Institution: University of Hertfordshire		
Unit of Assessment: 9 - Physics		
Title of case study: Health, economic and environmental benefits through commercialising bioaerosol detection technologies		
Period when the underpinning research was undertaken: 2001 – 2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Paul Kaye Edwin Hirst Warren Stanley	**Role(s) (e.g. job title):** Professor Researcher Senior Research Fellow	**Period(s) employed by submitting HEI:** 1974 – present 1990 – present 1999 – present
Period when the claimed impact occurred: 1 Aug 2013 – 31 Dec 2020		
Is this case study continued from a case study submitted in 2014? N		

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

A patented light-scattering technology developed through University of Hertfordshire (UH) research, initially for the real-time detection of airborne pathogens like anthrax in military and counter-terror scenarios, has been commercially exploited for bioaerosol monitoring in health and environmental contexts. Licensed by the MOD's Ploughshare Innovations to two SMEs in the United States to maximise returns from UK defence spending, the technology has generated £700,000 in licensing income [TEXT REDACTED FOR PUBLICATION], created 22 jobs and raised £3m in investment. Use of the technology resulted in further economic and societal impact. It has delivered significant commercial advantages and revenues to a Fortune 1000 company, SMEs, business franchises and individual contractors in the specialist cleaning and disaster restoration sector. It has supported schools, hotels, cultural institutions and governments with building decontamination following Covid-19 lockdowns in the US. [TEXT REDACTED FOR PUBLICATION], informed the UK and Irish governments' policy approaches to pollen, spore and biowaste monitoring, and identified infection risk in hospitals.

2. Underpinning research (indicative maximum 500 words)

The ability to rapidly detect airborne biological warfare agents was a government imperative following the Gulf War in 1991 and the rise in terror attacks in the early 2000s. This drove the development of technologies for the real-time detection and classification of airborne microorganisms. A technology of growing interest was that of autofluorescence; the identification of an organism from its intrinsic fluorescence spectrum under ultraviolet excitation. However, all commercially available biofluorescence instruments used frequency-quadrupled UV Diode Pumped Solid State lasers and their prohibitive cost made implementing wide-area networks of bioaerosol detectors impractical.

Kaye, Hirst and Stanley at UH's Centre for Atmospheric and Climate Physics Research had developed a class-leading diode pumped solid state (DPSS) UV laser-based detector for the UK Defence Science and Technology Laboratory (Dstl) in 2000 [**3.1**]. In 2001 they were challenged by Dstl to develop a new type of bioaerosol detector that was affordable enough to be deployed in wide networks (i.e. for large numbers of troops) to detect potential biowarfare agents. Very few alternatives to DPSS lasers existed that could offer similar UV radiant powers. One was the ubiquitous xenon flashlamp, then being widely used in disposable cameras. However, such flashlamps presented major research challenges. These included the need to: substantially improve the 'blocking' of radiation from the flashlamps outside the desired UV wavelength bands; designing compact high-efficiency optical systems both to deliver the UV radiation to the particle and capture resulting fluorescence (involving custom-designed mirrors and coatings); aerodynamic modelling of aerosol delivery systems to ensure particles carried in the sample airflow were exposed individually to the UV radiation; and optically quenching unwanted fluorescence from other components within the instrument that threatened to dominate the ultra-weak fluorescence from the microorganisms.

Under the initial Dstl grant [**G1**], the Group developed the world's first low-cost xenon-based UV biofluorescence detector, the WIBS (Wide Issue Bioaerosol Sensor) [**3.2, 3.3**]. Follow-on funding from Dstl – £500,000 over five years [**G2**] – allowed researchers to further develop the WIBS technology, greatly improving the fluorescence efficiency and dynamic range of the design, improving aerodynamic management of the aerosol sample flow and, for the first time, incorporating a light-scattering-based particle shape measurement to enhance microorganism classification. By 2009, the WIBS biodetection technology was class-leading, as demonstrated in joint field trials by the US and UK military, and sensitive enough to detect a single airborne spore of *Bacillus globigii*, a surrogate for anthrax. It was patented worldwide by Dstl [**3.3**].

