Institution: Nottingham Trent University (NTU)		
Unit of Assessment: B12 - Engineering		
Title of case study: HALO X-ray Technologies Ltd: Commercialisation of high-energy X-ray diffraction imaging innovations for next generation security screening		
Period when the underpinning research was undertaken: 01 Jan 2000 to 31 Dec 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Names:	**Roles:**	**Periods employed by submitting HEI:**
Paul Evans	Professor, Royal Society Wolfson Fellow	1993-present
David Downes	Senior Lecturer	2006-present
Anthony Dicken	Post-Doc. Research Fellow Senior Research Fellow	2011-2015 2015-2019
Farid Elarnaut	Post-Doc. Research Fellow Senior Research Fellow	2017-2019 2019-present
Period when the claimed impact occurred: 1 August 2013 to 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Collaborative research led by NTU has resulted in patented X-ray diffraction techniques to identify explosives and other threats as well as illicit drugs and contraband items in scans of luggage and cargo. Unique, hollow-beam '*molecular fingerprinting*' underpins the unprecedented capability of HALO's technology to discriminate between benign and threat materials at operational speeds. These innovations have led to the creation of HALO X-ray Technologies Ltd, based in Nottingham, to commercialise a range of security X-ray scanners (HXT132, HXT264, HXT364 and HXT464 product series) through assigned IP assets and a pipeline agreement. HALO product development has been funded during the period by significant investment of $3.6 million from the U.S. Department of Homeland Security and [text removed for publication] VC investment in 2019. A HXT264 scanner has been installed at the U.S. Transportation Security Laboratory's William J. Hughes Technical Center at Atlantic City International Airport, and HXT264 scanners have been sold [text removed for publication].

2. Underpinning research

A major problem for aviation security is that the current generation of X-ray scanners is limited fundamentally in their ability to discriminate between benign and threat materials in luggage being placed on-board aircraft. For example, while such technologies may be able to detect well-engineered military or commercial grade explosives they cannot reliably identify homemade explosives. This is because the transmitted X-rays, which form a spatial image, do not contain sufficient information to provide a definitive "fingerprint". This is true of all transmission X-ray imaging techniques, including state-of-the-art (spectroscopic) computed tomography (CT).

Historically, capability weaknesses are exploited, by chance or by design, by terrorists. The increasing ingenuity applied to homemade explosives by terrorists is therefore a major and globally pressing concern. One possible countermeasure would be to broaden the classification of threat signatures via software in currently deployed X-ray systems. However, this would lead inevitably to increases in false-alarm rates and hand-searches of luggage. The potential consequences for the travelling public would be profound with ever increasing delays at travel hubs and spiralling security costs. To ensure the continued safety and security of the travelling public a step change in technology was required.

The U.S. and U.K. governments have pursued bilateral research programmes to initiate a disruptive advance to reduce false alarms and increase threat detection rates. One potential approach is to employ the measurement of scattered or diffracted X-rays from luggage. Such "XRD" measurements, employed routinely in laboratory diffractometers, are the 'gold standard' for material phase identification. However, the translation of laboratory instrument technology – capable only of penetrating a fraction of a mm into a carefully prepared sample – into a viable luggage screening modality was severely hampered by fundamental scientific and technological limitations. Despite strenuous efforts by the industry, over two decades, no commercially viable XRD security luggage scanner ever emerged.

Evans leads a collaboration with Rogers at Cranfield to combine X-ray radiography and X-ray diffraction (**G1**, **G2**, **G3**, **G4**, **G5**, **G6**, **G7**, **G8**, **G9**, **G10**) as the basis for a "threat tuneable" futureproof solution. Initially, Evans led work on scatter enhanced 3D imaging (**G1**, EPSRC grants EP/F017596/1 and EP/F017804/1) combining diffraction and absorption imaging by exploring novel multiple X-ray beams for 3D scatter collection. In parallel with this multiple beam method Evans originated a radical new idea (**R1**), which he developed in close collaboration with Rogers. Namely, the invention of hollow or shell-beam X-ray probes, termed focal construct technology. The probe shape concentrates diffracted X-rays from a sample/threat onto a detector to improve greatly the diffraction signal, by orders of magnitude. This method provides high-speed (**R2, R3**) – fraction of a second– operation with commercial-off-the-shelf source/sensor components to enable cost-effective high-energy XRD screening. This new invention from the NTU led collaborative research was patented, US8462913-B2/EP2171435-B1 (Evans and Rogers, priority date 2 June 2007), and subsequently developed and tested for the first time with funding under CONTEST the UK's counter terrorism strategy (**G2**, **G3**). This work was sponsored by: U.K. Home Office; U.K. Dept for Transport; U.K. Centre for the Protection of National Infrastructure; U.K. Metropolitan Police Service, and the U.S. Dept. of Homeland Security. Thus, a completely new high-energy XRD method (**R1**, **R2**, **R3**) was demonstrated together with sophisticated tomographic – diffraction and absorption – approaches (**R4**, **R5**, **R6**) to provide high-speed materials identification capability. This work provided the scientific and IP underpinning for further research in security, process control and diagnostic medical imaging (**G4**, **G5**, **G6**, **G7**, **G8**, **G9**, **G10**).

