Institution: London South Bank University		
Unit of Assessment: 12 – General Engineering		
Title of case study: Sellafield Ltd Hydrogen Safety Support Work		
Period when the underpinning research was undertaken: 2008-2020		
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:**
Paul Holborn James Ingram	Senior Research Fellow Senior Research Fellow	2008 – current 2008 – current
Period when the claimed impact occurred: 2013 – 2019		
Is this case study continued from a case study submitted in 2014? N		

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

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, as occurred at Fukushima in 2011. Even a small hydrogen explosion incident at Sellafield could delay or shut down operations and incur significant costs of the order of GBP1,000,000 (£1m) per day.

The London South Bank University (LSBU) Explosion and Fire Research Team has had a significant impact on the safe management of hydrogen hazards, through its collaboration with Sellafield Ltd, a large multi-function nuclear site close to Seascale in Cumbria, England. This research work has helped Sellafield Ltd to:

- Support a revolutionary breakthrough saving approximately GBP100,000,000 (£100m) on cleaning up the Sellafield site.
- Design a process to safely stack and store nuclear waste filled boxes which generate hydrogen as a by-product (~10,000 boxes each costing GBP60,000 (£60k)).
- Safely transfer special nuclear materials containing plutonium from Dounreay (DSRL) to Sellafield for secure long-term storage.
- Improve operator safety by ascertaining the potential consequences of explosions involving small volumes of hydrogen.
- Gain industry recognition with a “Highly Commended” award in the Process Safety category at the IChemE Global Awards 2015.

2. Underpinning research (indicative maximum 500 words)

Sellafield Ltd (SL) manage the UK’s largest nuclear site, which presents a unique and diverse range of complex challenges due to 60 years of varied nuclear operations. Covering six square kilometres, it is home to more than two hundred nuclear facilities and the largest inventory of untreated nuclear waste in Europe. The hazardous radioactive nature of this waste means it must be carefully managed and stored for thousands of years. Retrieval operations are therefore required to transfer the nuclear waste, fuel and sludge that are currently stored inside legacy ponds and silos into robust radiation-shielded boxes that are better suited to long term storage.

The storage of this waste also leads to the generation of hydrogen gas through radiolysis and corrosion. This hydrogen must be carefully managed since an uncontrolled release inside a plant enclosure could result in an explosion with potential loss of human life, significant infrastructural damage and environmental impact due to radioactive contamination, as occurred at Fukushima in 2011.

Even a small hydrogen explosion incident could delay/shutdown storage operations and incur significant costs. Such a hydrogen incident at Sellafield involving a Magnox encapsulation plant swarf flask in 1996 resulted in plant shutdown for months at an estimated cost of GBP1,000,000 (£1m) per day. As a result of this incident the SL Hydrogen Working Party (HWP) was formed to generate common guidance and act as a focal point for advice on hydrogen related issues. The work of the HWP has now been encompassed within the SL Flammable Gases Centre of Expertise (FGCoE). SL entered into a long-term partnership with LSBU Explosion and Fire Research Team in 2012 on the basis of their expertise in the field of hydrogen safety and strong research track record.

The research carried out by LSBU has been, and continues to be, funded by Sellafield Ltd. (~£3M since 2000). The objective of the research has been to underpin the development of a comprehensive Hydrogen Technical Guide (HTG) to safely manage hydrogen and solve problems arising due to hydrogen generation that occur across the Sellafield site. To meet this objective, the LSBU Explosion & Fire Research Team (Drs Ingram, Holborn, Battersby, Averill and Benson) have undertaken a range of underpinning research studies for Sellafield Ltd The findings of these studies include:

