Institution: University of York		
Unit of Assessment: 9 - Physics		
Title of case study: Gamma ray detectors for homeland security		
Period when the underpinning research was undertaken: 2009-2014		
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:**
David Jenkins Stefanos Paschalis	Professor Lecturer	2002- present 2016- present
Period when the claimed impact occurred: Aug 2013-Dec 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Advances in radiation detector technology for fundamental research at the University of York have been translated through partnership with a British company, Kromek PLC, into a wearable gamma-ray detector called the **D3S**. The **D3S** has achieved rapid dominance in the homeland security market, being used in a wide range of security applications and in many countries worldwide. A major customer is the US Government who placed an initial order for 10,000 units with an order value of USD6,000,000. The **D3S** provides a factor of 100 improvement in localisation and identification of radioactive sources with respect to pre-existing technology, and allows significantly improved reaction times and speed of threat analysis.

2. Underpinning research (indicative maximum 500 words)

The nuclear physics group at York has a long-standing track record in developing detectors and instrumentation for use at international facilities such as CERN. The pathway to the present impact started with Professor David Jenkins being made technical director for the design and construction of the PARIS calorimeter in 2010. PARIS comprises an array of gamma-ray detectors using scintillator crystals such as Lanthanum Bromide **[3.1]**. This research positioned the York group to be world-leading experts on scintillator detectors and, in particular next-generation scintillator detectors **[3.2]**. As part of the PARIS project, Prof Jenkins focussed on exploring the potential of silicon photomultipliers (SiPMs) as a replacement for conventional photomultiplier tubes (PMTs). In the early 2010s, SiPMs were just coming to market driven by advances in positron-emission tomography (PET). SiPMs are highly compact, solid state replacements for PMTs and operate on low voltage (typically 30 – 60 V) making it possible even to operate them from a battery. In a parallel project, Prof Jenkins led the coupling of SiPMs to a plastic scintillator to create a charged-particle veto detector used at the University of Jyvaskyla in Finland **[3.3, 3.4]**. He also led a joint project with the University of Hull to develop a SiPM-based detector for PET isotope assay, for which there is now a joint patent **[3.5]**. These achievements constitute the underpinning research and development work which led to York being world-leading in using SiPMs and scintillators for gamma-ray detection applications and allowed us to collaborate with Kromek PLC in developing the **D3S** wearable gamma-ray detector and further detector variants from 2013.

York has continued to collaborate closely with Kromek since the initial development supported by Innovation Partnership Scheme (IPS) grants from STFC where Kromek was the industrial partner alongside the US Defense Threat Reduction Agency (DTRA), as well as the EU-funded project, ENSAR2. In addition, Kromek provided direct industrial funding which led to the hiring of a new academic, Dr Stefanos Paschalis in 2016 as well as supporting laboratory infrastructure and staffing. Dr Paschalis brought new expertise in gamma-ray detection technologies having played a leading role in the gamma-ray tracking array called GRETINA **[3.6]**. This additional support allowed a range of improvements to the basic **D3S** detector technology to be explored in collaboration with Kromek. For example, Dr Paschalis led Monte Carlo simulations at York that permitted the **D3S** to be repackaged as a personal dosimeter, the **D3S PRD**. He led research and development on alternative scintillator crystals such as CLLBc which led to the very recent **D5 RIID** product from Kromek which significantly exceeds the performance of the original **D3S** in terms of energy resolution and sensitivity as well as offering combined gamma-ray and thermal neutron detection. Dr Paschalis and Prof Jenkins also developed a collimated gamma-ray beam system to probe position sensitivity in monolithic scintillator crystals which is a pathway to a future Compton-camera based variant of the **D3S** which would provide improved localisation of radioactive sources in the field.

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

3.1. The PARIS project, A. Maj, F. Azaiez, **D. Jenkins** et al., Acta Physica Polonica B40, 565 (2009). https://www.actaphys.uj.edu.pl/R/40/3/565/pdf

3.2. Novel Scintillators and Silicon Photomultipliers for Nuclear Physics and Applications, **D.G. Jenkins**, J. Phys. Conf. Ser. 620, 12001 (2015). https://iopscience.iop.org/article/10.1088/1742-6596/620/1/012001

3.3. Enhancing the sensitivity of recoil beta tagging, J. Henderson, **D.G. Jenkins** et al., Journal of Instrumentation 8 P04025 (2013). https://iopscience.iop.org/article/10.1088/1748-0221/8/04/P04025/meta

3.4. Spectroscopy on the proton drip-line: Probing the structure dependence of isospin nonconserving interactions, J. Henderson, **D.G. Jenkins** *et al.,* Phys. Rev. C. 90, 051303 (2014). https://doi.org/10.1103/PhysRevC.90.051303