3. References to the research

High underpinning research quality evidenced by rigorously externally peer reviewed outputs:

R1. ***Evans, P**.; Rogers K.; Chan J.; Rogers J.; **Dicken, A.**; Title: High intensity x-ray diffraction in transmission mode employing an analog of Poisson's spot; (2010); Applied Physics Letters; Vol. 97, 20, p204101; https://doi.org/10.1063/1.3514235

R2. **Dicken, A., *Evans, J.P.O.,** Rogers, K.D., Greenwood, C., Godber, S.X. (HALO Ltd), Prokopiou, D., Stone, N., Clement, J.G., Lyburn, I., Martin, R.M., Zioupos, P., 2015. Energy-dispersive X-ray diffraction using an annular beam. Optics Express, 23 (10), pp. 13443-13454. ISSN 1094-4087 https://doi.org/10.1364/OE.23.013443

R3. **Dicken, A., *Evans, J.P.O.,** Rogers, K.D., Prokopiou, D., Goder, S.X. (HALO Ltd), Wilson, M. (STFC), 2017. Depth resolved snapshot energy-dispersive X-ray diffraction using a conical shell beam. Optics Express, 25 (18), pp. 21321-21328. ISSN 1094-4087 https://doi.org/10.1364/OE.25.021321

R4. ***Evans, P.**; Rogers, K.; **Dicken, A.**; Godber, S. (HALO Ltd); Prokopiou, D; X-ray diffraction tomography employing an annular beam; (2014); Optics Express; 22(10) 11930-11944; DOI https://doi.org/10.1364/OE.22.011930

R5. **Elarnaut, F; *Evans, J.P.O.; Downes, D.; Dicken, A.J.**; Godber, S.X. (HALO Ltd); Rogers, K. D.; Sporadic absorption tomography using a conical shell X-ray beam; (2017); Optics Express; 25(26) 33029-33042; https://doi.org/10.1364/OE.25.033029

R6. **Dicken, A., *Evans, J.P.O.**, Rogers, K.D., Prokopiou, D., Goder, S.X. (HALO Ltd), **Elarnaut, F.,** Shevchuk, A.**, Downes, D.,** Wilson, M. (STFC), 2019. Confocal energy-dispersive X-ray diffraction tomography employing a conical shell beam. Optics Express, 27 (14), pp. 19834-19841. ISSN 1094-4087 https://doi.org/10.1364/OE.27.019834

The high quality of the underpinning research is further indicated by the significant investment in the research and its dissemination. This extensive research and innovation grant funding has been captured competitively from a range of prestigious national and international agencies (only awards >£100k listed):

G1. **J.P.O. Evans**; Scatter enhanced 3D X-ray imaging (EP/F017596/1); Collaborators: Home Office Science & Technology Group, US Dept of Homeland Security (DHS), Durham Scientific Crystals Ltd, EPSRC; (2008-11); £306k (+Linked EPSRC EP/F017804/1 with K. Rogers at Cranfield U £138k)

