Institution: Heriot-Watt University		
Unit of Assessment: B09 Physics		
Title of case study: Novel optical sensing technologies and techniques for in-situ material and environmental monitoring		
Period when the underpinning research was undertaken: 2004 – 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:**
Julian Jones	Senior Deputy Principal	Oct 1988 – present
Robert Maier	Honorary Assistant Professor	Aug 2017 – present
Richard Carter	Research Fellow	Dec 2011 – present
James Barton	Reader	Sep 1978 – Jan 2012
William MacPherson	Associate Professor	Oct 1998 – present
Jinesh Mathew	Research Associate	Jul 2013 – Jan 2017
Andrew Moore	Professor	Jun 1997 – present
Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The Atomic Weapons Establishment (AWE) is responsible for maintaining the UK's Continuous at Sea Deterrent in the age of the comprehensive test ban treaty. That responsibility requires the ability to assess and evaluate with extreme confidence the condition of highly complex assemblies comprising multiple and exotic materials. Research at Heriot-Watt University (HWU) has developed key relevant optical, non-destructive in-situ inspection techniques to provide essential physical and chemical data, within complex and costly engineering trials and long-term materials ageing experiments. AWE deploy HWU's technologies to provide invaluable and previously unobtainable key information that AWE uses in its critical role supporting the defence and security of the UK.

2. Underpinning research

Common to all of AWE's needs is the ability to monitor conditions in extremely hazardous (ionizing) and space-constrained environments, often where the capacity to monitor these conditions over long periods was not part of the original design. These measurements are essential to determine component health over decades of use, maintenance, and storage and must be achieved without intervention. This imposes extreme requirements on sensor configuration, reliability and longevity and is exacerbated by very limited permitted changes to the engineered environment. Heriot-Watt researchers have successfully addressed these challenges by developing optical sensing solutions uniquely configured for this demanding application.

Heriot-Watt research enables key areas of interest to AWE, including i) Gap and shape sensing [3.1, 3.2], ii) Gas sensing [3.3, 3.4] and iii) System Integration [3.5, 3.6].

Gap sensing using fibre optic based interferometry to permit sub-micron measurement accuracy coupled with flexible deployment in complex structures and hazardous environments was researched at Heriot-Watt (Harrison, Maier, Barton, Jones) and subsequently transferred to AWE from 2004-present. That research has created a core technology that underpinned a series of critical AWE internal engineering trials which could not have been performed otherwise. These trials are essential to assurance activities, enabling access to empirical data to inform key decisions whilst enabling the development of a more cost-effective future programme.

Trace gas sensing has provided a route to monitor material changes in sealed environments. The complexity of the environment and sensor constraints posed by AWE are unique and pose demands which could not be met by existing technologies. Heriot-Watt researchers (Carter, Maier) demonstrated optical technologies which enabled AWE, to achieve continuous in-situ monitoring of gaseous species in the test environment.

System Integration poses specific challenges in meeting AWE requirements. There is the need to provide fibre optic access to sealed cavities without compromising structural component integrity. This was addressed by developing original fibre embedding processes through Heriot-Watt's innovative additive manufacturing of polymers (Maier) in which the fibre is embedded as an integral part of the manufacturing process. These manufacturing strategies and novel architectures are at the forefront of sensor integration. As a result AWE and Heriot-Watt are now able to embed fibres and optical sensors directly into metallic composites (Maier, MacPherson). The resultant know-how and capabilities are enabling AWE to progress in implementing sensor suites in long term, engineering test environments prior to deployment in increasingly complex systems. AWE consider that this disruptive technology has the potential to deliver more efficient manufacturing processes with savings in the tens of millions of pounds.

The AWE Heriot-Watt research partnership has culminated in research that has created bespoke sensor and instrumentation systems designed to support long duration tests, typically 25+ years. HWU and AWE have worked together to achieve understanding of commercially available components and those developed by research in order to satisfy those timescales. Together they possess all necessary expertise to build and deploy complete instrumentation systems (MacPherson), and hold all relevant development knowledge and IP. That expertise has become the backbone of future sensing capabilities across a wide range of sensing requirements in AWE. This knowledge provides AWE with an unprecedented new capability in deploying the technology across their development, test, engineering, storage, monitoring and maintenance activities. The direct benefit is the ability to make otherwise infeasible but critical measurements, hence improving safety and reducing risks, and substantially reducing costs. Indirectly, access to and the ability to influence the direction of emerging technologies and techniques, ensures that AWE's scientific and engineering expertise benefitting their staff in their wider professional networks.

3. References to the research

[3.1] Harrison, PB, Maier, RRJ, Barton, JS, Jones, JDC, McCulloch, S & Burnell, G 2005, 'Component position measurement through polymer material by broadband absolute distance interferometry', *Measurement Science and Technology*, vol. 16, no. 10, pp. 2066-2071. https://doi.org/10.1088/0957-0233/16/10/023

[3.2] Fender, A, Rigg, EJ, Maier, RRJ, MacPherson, WN, Barton, JS, Moore, AJ, Jones, JDC, Zhao, D, Zhang, L, Bennion, I, McCulloch, S & Jones, BJS 2006, 'Dynamic two-axis curvature measurement using multicore fiber Bragg gratings interrogated by arrayed waveguide gratings', *Applied Optics*, vol. 45, no. 36, pp. 9041-9048. https://doi.org/10.1364/AO.45.009041

[3.3] Maier, RRJ, Jones, BJS, Barton, JS, McCulloch, S, Allsop, T, Jones, JDC & Bennion, I 2007, 'Fibre optics in palladium-based hydrogen-sensing', *Journal of Optics A: Pure and Applied Optics*, vol. 9, no. 6, S08, pp. S45-S59. https://doi.org/10.1088/1464-4258/9/6/S08