3.5. Plastic Scintillator-Based Microfluidic Devices for Miniaturized Detection of Positron Emission Tomography Radiopharmaceuticals, M.D. Tarn, **D.G. Jenkins** *et al.,* Chem. Eur. J. 24, 1 (2018). https://doi.org/10.1002/chem.201802395

3.6. On the self-calibration capabilities of gamma-ray energy tracking arrays, S. Heil, **S. Paschalis** and M. Petri, Eur. Phys. J. A 54, 172 (2018). https://doi.org/10.1140/epja/i2018-12609-0

[3.1] and **[3.2]** are peer-reviewed conference proceedings
[3.3-3.6] are peer-reviewed publications

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

It is often said that the first priority of government is the safety and security of its citizens. Accordingly, homeland security is an area of high importance internationally especially in the US where it has received high levels of funding, particularly since the tragic events of September 2001. A key area of interest is the detection and location of illicit radiological material in the environment. Such material could be used to fabricate a "dirty bomb" i.e. a radiological weapon where conventional explosive is used to disperse radioactive material to create panic in an urban environment. The most likely materials to be used in such a weapon are gamma-ray emitting isotopes since gamma rays are very penetrating. The detection of such illicitly stored and transported radioactive material is of high importance. Moreover, tracing the origin and distribution of material following an explosion would be an immediate priority for a forensic investigation. Gamma-ray detectors designed to solve these challenges need to carry out several functions i.e. to quantify the level of radiation, determine its origin in terms of the specific radioactive isotope and locate it spatially within the built environment. To cover a large area, many detectors (in the 100s or even 1000s) would need to be deployed requiring them to be not only sensitive but highly portable and inexpensive. Prior to the present impact described here, traditional detector technology could cover some of the requirements but failed to satisfy others, e.g. they were highly sensitive but not portable, or relatively inexpensive but of limited sensitivity, or fragile or power-intensive in a field deployment.

Prior to 2013, Kromek had developed a gamma-ray detector based on the semiconductor material CZT which they hoped could partially address the challenges in homeland security described above. Such a detector proved not to be suitable as CZT crystals cannot be grown larger than about 1cm^3 which leads to a very low detection efficiency. The material is also intrinsically very expensive and could not be deployed at a realistic cost to thousands of first responders in the field.

Prof Jenkins originally visited Kromek in 2013 to learn about the CZT technology as a possible solution to a challenge in monitoring drains in nuclear power stations. During this visit, Kromek asked what York were working on and Prof Jenkins presented highlights of recent work on scintillators and silicon photomultipliers. Kromek realised quickly that this technology, which was not in their area of expertise, offered the solution they needed **[5.1]**. Under a short KTP, York and Kromek co-developed a hand-held gamma-ray detector called **SIGMA**. This device incorporates a CsI(TI) scintillator crystal coupled to a SiPM and can run off battery power. Kromek initially marketed the **SIGMA** detector and then reconfigured it to form part of a rugged, wearable, network-capable device called the **D3S [5.2]** at the request of the US Government. This wearable detector has attracted high interest from relevant US agencies such as the DTRA. Indeed, in 2016, the US government made an initial order for 10,000 units of the **D3S** representing a USD6,000,000 order. The CEO of Kromek Ltd comments, *"The D3S is the world's first fully approved combined gamma and neutron detector available in volume shipment and at a market leading unit price of $400, which is also available to other user organisations buying over 10,000 detectors in a single procurement. It is a significant breakthrough for us and we are pleased to have achieved the technological advancement that has enabled DARPA to be ahead of their own original programme performance expectations."* **[5.3]**. UK government agencies have also placed orders for the system **[5.4]**. The **D3S** currently has several variants on the market including one where it serves as a personal dosimeter, the **D3S PRD**, and the **D3S NET** which is a networked version designed for large numbers of individual units **[5.2]**. The York group supported the development of the **D3S PRD** through GEANT4 Monte Carlo simulation.