The success of these trials led to further funding [**G3**] from Dstl and the Home Office (whose interest lay in counterterrorism) to enhance fluorescence sensitivity and particle shape classification, and to support enhanced data analysis and bio-organism classification algorithms. WIBS' versatility in detecting and classifying airborne bio-organisms attracted attention from other academic groups interested in exploiting WIBS to study the role of bioaerosols in atmospheric dynamics and in health-related fields such as allergen (e.g. spores, pollen) dispersion. UH worked with the University of Manchester to use the WIBS instrument to gather, for the first time, detailed temporal information on the dispersal of biological particles below and above a tropical rainforest canopy in Borneo [**3.4**]. Ireland's Environmental Protection Agency funded UH to increase WIBS' range to allow pollen detection, leading to WIBS-4, the fourth generation of the instrument. The UH-Manchester collaboration, with Dstl, used this WIBS to analyse biological aerosol particles in a Colorado forest [**3.5**], as part of the BEACHON project in the US, which explored the roles of biogenic aerosols, nitrogen trace gases and oxidants in regulating carbon and water cycles.

As the applicability of WIBS beyond the military became evident, Dstl explored commercial opportunities through Ploughshare Innovations, the MOD's technology transfer arm. Research and development of the WIBS technology continued at UH with the design of the Multiparameter Bioaerosol Spectrometer (MBS), which offered enhanced particle fluorescence spectral resolution and high-resolution particle shape and surface feature analysis for single airborne biological particles [**3.6**]. The UH team has since continued to build new MBS research instruments and improve the existing ones, including a major upgrade for the University of Manchester that was completed in 2019.

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

3.1 Kaye PH, Barton JE, Hirst E, Clark JM. Simultaneous light scattering and intrinsic fluorescence measurement for the classification of airborne particles. Applied Optics. 2000;39(21):3738-3745. https://doi.org/10.1364/AO.39.003738 (123 citations)
3.2 Kaye PH, Stanley W, Hirst E, Foot EV, Baxter K, Barrington SJ. A single-particle multichannel bio-aerosol fluorescence sensor. Optics Express. 2005;13(10):3583-3593. https://doi.org/10.1364/OPEX.13.003583 (182 citations)
3.3 Representative Patent: United States Patent 7,436,515 B2; 'Fluid borne particle analyzers'. Inventors: KAYE Paul Henry [GB]; HIRST Edwin [GB]; Applicant: UK Secretary of State for Defence; Date of Patent: 14 October 2008.
3.4 Gabey A, Gallagher M, Whitehead J, Dorsey JR, Kaye PH, Stanley W. Measurements and comparison of primary biological aerosol above and below a tropical forest canopy using a dual channel fluorescence spectrometer. Atmospheric Chemistry and Physics. 2010;10(10):4453-4466. https://doi.org/10.5194/acp-10-4453-2010 (140 citations)
3.5 Robinson NH, Allan JD, Huffman JA, Kaye PH, Foot VE, Gallagher MW. Cluster analysis of WIBS single-particle bioaerosol data. Atmospheric Measurement Techniques. 2013 Feb 13;6(2):337-347. https://doi.org/10.5194/amt-6-337-2013 (59 citations)
3.6 Ruske S, Topping DO, Foot VE, Kaye P, Stanley W, Crawford IP et al. Evaluation of machine learning algorithms for classification of primary biological aerosol using a new UV-LIF spectrometer. Atmospheric Measurement Techniques. 2017 Mar 3;10(2):695-708. https://doi.org/10.5194/amt-10-695-2017 (30 citations)

Key underpinning grants
G1 Dstl; Fluorescence Detector for Unmanned Operation (WIBS); 2002-2004; £149,609.

G2 Dstl; WIBS-2, WIBS-2s, WIBS-3, WIBS-4 development grants; 2004-2009; £505,288.
G3 Dstl and Home Office; Bioaerosol Detection; 2009-2011; £193,630

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

The patented WIBS technology has generated licensing revenues for reinvestment in UK defence by the MOD. It has generated commercial revenues for both SMEs and large corporations in the United States, created new jobs and raised external investment. It has delivered significant benefits to companies within the specialist cleaning and disaster restoration sector, and has supported schools and public buildings in their responses to Covid-19. It has also [TEXT REDACTED FOR PUBLICATION], informed environmental policy in the UK and Ireland, and identified infection risks in hospitals.