Mechanical ignition of hydrogen-air (August 2008 – Present): Heavy machinery (grabs cranes etc.) and manual handling used in waste retrieval and transfer operations has the potential to generate hot surfaces and sparks through contact friction and drop impacts which could ignite a flammable hydrogen gas mixture resulting in an explosion. This work characterised the likelihood of ignition of hydrogen-air atmospheres due to mechanical stimuli for different velocities and masses, projectile geometries, types of material and surface conditions. Novel experimental tests were conducted using surface friction and drop weight impact rigs to quantify the hydrogen-air ignition probability under conditions which had not previously been studied before (e.g. for high loads up to 1 tonne), simulating what might occur when using heavy machinery during decommissioning operations at Sellafield **[R1, R2]**. It determined that the effect of pyrophoric materials, hard surfaces and wet corroded Magnox sludge on sliding friction all make the ignition of hydrogen far more likely to occur, even under low velocity contact sliding conditions (< 1m/s) previously thought to pose little risk **[R3]**. The research derived new and useful theoretical relationships for calculating impact energies from the initial drop impact velocities. It also identified for the first time the key role of even very small amounts of grease contamination in greatly reducing the friction coefficient and significantly changing projectile impact behaviour **[R4]**. The results inform the quantified risk assessment of the process and storage operations carried out on nuclear plants, predicting those conditions - velocities, masses, materials (steel, magnesium, aluminium etc.) and surface conditions (clean/rusty/Magnox coated etc.) - where ignition of hydrogen would be likely to occur and which must be mitigated against and those where it can be ruled out as being highly unlikely or not credible.

Buoyancy driven flow and diffusion for removing hydrogen (July 2016 – Feb 2019): During decommissioning operations carried out at Sellafield, nuclear waste will be retrieved from legacy silos and placed in purpose built robust shielded skips and boxes for secure long-term storage. The waste placed in the boxes will generate hydrogen. Filters will therefore be fitted to the lids to prevent the build-up of flammable concentrations of hydrogen. Furthermore, the boxes will be stacked with a small horizontal channel being formed between each lower box and the box above it in the stack. The hydrogen released via the filters in the top of the skip/box must also therefore be able to flow through the narrow horizontal channel between the boxes and safely dispersed. This work investigated the performance of buoyancy driven flow and diffusion in removing hydrogen (using helium as a safe analogue) from waste storage boxes via filters fitted to the lids and the narrow channels formed between the stacked boxes. The experimental tests characterised the effect of different filter designs (e.g. areas, spacings) and horizontal channel sizes on hydrogen gas transport behaviour. The experimental results suggest that for narrow channels, less than 20 mm high, buoyancy driven flow will be significantly inhibited. The results were also used to construct a Bayesian network predicting the effect of different plant conditions on the likelihood of a flammable hydrogen atmosphere forming **[R5]**.

Explosion consequences of small volumes of hydrogen (Jan 2017 - July 2017): This work investigated the explosion consequences of ignition of small volumes of hydrogen such as could form in bagged bottles containing radioactive materials stored at Sellafield **[R6]**. The results characterised the impulse/temperature/pressure behaviour exhibited by hydrogen bag/balloon ignitions via detailed measurements and high-speed video footage of the explosions. The work addressed a knowledge gap in the understanding of hydrogen bag ignitions and identified the harmful effect of overpressure to the ears as being the main risk to operators working in close proximity to a bagged bottle containing hydrogen.

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

All publications are peer-reviewed. R1, R2, R3, R4, R5 and R6 are all submitted as outputs for REF2021 in UoA 12.

[R1] A.F. Averill, J.M. Ingram, P. Battersby, P.G. Holborn; Ignition of flammable hydrogen/air mixtures by mechanical stimuli. Part 1: Ignition with clean metal surfaces sliding under high load conditions, International Journal of Hydrogen Energy; Volume: 39 Issue: 32, Pages: 18472-18479; 2014. doi: http://dx.doi.org/10.1016/j.ijhydene.2014.09.031

[R2] A.F. Averill, J.M. Ingram, P. Battersby, P.G. Holborn; Ignition of flammable hydrogen/air mixtures by mechanical stimuli. Part 2: Ignition under conditions of rust and surface pyrophoric material contamination, International Journal of Hydrogen Energy; Volume: 40 Issue: 12 Pages: 4392-4400; 2015. doi: https://doi.org/10.1016/j.ijhydene.2015.01.138

[R3] Averill, A. F., Ingram, J. M., Battersby, P., & Holborn, P. G.; Ignition of flammable hydrogen in air (and other H2/N2/O2 mixtures) by mechanical stimuli. Part 3: Ignition under conditions of low sliding velocity (<0.8 m/s). International Journal of Hydrogen Energy, 40 Issue 31 Pages: 9847-9853; 2015. doi: https://doi.org/10.1016/j.ijhydene.2015.05.161

[R4] Averill, A.F., Ingram, J.M., Holborn, P.G., & Battersby, P. (2017). Energy losses during drop weight mechanical impacts with special reference to ignition of flammable atmospheres in nuclear decommissioning: theory and determination of experimental coefficients for impact analysis and prediction, International Journal of Impact Engineering, 109, 92-103. https://doi.org/10.1016/j.ijimpeng.2017.05.019

