chemical Engineering) together with members of the Explosion and Fire Research Team (EFRT) at London South Bank University (Dr P Holborn (Senior Research Fellow), Dr J Ingram (Senior Research Fellow), Dr P Battersby (Research Fellow) and Dr A Averill (Research Fellow)) have explored a wide range of phenomena relating to hydrogen generation and explosion mitigation since 1999 [1]. Apart from Battersby (commenced employment at LSBU in 2000), all other EFRT staff involved in this research were employed by LSBU before 1999 and are still LSBU employees.

The research has been, and continues to be, funded by Sellafield Ltd (~£2M since 2000) who now also sponsor (£100k pa) the Team, and have awarded it Centre of Expertise status. The objective of the research was to develop a comprehensive Hydrogen Technical Guide (HTG) and an associated road map to identify and solve problems due to hydrogen generation across Sellafield's nuclear decommissioning operations.

To characterise the probability of ignition of hydrogen-air gas mixtures by mechanical stimuli, research employing a large number of experimental tests has been carried out [2] using (i) a drop-weight impact apparatus (2003-7), (ii) glancing angle impact tests using a double-pendulum apparatus (2007-9) and (iii) a pure friction force apparatus using hydraulic or pneumatic rams to push loads up to 1000 kg in mass across a target plate (2009-12). Theoretical analyses for both impact and frictional force ignition mechanisms have been successfully developed. Experiments employing a dynamic thermocouple have also been performed to characterise the surface temperature generated during a mechanical stimulus event [3] (2012-13).

The results suggest that in any analysis of ignition probability the maximum surface temperature should be determined and considered in relation to the temperatures that would be required to initiate hot surface reactions sufficient to cause sparking and ignition. The research also:

- Identified the crucial parameters that influence mechanical ignition;
- Predicted the surface temperatures that could be generated by mechanical stimuli;
- Related surface temperatures to ignition probability;
- Demonstrated that ignition can occur at lower sliding velocities than previously thought.

Early research into the mitigation of hydrogen explosions (2003-6) focused on establishing proofof-concept using water mist spray [4]. Subsequent experimental work has been performed (2007-12) using both a laminar burning velocity apparatus and a small scale cylindrical explosion vessel, to investigate the usage of very fine water fog, nitrogen dilution and sodium hydroxide additives upon the mitigation of hydrogen deflagrations. The experiments were used to characterise (i) the inhibition of the flame burning velocity [5], (ii) the mitigation of the explosion overpressure [6] and (iii) the narrowing of the flammability limits of hydrogen-oxygen-mixtures, in terms of fog density, nitrogen dilution level and presence of additive [7]. Complementary research was also performed (2007-12) to model the effect of these mitigation measures upon the burning velocity, explosion overpressure and flammability limits of hydrogen mixtures and to investigate the potential for mitigation of explosion overpressure in a full scale plant silo ullage [8]. The research characterised the conditions required for effective mitigation of hydrogen-air explosions using water mist and demonstrated that:

- water mist can significantly reduce the rate of pressure rise and peak explosion overpressure;
- addition of sodium hydroxide to water fog produces an abrupt reduction in the burning velocity of hydrogen flames above a critical fog density;
- a combination of water mist, nitrogen dilution and sodium hydroxide additive can significantly narrow the flammability limits of hydrogen-air mixtures.

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

[1] Kempsell ID, Wakem, MJ, Fairclough MP and Ingram JM. Hydrogen explosions – an example of hazard avoidance and control. In: Hazards XVI, Symposium Series No. 148, IChemE; pp. 523-540, 2001.

[2] Jones S, Averill AF, Ingram JM, Holborn PG, Battersby P, Nolan PF, et al. Impact ignition of hydrogen-air mixtures. In: Hazards XIX, Symposium Series No. 151, IChemE; pp. 401-409, 2006.

[3] Averill AF, Ingram JM, Battersby P, Holborn PG, Nolan PF. A fundamental study of the generation of interfacial temperatures with metal surfaces and coatings under conditions of sliding friction and mechanical impact. Part 1: thermal analysis and theoretical evaluation of surface temperature. Transactions of the Institute of Metal Finishing, 2013, 91, pp. 269-274. Doi: http://dx.doi.org/10.1179/0020296713Z.000000000114

[4] Jones S, Averil AF, Ingram JM, Holborn PG, Battersby P, Nolan PF, et al. Mitigation of hydrogen-air explosions using fine water mist sprays. In: Hazards XIX, Symposium Series No. 151, IChemE; pp. 440-447, 2006.