Commercial and reputational benefits to the Ministry of Defence (MOD)

Ploughshare Innovations is an MOD-owned company with a remit to maximise the benefit of public expenditure in defence research through commercial exploitation of technology developed by Dstl. Ploughshare licensed the WIBS technology to US company Droplet Measurement Technologies (DMT), a world-leading manufacturer of aerosol measurement devices, in 2012, and to another US company DetectionTek, a specialist in indoor air quality monitoring, in 2015, and has received royalties from sales throughout the impact period. Since 1 August 2013 it has accrued total revenues of £700,000: £350,000 from the DMT licence; £200,000 from the DetectionTek licence; and £150,000 from another US company who purchased the option to bring WIBS to the pharmaceutical market [**5.1**]. In the context of Ploughshare's £2m annual turnover the company's Chief Operating Officer confirmed: *"For us these are significant deals and we are optimistic about the potential for high revenue growth in the near future across both licences."* In 2016 Ploughshare amended the licensing agreement with DMT to specify new applications of WIBS and new markets, including China and India, benefitting from an increase in royalties through sales to these countries. Revenues generated by Ploughshare are reinvested by Dstl in the UK's defence capabilities. The successes of the WIBS technology have also helped Ploughshare demonstrate the effectiveness of the MOD's technology transfer model. According to Ploughshare's COO: *"While we are judged on our contribution to the MOD's commitment to economic growth creation, we want to make sure that great technologies developed for defence purposes are put to wider societal use for the benefit of as many people as possible. The WIBS licensing agreements have helped us to achieve this."* [**5.1**]

Direct economic impact via commercial exploitation of WIBS in the United States

With technical support from Kaye, DMT further developed the WIBS technology and in 2016 launched the WIBS-NEO, an instrument providing detailed information on atmospheric bacteria, moulds, pollen and other bioaerosols. [TEXT REDACTED FOR PUBLICATION] [**5.2**]. [TEXT REDACTED FOR PUBLICATION]. DMT's WIBS-NEO customers comprise government agencies, research institutes and universities, who use it in a range of applications including biological testing, indoor air quality monitoring, airborne bioaerosol concentration and atmospheric monitoring. Since 1 August 2013, around 280 peer-reviewed journal publications have cited WIBS data. [TEXT REDACTED FOR PUBLICATION] [**5.2**]

DetectionTek, which agreed a licence with Ploughshare in 2015, worked with the University of Colorado Boulder to adapt the WIBS instrument into the commercial product InstaScope for indoor air quality monitoring and assessment. By counting and characterising bioaerosols on a particle-by-particle basis, the instrument, built around WIBS technology, provides real-time data on viruses, bacteria, mould and pollen. It was first used by disaster restoration companies and technicians dealing with floods and leaks to quantify, on site, how much airborne contamination was present as remediation progressed. InstaScope can deliver results in real-time (this process used to take several days) and at far less cost than previously possible [**5.3**]. This allows contractors to deploy equipment to control contamination levels (thus protecting the health of occupants) and to defend their billing to insurance companies [**5.3**].

Responding to the Covid-19 pandemic, DetectionTek made a significant investment in the development of new software that allows InstaScope to assess whether or not a room, such as a school classroom, has the lowest possible occupant exposure to bio particles after it has been sanitised. Before cleaning, the instrument is used to measure (in real time) the total bio load, which forms the baseline for subsequent scans. After cleaning and with high-efficiency particulate air (HEPA) filtration placed, InstaScope remeasures the total bio load to check it has been sufficiently reduced. The WIBS licence has enabled DetectionTek to raise $3.5m (£3m) in external investment and create 18 jobs [**5.3**]. The company projects that income across the impact period and up to 31 December 2021 will total $5m [**5.3**]. The licence also resulted in $420,000 (£356,000) in industry investment (from US companies including Intel Corporation, Carrier Global and Clorox) for research at the University of Colorado Boulder to further evaluate and optimise the technology [**5.3**].

Wider societal and economic impact via use of WIBS technology by customers of DMT and DetectionTek, and academic research groups

Individual contractors and large companies have benefitted from the availability of DetectionTek's InstaScope instrument. ServiceMaster is a Fortune 1000 company that provides residential and commercial services. It has 13,000 employees and a franchise network that independently employs over 33,000 additional people. The operations manager for ServiceMaster National Capital Restoration (NCR) described InstaScope in 2017 as a technological advancement that has '*changed an entire industry*' [**5.4**]. He wrote in an article on ServiceMaster NCR's website: *"The InstaScope has taken the average downtime and loss of use on a mold project from 8 days to 1.5. The positive impact on project timetables and client perception is immeasurable and is borne out by numerous case studies* [**5.4**].'

The nature and significance of the benefits to end users is indicated through DetectionTek's client testimonials. The CEO of a ServiceMaster franchise in Newark wrote: *'The InstaScope has changed my career. I have gone from a commodity service provider to a trusted consultant and expert for my customers* [**5.5**]*.'* The owner of SME Indoor Air Quality Services wrote: *'The ability to have real-time information and evaluate every room has changed the way I conduct assessments. I am able to focus on problem areas immediately, without the need for a return visit* [**5.5**].' As an indication of the significance of the downstream economic impact of the WIBS technology, one ServiceMaster franchise employing 50-60 people generates an annual turnover of around $15m of which over $1m (£755,000) is attributed directly to InstaScope billing [**5.3**].

