Institution: The Open University		
Unit of Assessment: B9 Physics		
Title of case study: Safeguarding the security of the nation: Developing a national capability for air quality monitoring on UK submarines		
Period when the underpinning research was undertaken: 2000-2020		
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:**
Dr Geraint Morgan	Research Fellow	1993 – present
Dr Simon Sheridan	Senior Research Fellow	1995 – 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

The continuous at sea deterrent (CASD) has provided the United Kingdom with the ultimate security insurance policy for the last fifty years. Our development of an innovative, next generation, UK-based air quality monitoring capability, for use on all future UK submarines, providing greater performance at a significantly reduced cost thus ensuring the on-going delivery of CASD, has delivered impact with reach and significance for beneficiaries including the Ministry of Defence, BAE Systems, Analox, UK submariners and the nation.

Impact areas include: **Commerce and the Economy; Enhanced Performance and Delivery of Professional Services; and Health and Wellbeing.** It has already created 7 highly skilled jobs in a SME [text removed for publication]. The MoD have published their decision to place a further [text removed for publication] contract with the same SME, creating another 6 jobs, with further [text removed for publication] sales to supply the Dreadnought class in prospect.

2. Underpinning research

The Distributed Atmospheric Monitoring System (DAMS) project was initiated as a result of Ministry of Defence's (MoD) Successor Technology Development Programme (TDP), via the UK's largest defence manufacturing company, BAE Systems Submarines. In January 2010, following an assessment of the UK's technologies and expertise, BAE's submarine design division selected and engaged researchers in the Space Instrumentation Discipline at The Open University (OU) to develop the best technical solution to their challenge.

The aim was to lower the detection levels for a wide range of target compounds whilst also making the monitoring system a smaller, lighter and more robust solution that would reduce the through-life servicing costs and the cost of manufacture, not only of the monitoring instruments but also the submarine itself.

[Text removed for publication.]

Much of the underpinning research associated with this case study relates to our team's work in planetary sciences at the OU. There we faced almost identical constraints in designing mass spectrometer-based instruments that can deliver accurate analytical results despite severe constraints on mass, volume, power, energy as well as having to work in harsh environmental conditions (temperature, radiation, shock and vibration). Another common design consideration is that the solutions must be robust and maintenance free, as neither spacecraft nor submarines have ready access to service engineers.

Some of our publications, detailed below, relate to robust and maintenance-free design solutions that allow us to address key scientific questions using space instrumentation; in particular, the Ptolemy instrument for the Rosetta cometary mission **[O1, O2]**. Prior to the submarine project we had also developed a track-record of translating our extensive multi- disciplinary knowledge base to developing novel assays and robust, field portable instruments as bespoke solutions to complex terrestrial challenges, including air monitoring **[O3]**.

As with any space mission, the submarine project first required a feasibility study of the analytical requirements and the operational constraints, allowing a range of suitable solutions to be proposed for evaluation. We then developed and tested a range of versions of the system to demonstrate

its performance and iteratively refined the gas handling and calibration processes until they met specification. A hybrid MS/FTIR system was developed to measure the key 'life' gases requiring constant monitoring for submariner safety.

The key research outcome was the final DAMS instrument, which was a hybrid instrument with on board, fully automated gas handling and control software, computational algorithms, graphical interface and calibration libraries. The project was milestone driven with a series of stage-gate approval reviews, including: Feasibility Study (April 2010), Preliminary Design Review (Dec 2010); Detailed Design Review (Mar 2011); Integrated System Testing Review (July 2011, Dec 2011), Evaluation of Sea Trial Results (July 2012), End of Project Report (July 2012) **[O4, O5, O6]**.