[5] Ingram JM, Averill AF, Battersby P, Holborn PG, Nolan PF. Suppression of hydrogen oxygen-nitrogen explosions by fine water mist: Part 1. Burning velocity. Int J Hydrogen Energy 2012, 37, 19250-57. Doi: 10.1016/j.ijhydene.2012.09.092

[6] Battersby P, Averill AF, Ingram JM, Holborn PG, Nolan PF. Suppression of hydrogen-oxygen-nitrogen explosions by fine water mist: Part 2. Mitigation of vented deflagrations. Int J Hydrogen Energy 2012, 37, 19258-67. Doi: 10.1016/j.ijhydene.2012.10.029

[7] Ingram JM, Averill AF, Battersby P, Holborn PG, Nolan PF. Suppression of hydrogen oxygen-nitrogen explosions by fine water mist containing sodium hydroxide additive. International Journal of Hydrogen Energy, 2013, 38, 8002-8010. Doi: 10.1016/j.ijhydene.2013.04.048

[8] Holborn PG, Battersby P, Ingram JM, Averill AF, Nolan PF. Modelling the mitigation of a hydrogen deflagration in nuclear waste silo ullage with water fog. Process Safety and Environmental Protection, 2013, 91, 476-482. Doi: 10.1016/j.psep.2012.11.001

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

This case study illustrates how the research of the Explosion and Fire Research Team (EFRT) has benefitted the UK's leading nuclear decommissioning and reprocessing company, Sellafield Ltd, through the provision of technical expertise and knowledge that has enabled the Company to manage effectively aspects of its decommissioning operations where potential hydrogen explosion hazards may exist.

Nuclear plants pose many challenges in relation to hydrogen safety. An uncontrolled release of hydrogen (generated through radiolysis and corrosion) in a plant enclosure with a suitable ignition source could result in an explosion with potential loss of human life, significant infrastructural damage and environmental impact due to radioactive contamination, for example, as occurred at Fukushima in 2012.

In this context, Sellafield Ltd (formerly British Nuclear Fuels Ltd), the UK's pre-eminent nuclear decommissioning and reprocessing company, approached the ERFT (1999) because of their modelling and experimental expertise in the area of Flammable Gas explosions.

In recognition of the potential safety risks associated with hydrogen in its decommissioning and reprocessing operations, Sellafield established a Hydrogen Working Party in 1995 with overall responsibility for the technical guidance and advice on hydrogen safety matters to all Sellafield sites and its accountability to government regulatory agencies. The research of the EFRT has, and continues to make, a major contribution to the scientific understanding, direction and activities of the Hydrogen Working Party (HWP). The HWP has met over 100 times in total, including 34 times since 1 January 2008. It is made up of Sellafield plant safety and design managers and engineers with Professor Nolan and Dr Steve Graham (National Nuclear Laboratory) as the only two external members of the HWP. Nolan remains the only formal academic representative on the HWP, and other members of the EFRT attend on a regular basis to present on specific matters.

In this context, EFRT staff were the primary authors of Sellafield's Hydrogen Technical Guide (HTG), first issued in 2002, which continues to be expanded and updated on the basis of the latest research findings by the EFRT, for example, with a guide to the assessment of ignition probability carried out since 2008 [1-3]. The HTG remains the Company's standard for the management of hydrogen safety and is applicable to all existing and new facilities. The HTG also provides the national regulator (Office for Nuclear Regulation) with the necessary assurances that Sellafield can manage its hydrogen safety affairs effectively and with confidence; even a minor incident can result in a plant shutdown with significant cost implications.