In response to Covid-19, DetectionTek worked with hotels, cultural institutions and government agencies to help them return to activity post lockdown [**5.6**]. The company then made schools their strategic priority. In the summer of 2020 InstaScope funded ($200k) a pilot with the University of Colorado Boulder in Denver Public Schools (operates 207 schools in the county) to validate classroom sanitisation. As a result, Denver Public Schools made a formal commitment to purchase instruments for use in around 6,000 classrooms [**5.3**].

[TEXT REDACTED FOR PUBLICATION] [**5.7**]. The WIBS technology has been cited in around 280 peer-reviewed journals authored by researchers using the instrument in bioaerosol studies, having purchased it from DMT. Interviews with researchers on some of these projects have revealed further examples of impact *beyond the research community*.

<u>Informing Irish and UK government approaches to pollen, spore and green waste monitoring</u>: UH researchers worked with Professor John Sodeau at University College Cork (UCC) to adapt the WIBS for biological spore and pollen monitoring. In Killarney National Park, in collaboration with Ireland's Environmental Protection Agency (EPA), Sodeau found that the impact of fungal spores in indoor areas (e.g. workers' cabins) can be significant. He also identified the risk of public exposure. The EPA published a report on the findings, which recommended continuous monitoring of green waste facilities [**5.8**]. Following on from this project, the EPA and Met Eireann invested €500,000 in the development of a daily pollen forecast for Ireland using WIBS

[**5.9**]. The UK Environment Agency notes that driving down people's exposure to particulate matter in order to protect their health represents a '*major challenge*' for government. It uses the WIBS technology at biowaste sites to '*pinpoint precisely when spikes of bioaerosol emission are observed, enabling us to deduce the worst-offending parts of the process (some of which can be highly intermittent), which we can then focus on mitigating*' [**5.10**].

Informing health policy in Ireland to protect patients: In 2016, evidence was published to show that hundreds of thousands of patients worldwide could be at risk from a deadly bacterial infection (*Mycobacterium chimaera*) linked to aerosols from a heater-cooler unit used during cardiac surgery. This medical device is an essential part of life-saving surgeries as it helps keep a patient's organs at a specific temperature during the operation. Twenty-eight cases were confirmed in England alone, leading to 15 deaths. The WIBS was used as part of a case-finding investigation for Ireland's Health Service Executive by Professor Michael Prentice of University College Cork [**5.11**]. He concluded that one specific model of heater-cooler device did indeed produce aerosols in normal operation and therefore carried an infection risk; it was subsequently removed from hospitals in Ireland. Prentice had previously used WIBS for source investigation in an operating theatre that was failing microbial air testing, finding that automatically flushing taps in the scrubs sinks were producing aerosols reaching the operating table, and that redesign of the operating theatre was required. In the Covid-19 pandemic he also used WIBS to validate the effectiveness of an aerosol control tent and a suction device promoted to reduce biological aerosols capable of transmission of SARS-CoV2 [**5.11**].

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

5.1 Corroborating statement from the Chief Operating Officer, Ploughshare Innovations Ltd.
5.2 Corroborating statement from VP, Strategy & Innovation, Droplet Measurement Technologies.
5.3 Corroborating statement from Chief Executive Officer, DetectionTek Holdings LLC.
5.4 Company website article authored by the operations manager for ServiceMaster National Capital Restoration: https://www.servicemaster-ncr.com/healthy-building-technology-instascope/
5.5 Testimonials from DetectionTek customers on the benefits of InstaScope.
5.6 *Boulder company scales up with device that can detect viruses and bacteria in the air*, Denver Business Journal article (available as PDF), June 2020.
5.7 [TEXT REDACTED FOR PUBLICATION].
5.8 Environmental Protection Agency (Ireland) report: Online Bioaerosol Sensing. http://www.epa.ie/pubs/reports/research/air/Research_Report_269.pdf
5.9 Website of the POMMEL project: a fully operational pollen forecast system for Ireland. https://www.pommel.ie/about-us.html
5.10 Corroborating statement from Principal Scientist, Evidence Directorate, Environment Agency.
5.11 Corroboration available from Chair of Medical Microbiology at University College Cork and Consultant Microbiologist at Cork University Hospital.