Unfortunately, as these project reports contain details of the chemical species to be measured in the submarine, they are not available for review as the data is potentially classified [text removed for publication]**[C1]**. However, the former Managing Director [text removed for publication] at Analox had the following to say:

"The Open University handed over a prototype submarine atmosphere analyser. This was probably at a Technology Readiness Level of 6 but had been proven in a submarine environment on a lengthy sea trial. The benefit of this to Analox was that we knew that the base technology worked. We then had to convert this technology into a more modular, easier to service package with the associated rigour to meet the safety / functional requirements specified by the customer. Very little time was spent proving the technology from a gas sensing perspective as this work had already been done by The Open University […]. It is revealing that Analox had very little dealings with the Open University once the prototype and its associated documentation were handed over. This is because the research was properly completed and documented" **[C1]**.

3. References to the research

Journal Articles:

O1. Wright, I.P., **Sheridan**, **S**., Barber, S.J., **Morgan**, **G**.**H**., Andrews, D.J., and Morse, A.D. (2015) CHO-bearing organic compounds at the surface of 67P/Churyumov-Gerasimenko revealed by Ptolemy. *Science,* 349(6247). https://doi.org/10.1126/science.aab0673. Blind peer reviewed.

O2. Wright, I.P., **Sheridan**, **S**., **Morgan**, **G**.**H**., Barber, S.J., and Morse, A.D. (2017) On the attempts to measure water (and other volatiles) directly at the surface of a comet. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 375(2094), article no. 20150385. https://doi.org/10.1098/rsta.2015.0385. Blind peer reviewed.

O3. Nicoara, S., Tonidandel, L., Traldi, P., Watson, J., **Morgan**, **G**., and Popa, O. (2009) Determining the levels of volatile organic pollutants in urban air using a gas chromatography-mass spectrometry method. *Journal of Environmental and Public Health*, 2009 (148527). https://doi.org/10.1155/2009/148527. Blind peer reviewed.

DAMS TDP Project Reports from the OU Project Team to BAE Systems & Defence Equipment &Support (DE&S) at the MoD:

O4. Stage 1: Feasibility Study (April 2010); Stage 2: Preliminary Design Review (Dec 2010); Detailed Design Review (Mar 2011); Integrated System Testing Review (July 2011, Dec 2011)

O5. Evaluation of Sea Trial Results (July 2012).

O6. End of Project Report (July 2012).

Journal articles are available using the digital object identifiers provided; however, given the sensitivity of much of the data contained in the DAMS project reports, these are not available to the panel.

4. Details of the impact

Pathway to Impact:

Translation of the research to impact with reach and significance was facilitated by funding from the Defence Equipment and Support (DE&S) arm of the MoD, in the form of the Technology Development Programme (TDP) to BAE Systems Ltd. BAE Systems were tasked with the design of the Successor Trident replacement submarine and, following an assessment of the requirements and expertise available nationally, selected the OU as their partner to develop a novel Distributed Atmospheric Monitoring Systems (DAMS) as part of this programme. Following successful delivery of the research project [text removed for publication], BAE contracted the OU to support them in: a) developing the Technical Design Specification for the in-service air monitoring system; and b) selecting the UK company for the follow-on Design Development Qualification (DDQ) Phase to take the system design through from TRL6/7 to TRL9. Analox Ltd was awarded the two-year contract to develop an operational in-service system, following an Invitation to Tender (ITT) process in 2014, fully supported by the OU.

Impacts on industry, sub-mariners and MoD/government/nation are discussed below:

1. Analox Ltd

In his testimonial letter **[C1]** Analox's former Managing Director (to January 2019), now Chairman/Director, states *"We headed up collaboration with The Open University […] in 2014, to review research work carried out by The Open University on the DAMS TDP Project. This allowed Analox to win the Atmosphere Analyser DDQ contract [text removed for publication] in August 2014.*" He went on to confirm that the project had delivered impacts on **commerce and economy**: *"the impact of [The] Open University research programme on [the] Analox Group between 2014 and the end of 2020 was the Atmospheric Analyser Contract [text removed for publication], Atmospheric Analyser unit sales [text removed for publication], and 7 jobs created within the Analox Group."* He continues: *"On the 25th June 2019, the Ministry of Defence (Submarines, In-Service Submarines Team) took the decision to award Analox a further contract for the Analox Atmosphere Analyser. This contract notification* **[C2]** *was published in Annex A of the Official Journal of the European Union on the 5th July 2019. The total stated contract value is GBP14.25M, which covers sales of Analox Atmosphere Analysers to equip the UK submarine fleet, spares, initial training and the maintenance of the Atmosphere Analysers […].[text removed for publication] Six additional jobs will be created within the Analox Group by 2027 as a result [text removed for publication]* **[C1].**