G2. **J.P.O. Evans**; HotSpot X-ray Diffraction Imaging for Materials ID Innovative Research Call in Explosives & Weapons Detection, Home Office Explosives & Weapons Detection Programme part of the UK CONTEST strategy; Home Office Scientific Development Branch (HOSDB), Dept

for Transport (DfT), Centre for the Protection of National Infrastructure (CPNI), Metropolitan Police Service (MPS); (2008–11); £452k.
G3. **J.P.O. Evans**; HALO Tomography (as above) UK CONTEST strategy; Sponsors: HOSDB, DfT, CPNI, MPS, US DHS: (2011-14); £400k.
G4. S. Godber (HALO Ltd); **J.P.O. Evans**; K. Rogers (Cranfield U); HALO Tunable X-ray Technology - High Speed Materials ID (TSB 131257); Tech. Inspired CRD (Fast track)-Electron., sensors & photonics; TSB; (2013-14); £150k.
G5. K. Rogers (Cranfield U); **J.P.O. Evans**; N. Stone (Exeter U); R. M Martin (Bristol U); P. Zioupos (Cranfield U); J. G. Clement (U of Melbourne); Grant title: Point-of-Care High Accuracy Fracture Risk Prediction (EP/K020196/1); Collaborators: HALO X-ray Technologies Ltd; Radius Diagnostics Ltd; EPSRC; (2013-16); £776k (£302k to NTU).
G6. M. Wilson (STFC); **J.P.O. Evans**; K. Rogers (Cranfield U); ACID - Accelerated Contraband Identification by Diffraction (ACID); STFC CLASP (2016-2017) £108k.
G7. K. Rogers (Cranfield U); **J.P.O. Evans**; I. Lyburn (NHS); M. Wilson (STFC); PICUP-Point-of-Care Fracture Prediction (EP/R024316/1) (2018-2020) £712k
G8. **J.P.O. Evans**; Material specific 3D X-ray imaging for security and medical applications; Royal Society Wolfson Fellowships (RSWF\R1\180012) (2018-2023); £150k.
G9. **J.P.O. Evans**, K.D. Rogers (Cranfield U.); Sporadic diffraction and absorption volumetric X-ray imaging (EP/T034238/1); Collaborators: Adaptix, HALO X-ray Technologies Ltd; STFC, Dstl, Cobalt; EPSRC; (2020/1-2023/4); £1.013 million.
G10. **J.P.O. Evans**, Cellular XRD, Innovative Research Call 2020 for Explosives and Weapons Detection, Defence and Security Accelerator (DASA) (2020/1-2023); £300k.

4. Details of the impact

4.1. A spin-out, HALO X-ray Technologies Ltd, has been created to commercialise patented new technologies from NTU's collaborative research, established its viability, creating jobs, and generating revenue

HALO X-ray Technologies Ltd. (HALO) is commercialising novel tools and technologies invented through the ground-breaking research carried out by Professor Paul Evans' team at Nottingham Trent University in collaboration with Professor Keith Rogers' team at Cranfield University. Professor Evans at NTU led the formation of this Nottingham based spinout company, Evans was the Founder on 4 April 2012, Director and CTO up until significant Venture Capital investment in 2019 (**S1**). HALO's CEO (who is also current Company Director) completed a PhD in Evans' Group in 2015. HALO's Science Lead was a Senior Research Fellow in Evans' Group for eight years having previously obtained his PhD at Cranfield University with Evans (at NTU) as a supervisor and lead on the sponsoring EPSRC grant with Rogers.

The HALO CEO wrote (**S2**), "*HALO was formed in partnership with Cranfield University to exploit Professor Evans' and Professor Rogers' work in material specific X-ray diffraction imaging*", and, "*HALO has 14 employees/contractors and wholly owned by its shareholders who include NTU, Cranfield University and Midven Limited. Paul Loeffen, who until December 2020 was the Vice President and General Manager of Agilent Technologies Molecular Spectroscopy Division, became a consultant to the Board of HALO in 2019. The core Granted Patents US8462913-B2/EP2171435-B1* (*Evans and Rogers, priority date 2 June 2007*) *and US9921173-B2/EP2946201-A1* (*Evans and Rogers, priority date 17 Jan 2013) that underpin HALO X-ray Technologies Limited were assigned to HALO on the 22nd March 2019 as part of an investment round completed at that time. In addition, there is a pipeline agreement in place between HALO X-ray Technologies and the university partners Nottingham Trent University and Cranfield University with four further patent families* (*priorities: GB1703077.6, GB1812042.8*", [Inventors Evans and Rogers], "*GB1010233.3, GB1909917.5*", [Inventor Evans] "*that are under option to HALO*" (**S2**).