[R5] Averill, A.F., Ingram, J.M., Holborn, P.G., Battersby, P., and Benson, C.M. (2018). Application of Bayesian methods and networks to ignition hazard event prediction in nuclear waste decommissioning operations. Process Safety and Environmental Protection doi: https://doi.org/10.1016/j.psep.2018.03.002

[R6] Averill, A., Ingram, J., Gomez-Augustina, L., Holborn, P., Battersby, P., and Benson, C. (2018). Potential hazard consequences to personnel exposed to the ignition of small volumes of weakly confined stoichiometric hydrogen/air mixture. International Journal of Hydrogen Energy doi: https://doi.org/10.1016/j.ijhydene.2018.10.092

Grants to fund the work:

Partnership to Support Sellafield Ltd Flammable Gases Centre of Expertise 2012-2018 approx. £800k.

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

The impact and reach of LSBU's work for Sellafield Ltd and other nuclear sites managed by the Nuclear Decommissioning Authority (NDA) across the UK (e.g. Dounreay DSRL) is corroborated by the Sellafield testimonial statement **[S1]**. The results have been used to inform Sellafield operations and address knowledge gaps regarding the **effect of mechanical stimuli** (i.e. different masses, velocities, surface condition) upon the likelihood of ignition of hydrogen-air mixtures (see section 2) - feeding into the continuing **evolution of the Hydrogen Technical Guide** (HTG) - a comprehensive guide to hydrogen hazards and their management – and assisting in the **development of safety cases** for **nuclear decommissioning** operations **[S2]**. The HTG is now used across the Sellafield sites and the NDA Estate and is widely regarded, both nationally and internationally, as being the best practice guide to hydrogen safety in the nuclear industry. The international importance of the development of the HTG was recognised at the IChemE Global Awards 2015 where

Sellafield Ltd and LSBU were jointly awarded the accolade of “Highly Commended” in the Process Safety category **[S3]**.

Specific examples of the impact of LSBU’s research work at Sellafield Ltd are:
1) Informing a breakthrough in the management of nuclear waste at Sellafield
The group’s underpinning research on ignition of hydrogen-air mixtures due to mechanical stimuli was used by Sellafield Ltd to inform the development of an alternative approach to managing Intermediate Level Waste (ILW) from one of their legacy silos - the Magnox Swarf Storage Silo (MSSS). The new approach represents a revolutionary breakthrough in the management of nuclear waste and is designed to accelerate progress at Sellafield and save approximately GBP100,000,000 (£100m) for cleaning up the site **[S4]**. SL were able to use LSBU’s results characterising the likelihood of ignition due to mechanical stimuli to help make an informed judgement on the behaviour of the raw waste retrieved from MSSS and so produce a safe and secure waste package, suitable for interim storage, using a far more straightforward approach – saving time and reducing costs. In a statement announcing the research breakthrough **[S4]**. Dr Adrian Simper, the NDA’s Strategy and Technology Director, said:

“This research has delivered the underpinning to what could be a paradigm shift in the management of nuclear waste. Having a greater understanding of the long-term behaviour of this material allows us to design a truly fit-for-purpose approach to its management and disposal. To be able to deliver a technical solution to historic ILW at Sellafield, which not only offers a safe and secure route but also opens up the possibility of a quicker and cheaper alternative to current technology, is a genuinely exciting development.”

2) Assisting Sellafield to assess and optimise the safe design of stacked filtered boxes for waste storage
The Sellafield Alternative Intermediate Level Waste Approach (AILWA) project for managing MSSS waste will retrieve waste directly into special purpose shielded boxes without further treatment, saving time and reducing costs. This is a huge undertaking since between 10,000 to 20,000 bespoke storage boxes will be required, with each box costing around GBP60,000 (£60k). LSBU’s underpinning research work (July 2016 – Feb 2019) on buoyancy-driven gas flow and diffusion of a buoyant gas (using helium as a safe analogue for hydrogen) from a filtered box via a narrow horizontal channel has been used by Sellafield Ltd to inform and optimise the safe design of stacked filtered boxes for AILWA e.g. by predicting how big the gap channel needs to be **[S5, S6, S7, S8]**. Such designs permit the effective removal of hydrogen from the waste boxes, mitigating the risk of a highly damaging and costly explosion event occurring, whilst also allowing the number of boxes that can be safely stacked in the available storage space to be maximised, thereby reducing operation costs.