He also writes **[C1]**: "*In technology terms, Analox is now looking at a greater range of gas sensing technologies than in previous times […]. This has given the company a greater confidence to take on more challenging gas sensing problems. The company is also in the process of acquiring companies with the technologies that we will need for the future*." He ends by saying: "*The Analox Atmosphere Analyser has changed the way Analox works fundamentally. Before the project Analox was a largely commercial market-based operation. After the project, over half the company's sales come from the military sector. This would not have happened without this project" thus* evidencing impact through **Enhanced Performance and Delivery of Professional Services.**

2. BAE Systems Ltd

In his testimonial letter **[C3]** the Research & Technology Manager (BAE Systems Submarines) confirms that *"The Open University were identified as experts in the field of atmosphere monitoring in harsh environments, due to their work on the Ptolemy gas analyser for the Rosetta comet mission and were approached and contracted to design the replacement analyser."* He also states "*Through a collaborative programme (Jan 2010 to July 2012) involving both MoD and the Royal Navy, The Open University developed an innovative, next generation atmosphere analyser (Distributed Atmospheric Monitoring System (DAMS)) providing greater performance at a significantly reduced cost*" **[C3]**.

Based on the stakeholder review of the Sea Trial results **[O5]** he further confirms **[C3]** that:

- *"This analyser ensures future submarines have the required operational capability, and also offers a significant cost saving to the UK defence procurement programme. Indeed, in the business case for the TDP we estimated that operationally it would save the MoD ~ GBP1.25m, over the 40-year lifetime of a platform. This figure doesn't take in to account the savings in the simplification of the design of the submarine."*
- *"The report included positive verbal feedback from the crew on the system performance during the Sea Trial and operator interface and usability."*
- *"This high-level stakeholder approval enabled BAE's platform engineers to approve the design of the atmosphere monitor onboard Dreadnought, with a much-improved design."*

He goes on to say **[C3]**:

"*Through our work with The Open University, BAE Systems Submarines have matured their understanding of working with universities for the mutual benefit of both academia and industry and have subsequently developed best practice to ensure future university engagement provides the same commercial opportunities […]. As you are aware, based on the positive experience of the original DAMS TDP, and in recognition of your team's expertise in this area, we will be seeking to engage you for the development of the next iteration of the Future Air Monitoring System (FAMS). Sadly, this activity has been delayed due to Brexit and COVID"* thus evidencing impact on **Commerce and the Economy; Enhanced Performance and Delivery of Professional Services; and Health and Wellbeing.**

BAE Systems has formally recognised the value of the DAMS project, as evidenced by the award of a 2013 BAE Systems Chairman's Award for Innovation (Silver & Bronze) *"for extraordinary behaviour that stimulates innovative design and application that delivers a proven solution, leading to improved business performance*." The award citation **[C4,** p.3**]** also went on to state:

"Submarine Atmosphere monitoring is a specialist area that holds particular challenges and requires specialist equipment for long term monitoring across the vessel. The incumbent equipment supplier of the Atmosphere Analyser holds a significant monopoly over the Western nuclear submarine fleet and has had the equipment on all RN submarines for the past three decades. The team identified the potential to develop new analyser equipment that would be smaller, cheaper and more capable -and therefore offers a safety benefit- than the existing solution […]. The equipment has been tested on patrol and has demonstrated a significant performance improvement over the existing equipment [text removed for publication].