The existence and capability of the **D3S** system is widely reported in the public domain, no doubt intended to act as a deterrent to those who would seek to do harm. The **D3S** is intended to be worn by first responders e.g. police, fire and ambulance personnel, and could also carried by civilians such as postal workers. The **D3S** can identify all common isotopes found in the environment, as well as those used in medical facilities and those generated as a by-product of nuclear energy production as well as *special nuclear materials* i.e. fissile materials associated with nuclear weapons production. Crucially, the wearer of the device does not need to do anything additional to their normal duties. The device operates autonomously, recording information on radioactivity in the environment and transmitting back to a base station along with GPS positional information. This allows a real-time radiological map of a city or port environment to be built up as workers carry out their regular business and alerts can be flagged should something unusual be identified. Following a demonstration, the **D3S** is currently being deployed by the Port Authority of New York and New Jersey **[5.5]**. An emergency management liaison officer at the Port Authority Police Department (PAPD) comments: *"Our legacy radiation-detection system takes a lot more time to identify if a radioactive hit is a threat or a non-threatening source, such as construction-site materials...SIGMA enables much faster reaction time, since you don't need to wait for additional equipment to be brought in to evaluate the radioactive material. With SIGMA, the first responder knows immediately via handheld display what the radioactive isotope is and can quickly determine if it's a threat or not."* **[5.5]**. The **D3S** has also been used to secure events such as a high-profile NATO summit in Brussels, where Kromek were informed that the deployment was successful and its radiation detection systems performed well and met the desired high standards for accuracy and efficiency **[5.6]**.

Field trials of the **D3S** technology indicate a 100-fold improvement in localisation and identification of sources relative to previous technology. Moreover, it provides a 10% radiation dose accuracy, can span a wide range of dose rates and has a very low false alert level. The **D3S** therefore represents a very significant addition to the technologies deployed by various agencies in tackling the threat from dirty bombs and other radiological incidents. A program manager in DARPA's Defense Sciences Office comments on the importance of the detectors to their programme, with particular reference to their size and cost: *"We are extremely pleased with SIGMA's achievements to date in advancing radiation detection technology to fit in a portable, pocket-sized form factor at a price that's a fraction of what current advanced sensors cost. The ability to network hundreds, and soon many thousands of these smart detectors would make cities in the United States and around the world safer against a wide variety of radiological and nuclear threats."* **[5.7]**.

The **D3S** has also found application outside the original remit particularly in nuclear decommissioning. For example, the **D3S** and **SIGMA** devices have been used on board drones to overfly Chernobyl and Fukushima and show considerable promise in monitoring such sites and for future radiological incidents of this type **[5.8, 5.9]**.
In November 2020, Kromek launched the **D5 RIID** which is a significant upgrade with respect to the **D3S** series **[5.10]**. It is again wearable or can be held easily in the palm of the hand. The **D5**

RIID replaces the CsI(TI) scintillator crystal with a next-generation scintillator CLLBc. In 2016-17, the York group performed a programme of lab-based tests for Kromek to evaluate CLLBc and to compare it with a number of similar scintillators to aid the selection of the scintillator material. Later, in 2019, the York group studied the CLLBc detector performance as a function of the number and arrangement of SiPM sensors around the CLLBc crystal using Geant4 simulation. Both studies were critical to the optimisation of the **D5 RIID** device. The **D5 RIID** has a number of distinct advantages over the earlier **D3S**. The new integral detector has an energy resolution almost twice as good as the **D3S** making it significantly more sensitive. Moreover, CLLBc is sensitive to both thermal neutrons and gamma rays making it dual functional in a single unit.

The large orders for the **D3S** from the US and elsewhere led to it becoming the major commercial activity of Kromek sustaining significant employment at their premises in Co. Durham. Clearly, it continues to be important as shown by the recent launch of the successor product, the **D5 RIID**. None of this product development and sales success would have been possible without the initial and ongoing knowledge transfer from the York group. Kromek's Chief Technical Officer concludes: *"The ongoing collaboration with UoY has been of great value to the development of Kromek's business and product lines."* **[5.1]**

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

5.1. Letter from Chief Technical Officer, Kromek Ltd
5.2. Details of Kromek SIGMA and D3S detectors https://www.kromek.com/product/sigma-scintillator-detectors/; https://www.kromek.com/product/d3s_riid/
5.3. Kromek Ltd Press Release, 22 February 2016
5.4. https://www.kromek.com/news/new-contracts-for-d3s-nuclear-detection-platform-in-the-uk-us-and-europe/
5.5. DARPA article https://www.darpa.mil/news-events/2020-09-04)
5.6. Kromek Press Release, 12 June 2017
5.7. https://cbrnecentral.com/darpa-field-tests-networked-radiological-detectors-ny-port-authority/9814/
5.8. Y. Tanimura et al. (2016). Photon Spectra Measured above Operating Floor of Unit 3 Reactor at Fukushima Daiichi Nuclear Power Station. Transactions of the Atomic Energy Society of Japan. 15. 10.3327/taesj.J16.001.
5.9. D. Connor et al. (2018). Application of airborne photogrammetry for the visualisation and assessment of contamination migration arising from a Fukushima waste storage facility. Environmental Pollution 234, 610
https://www.sciencedirect.com/science/article/pii/S0269749117323357
5.10. Details of Kromek D5 RIID detector https://www.kromek.com/product/d5-riid/