3) Improve risk assessment methodology and operator safety by understanding the potential consequences of explosions involving small volumes of hydrogen
LSBU have also carried out (Jan - July 2017) underpinning research work investigating the consequences of ignition of small volumes of hydrogen such as could form in bagged bottles containing radioactive materials stored at Sellafield **[S9]**. Rebottling activities for analytical purposes require that operators in air-fed suits must periodically pick up and move such packages/bottles. Research was therefore required to better understand and characterise what the likely consequences of a hydrogen explosion event might be. This novel piece of work has proved very useful to Sellafield Ltd in relation to specific manual handling operations, enabling the adequacy of personal protective equipment for such tasks to be assessed e.g. by highlighting the importance of wearing ear protection. In many cases it has also allowed operations to continue without significant delay or the potentially considerable cost of implementing additional protective measures.

4) Support the transfer of special nuclear material product packages from Dounreay to Sellafield.

One of the most complex challenges in dealing with the UK's nuclear legacy is the management of the inventory of special nuclear materials containing plutonium held in the UK. The safe and secure handling and storage of this plutonium inventory is a UK government priority due to concerns over its security and proliferation. Operations were therefore required to transfer a large number of special nuclear material product packages containing plutonium from Dounreay (DSRL) to Sellafield for their secure long-term storage. However, some of these packages could potentially contain pressurised hydrogen generated via radiolysis of absorbed moisture or organic contaminants. In view of the potential hydrogen challenge associated with the product packages LSBU applied their underpinning research work on the ignition of hydrogen-air mixtures due to mechanical stimuli to assess the likelihood of ignition occurring due to the potential mechanical and electrostatic stimuli that may arise during manual handling and transfer operations (Sep - Nov 2017) **[S10]**. The results were used to inform the package transfer process and identify those packages and operations where ignition of hydrogen was likely to occur and which would require further attention and those where it could be safely ruled out as being highly unlikely or not credible - hence facilitating their safe transfer to Sellafield.

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

[S1] Sellafield Impact Testimonial Statement, Sellafield Ltd 2021.

[S2] 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 LSBU Explosion and Fire Research team members.

[S3] Shortlists - IChemE Global Awards 2015

[S4] https://www.gov.uk/government/news/research-breakthrough-to-accelerate-sellafield-decommissioning

[S5] "Investigating the performance of buoyancy driven flow and diffusion in removing hydrogen (using helium as a safe analogue) from stacked filtered boxes via narrow channels": The Sellafield 2016/17 Technology Development and Delivery Summary (pg. 39): (https://www.gov.uk/government/publications/the-201617-technology-development-and-delivery-summary)

[S6] Battersby, P., Holborn, P., Ingram, J. (2017). Experimental Work to Assist AILWA with the Assessment of Hydrogen Flow through Horizontal Gaps between Stacked Boxes. LSBU Report to Sellafield Ltd, Ref#: RP/35-10220/4510360811/TECH/00009/A, January 2017*.

[S7] Battersby, P., Holborn, P., Ingram, J., (2018), Experimental Tests for the Assessment of Skip and Box Filter Assemblies for Hydrogen Dispersion in MSSS 3m^3 Packages. LSBU Report to Sellafield Ltd, Ref #: RP/35-0220/4510360811/TECH/00016/A, March 2018*.

[S8] Battersby, P., Holborn, P., Ingram, J., (2019), Experimental Tests for the Further Assessment of Skip and Box Filters for Hydrogen Dispersion in MSSS 3m3 Package. LSBU Report to Sellafield Ltd, Ref#: RP/3M3BOX/TECH/00017, February 2019*.

[S9] "Investigating the consequences of ignition of small volumes of hydrogen": The Sellafield 2016/17 Technology Development and Delivery Summary (pg. 19-21): (https://www.gov.uk/government/publications/the-201617-technology-development-and-delivery-summary)

[S10] Ingram, J., Holborn, P., Battersby, P. (2017). "An assessment of ignition probability for Dounreay product package transfer operations", LSBU Report to Sellafield Ltd, PTC/17/406, November 2017*.

*Confidential reports to Sellafield Ltd but likely that LSBU would be granted permission from Sellafield Ltd to submit to REF Panel.