[3.4] Carter, RM, Maier, RRJ, Biswas, P, Bandyopdhayay, S, Basumallick, N, Jones, BJS, McCulloch, S & Barton, JS 2013, 'Characterization of LPGs via Correlation Analysis of an Analytical Solution With Observed Transmission Spectra', *Journal of Lightwave Technology*, vol. 31, no. 18, pp. 3014-3020. https://doi.org/10.1109/JLT.2013.2278075

[3.5] Mathew, J, Hauser, C, Stoll, P, Kenel, C, Polyzos, D, Havermann, D, Macpherson, WN, Hand, DP, Leinenbach, C, Spierings, A, Koenig-Urban, K & Maier, RRJ 2017, 'Integrating Fiber Fabry-Perot Cavity Sensor into 3-D Printed Metal Components for Extreme High-Temperature Monitoring Applications', *IEEE Sensors Journal*, vol. 17, no. 13, pp. 4107-4114. https://doi.org/10.1109/JSEN.2017.2703085

[3.6] Dyer, TC, MacPherson, WN, Brooks, SJ & McCulloch, S 2018, Accelerated through-life performance evaluation of fibre Fabry-Pérot pressure sensors. in *Optical Fiber Sensors 2018.*, TuE33, Optical Society of America. https://doi.org/10.1364/OFS.2018.TuE33

4. Details of the impact

For AWE, the impact of this work has been both significant and enduring [5.1]. For almost 70 years, AWE has been responsible for delivering and maintaining the UK's nuclear deterrent. Since 1996, when the UK became a signatory to the Comprehensive Test Ban Treaty, it has no longer been possible to assure the safety and performance of the UK nuclear deterrent using data obtained from new underground tests. In response, AWE has retained an ongoing need to develop alternative approaches to obtain empirical data relating to the operation and safety of designs, systems, components and materials. AWE's Strategic Alliance Partnership with Heriot-Watt University has been invaluable in developing solutions to address these challenges [5.2].

The greatest individual success, in terms of impact, has been the successful deployment of optical gap gauge sensors within a unique AWE-fielded weapon sub-system engineering trial [5.3, 5.4, 5.5]. The challenge of retrofitting an existing design with miniaturised diagnostics, capable of operating to high level of accuracy and precision, is extremely demanding. To date commercially available devices are unable to meet the deployment requirements. The unique optical sensor technology and interrogation hardware used in this trial arose directly because of the research performed at Heriot-Watt. As a direct result of this trial, AWE has been able to obtain in-situ measurements that would have been impossible to obtain through any other means, providing new understanding of how weapon sub-systems perform within dynamic environments. The most significant benefit of performing this work has been to provide increased confidence and assurance in assessments made relating to the deterrent, helping AWE to underpin the UK's security and defense through its ability to continue to maintain Continuous at Sea Deterrence. A significant secondary benefit from this work has been the de-risking of future programme activities, enabling the scale of planned work to be reduced. This represents an estimated cost saving to the MoD of ~GBP25,000,000 within AWE's GBP1,000,000,000 annual budget.

In addition to engineering trials, a significant amount of work performed at AWE involves research into how a wide variety of unconventional materials types behave over extended timescales. AWE has benefited from joint research with Heriot-Watt in this area to develop new knowledge and expertise. Projects have been tasked with designing, developing and maturing technology options to enable empirical data linked to chemical ageing to be obtained [5.6]. These data are critical to the decades long deployment, storage and decommissioning cycles with which AWE must contend. The sensor technology developed so far has been able to facilitate a more targeted approach to future materials ageing programmes, which are costly and time consuming. Obtaining more frequent, higher quality data in an automated manner has led to a high degree of confidence that material and component properties have not changed over decades long deployment, thus significantly reducing the need for physical inspection with the associated safety benefit from reduced staff exposure to extreme-hazard materials. Fewer inspections and tests have also resulted in a reduction in the associated footprint and other overhead costs required to support these activities, again leading to a more cost-effective programme of work, saving many millions of pounds. [5.7]

The highly specialized nature of these applications has necessitated in radically new approaches being identified. However, impact for these techniques expands beyond AWE's interest as evidenced by an in-progress patent (GBP1,820,122.8), providing intellectual property for the UK Government, whilst others have been published in peer reviewed journals, enhancing AWE's reputation and visibility internationally.

The interactions with Heriot-Watt have also led to an increase in AWE's organizational agility, facilitating a significant amount of higher risk (in terms of success) lower Technology Research Level (TRL) research activities that would previously have been performed by AWE staff. Facilities, expertise, and capabilities made available to AWE via the alliance have further increased AWE's operational capabilities without increasing in-house costs in terms of staff and equipment. This has enabled the company to redirect these staff to support activities that can only be performed at AWE – improving the company's delivery to their customer, providing an indirect cost saving.

The overall span of work that has been run with Heriot-Watt has enabled AWE to demonstrate the effectiveness of our capabilities to our key customer, MoD and has significantly improved our visibility and standing with AWE's key partners in the US.

5. Sources to corroborate the impact

[5.1] Deputy Group Leader – Surety Engineering, Atomic Weapons Establishment

[5.2] AWE Internal Memoranda: AWE/EDMS3/803BF578, Reporting on the Extra-Mural Activities supporting the 10250 06.1.7 Diagnostics Integration Task for the Year 2017-2018

[5.3] AWE Report: AWE/DWE11/11/B/HB00008 "Trial Report 1"

[5.4] AWE Report: AWE/DWE11/11/B/ "Trial Report 2"

[5.6] AWE Report: AWE/DWE11/11/B/ "Trial Report 3"

[5.7] AWE Report: AWE/ "Materials Ageing Report"