Key areas of impact that EFRT staff have contributed to through their involvement with the HWP and the HTG since 2008, are:

- Ignition and flammability research applied to Sellafield's Magnox Swarf Storage Silo (MSSS) [4] retrieval project (2010): The EFRT research provided the HWP with greater understanding of (i) the effects of partial inerting/flammable limits on ignition; (ii) interpreting and applying international inerting standards to develop an operable ventilation design; (iii) mechanical ignition mechanisms and developing probability assessments; and (iv) hydrogen release and dispersion mechanisms from the waste in MSSS. The savings involved in installation and operating costs over the proposed fully inerted system and through an earlier start/quicker retrieval programme is estimated by Sellafield to be greater than £500 million [5].
- Ignition probability applied to Sellafield's Silo Direct Encapsulation Plant [6] (2010): The EFRT's work provided a detailed understanding of all ignition mechanisms and developing probability assessment associated with this plant. The saving to the Company is estimated to be greater than £50 million through reduced engineering requirements [5].
- Benefits to other projects since 2008, including: (i) the development of a safety case to allow the floc retrieval process to continue following submersible pump blockage; (ii) development of a safe method for sludge header closed pipe flange removal; (iii) a flask passive ventilation design; (iv) a hydrogen instruments engineering standard; (v) a strategy for sealed ion exchange cartridge hydrogen management, and (vi) allowing the feasibility of employing water mist explosion mitigation strategies on the MSSS plant to be evaluated [7]. Collectively, these projects are estimated to have saved Sellafield in excess of £100K through allowing alternative less costly options to be developed and justified [5].
- The HTG is widely used internally within Sellafield Ltd, with approximately 60% of the 10,000 staff regularly referring to the Guide to successfully deliver work, including safety assessments, new engineering projects and project planning. The HTG has been used as

the core of over 100,000 man-hours training and CPD on hydrogen hazard since 2008 [5].

- A senior member of the Flammable Gas Centre of Expertise at Sellafield Ltd referred to the HTG as “The Bible”, and has confirmed that the HTG has attracted interest from the Department of Energy in the US [8] where no equivalent exists [5].

The investment in contract research made by Sellafield in the above research carried out by the EFRT since 2008 has been just over £1M. In 2011, Sellafield selected and now sponsor the EFRT as its Centre for Expertise in Flammable Gases under a 5 year contract worth £500k. The EFRT also continue to receive contract research commissions from individual plants at Sellafield for specific issues.

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

[1] Wakem, M., Fairclough, M.P., Kempsell, I.D., Ingram, J.M., Hydrogen Technical Guide, E1.30 Issue 3, Sellafield Ltd, Nuclear Decommissioning Authority, September 2008 - (available on request from LSBU).
- The Sellafield Ltd. Hydrogen Technical Guide. Note that this is designed to be used in conjunction with the “Hydrogen Hazards Handbook” which is comprised of 15 supporting documents (426 pages) primarily written by EFRT staff.

[2] Averill A.F. Nolan P., Ingram J.M., Battersby P., Holborn P., A compendium of mechanical impact ignition results with an illustrative Bayesian Belief Network, Report to Sellafield Ltd. HWP(09)P107, February 2009 - (available on request from LSBU)
- A compendium of EFRT mechanical ignition research data used to provide the basis for an ignition probability assessment method.

[3] Ingram J.M., Thomas P.M., Assessment of ignition probability, S&ERM Technical Manual, E1.30 SD 10, July 2009 - (available on request from LSBU).
- The Hydrogen Technical Guide Supporting Document describing the assessment of ignition probability and developed using EFRT research data.

[4] Averill A.F., Mechanical ignition during waste retrieval in MSSS, Report to Sellafield, HWP(10) P128, March 2010 - (available on request from LSBU)
- The application of the LSBU mechanical ignition assessment methodology to the Sellafield MSSS plant.

[5] Report of independent consultants (The Innovation Partnership, 2013). Contact: Managing Director, The Innovation Partnership (tipl@innopartners.com) – *Summarises and quantifies Sellafield’s views on the contribution and value of the EFRTs research to its operations and the management of hydrogen hazards.*

[6] Averill A.F., Ingram J.M., Initial assessment of ignition event probability during lidding of SDP boxes and storage in the buffer location. Report to Sellafield Ltd. HWP(10)P136, December 2010 - (available on request from LSBU)
- The application of the LSBU mechanical ignition assessment methodology to the Sellafield SDP plant.

[7] Fairclough, M.P., Hydrogen explosion overpressure trials strategy, Report RP/B38PLN-3755/SAFE/00048, Sellafield Ltd. January 2009 - (available on request from LSBU).
- Report outlining different hydrogen explosion mitigation strategies for use in MSSS.

[8] Hydrogen Safety and Management Working Group – US Department of Energy (EFCOG SAWG) – www.efcog.org/wg/sa_hsig/docs/Hydrogen%20safety%20initiative.pdf