3. Submariners

An MoD article **[C5,** p.31**],** covering the above award to the DAMS project team, also reported *"The equipment has been tested on patrol, and has demonstrated a significant performance improvement over the existing equipment*". As a result of being able to detect more compounds, more accurately, at lower concentration levels, with graphical outputs of results, our solution will deliver **i*mpacts on health and wellbeing*** and ***impacts on environment*** for the submariners by providing a sequence of alarms that identify any issues with the composition of the atmosphere. This will allow the crew to undertake specific responses based on the different levels of the alarm. The trial also provided positive verbal feedback from the end-users when compared the existing CAMS interface **[O6, C3]**. The switch from a single analyser to three distributed analysers, enabled by this project, provides the submariners with better coverage and redundancy, should one of the systems fail.

Adoption of the Analox Atmosphere Analyser by the MoD has enabled the better management of environmental risks and hazards, influencing professional practice, specifically BR1326 – Control of Submarine Atmospheres.

4. Ministry of Defence (MoD) /Government / Nation

The latest (July 2020) Parliamentary Briefing Paper **[C6**, p.3**]** on Dreadnought evidences its scale and importance: *"In a vote in July 2016 the House of Commons approved the decision to maintain the UK's nuclear deterrent beyond the early 2030s." The UK is building the next generation of submarines (Dreadnought) to carry forward this vital role and "will have a service life of at least 30*

years" **[C6**, p.7**]**. Whilst "*BAE Systems, Rolls Royce and Babcock International are the Tier One industrial partners in this project […], BAE Systems has estimated that 85% of its supply chain will be based in the UK, potentially involving around 850 British companies […]. The cost of the programme has been estimated at GBP31 billion […]. A Trident replacement will support almost 26,000 jobs over its life-cycle (based on four boats and including some 1,850 Navy personnel jobs*)" **[C6**, p.4**].**

As previously demonstrated, a key design driver for these new submarines is the ability to accurately monitor the air quality to ensure the health and wellbeing of the crew **[C3]**. Without them, the submarine is not operational, and we would risk losing CASD **[C3]**. The MoD identified the need to develop a UK capability in this area and the need for a new analyser to replace the existing solution, which was described as *"obsolete*" **[C3]**, prone to failure, expensive to procure and maintain and was proving difficult to obtain spare parts. As demonstrated in a 2014 article **[C5]**, following the successful Sea Trial of the OU analyser, the MoD has acknowledged that this project has delivered *"a step-change in a vital piece of safety equipment for use on board future Royal Navy submarines"*. This was further confirmed in their justification for the direct award to Analox in the Contract Notice in the Official Journal of the European Union where they stated: *"The Authority requires a system which detects low levels of gases at a more accurate level, in line with UK legislation (including EH40 levels), and one which can provide graphical representations of the environment, the AA Unit is the only fixed atmosphere analyser monitoring system in the supply market with the capability to meet the Authority's requirements and Analox Military Systems Ltd are the only supplier with the capability, design rights and technical expertise to manufacture the AA unit"* **[C2]**.

The reach and significance of the impact of this translation of know-how from the Space sector, and its value to the nation, was also recognised in 2014 by the then Secretary of State for Business Innovation & Skills: *"Rosetta is a great example of how our investment in big space programmes delivers a wide range of benefits for the UK. Not only do we push the boundaries of science, but we reap the considerable economic and social benefits that new space technologies provide. It's great to see the skills and technologies our scientists and engineers have developed for this mission being applied in other areas*" **[C7**, p.1**]**.

5. Sources to corroborate the impact

C1. Testimonial Letter from Chairman and former MD of Analox Ltd.
C2. Annex A – Extract from Official Journal of European Union.
C3. Testimonial Letter from Senior Engineering Manager - Research & Technology, (BAE Systems Submarines) and the TDP Project Manager.
C4. 2013 BAE Chairman's Award for Innovation – Silver Award Citation and Brochure.
C5. DESider Magazine, Jan 2014, Issue 68, p31 – Subs staff earn partner's silver salute.
C6. Parliament Briefing Paper: Replacing the UK's Nuclear Deterrent: Progress of the Dreadnought Class (House of Commons Library, Number 8010, 17 July 2020).
C7. OU & BAE Systems' Joint Press Release – 4th December 2014.