4.2. U.S. Government contract funding investment in HALO ($3.6 million BAA funding and 'Opioid Detection Challenge') has underpinned development and testing of novel scanners

- ***$3.5 million U.S. Department of Homeland Security product development contracts***

The Broad Agency Announcement (BAA) is a funding call tool used by the United States Department of Homeland Security Science and Technology Directorate to solicit proposals from outside groups "*to quickly and efficiently execute research and development to deliver practical solutions to critical first responder problems*". The award of major BAA contracts to HALO X-ray Technologies Ltd. ($3.5 million spent by HALO in REF period, $1.6m as major subcontractor and $1.9m as Prime contractor, detailed below), is highly significant and important because the U.S. Government is the world's largest customer for X-ray security screening systems.

The HALO CEO wrote (**S2**), "*HALO attracted significant product commercialisation income of $1,591,292.532*", [i.e. $1.6 million], "*as the Industrial Partner and Major Subcontractor on a successfully delivered $5.2 million contract (Definitive Contract HSHQDC15CB0036, 31 Aug 2015 to 30 Sept 2019, $5,179,086.17 paid via Nottingham Trent University as the Prime Contractor) under the U.S. Department of Homeland Security Broad Agency Announcement BAA13-05 within the DoHS Science and Technology Directorate's 'Advanced X-ray Material Discrimination Program'. This contract enabled HALO prototype scanners to be developed and undergo 'live luggage' testing at Amsterdam's Schiphol Airport, which is the 3rd busiest airport in Europe*".

The HALO CEO wrote (**S2**), "*The U.S. Transportation Security Laboratory also tested a HALO prototype scanner on the BAA13-05 contract, using real explosives and other materials, at William J. Hughes Technical Center, Atlantic City International Airport, New Jersey in February 2020*". The William J. Hughes Technical Center has a core mission "*to enhance homeland security by performing research, development and validation of solutions to detect and mitigate the threat of improvised explosive devices*". The HALO prototype scanner testing took place under the Laboratory's remit to support the evaluation, maturation, and certification of emerging explosives detection technologies for the U.S. Department of Homeland Security and other customers.

The HALO CEO wrote (**S2**), "*The successful testing of these prototypes and delivery of the above BAA13-05 contract enabled HALO to secure a follow-on BAA17-03 contract of ~$3.3 million in 2018*". This contract (70RSAT18CB0000038) was awarded directly to HALO under the U.S. Department of Homeland Security Broad Agency Announcement BAA17-03 'Advanced X-ray Material Discrimination Program' within the DoHS Science and Technology Directorate's 'Screening at Speed Program'. $1.9 million of this contact has been spent by HALO in the REF2021 period (**S2**). This work is enhancing HALO's scanners capabilities by increasing the probability of detection and significantly reducing false-alarm rates at checkpoints, hence reducing the need for manual intervention, "*This reduction of false alarm rates is key to achieving automation at the checkpoint*" (**S2**).

- ***Award of $100k to HALO as a finalist in the US Government 'Opioid Detection Challenge'***

The US Government 'Opioid Detection Challenge' (2019) was a Department of Homeland Security Science and Technology Directorate led collaboration with U.S. Customs and Border Protection, the Office of National Drug Control Policy and the U.S. Postal Inspection Service to seek new tools and technologies to detect deadly opioids in parcels to combat large-scale drug trafficking into the U.S via international mail. HALO won $100k in the Challenge, one of only 8 finalists from 83 submissions (**S3**). The HALO CEO wrote, "*Powdered illicit opioids such as fentanyl, 50-100 times more potent than morphine, are commonly trafficked via small mail packages. HALO used the funding to develop and demonstrate a scanner capable of penetrating thick objects, i.e. U.S. Federal mail items, to identify hidden substances in real-time*" (**S2**).

- ***£0.5 million U.K. and U.S. Government DASA product development contracts***

HALO has received a total of £502k, during 2019-20, product development funding from the Defence and Security Accelerator (DASA) under the Future Aviation Security Solutions (FASS) Programme courtesy of the U.K. Department for Transport and U.K. Home Office as well as the U.S. Department for Homeland Security. The FASS programme forms part of the Strategic Defence and Security Review (SDSR) published in 2015 and set out the U.K. Government's National Security Strategy for the coming five years. HALO has received income of £218k for the development of an 'Alarm Registration Capability (ARC)' for the HXT264 series, under contract ACC6008370; and received an additional income of £285k to develop 'HEROS: High Energy

Resolver for Cargo Screening' (HXT2108) for the screening of cargo, bulk mail, and hold/checked bags, under contract ACC6007509 (**S4**).

4.3. Venture Capital investment [text removed for publication] **has been raised by HALO which has supported expansion and the establishment of a US Office**

The successful delivery of the BAA contracts enabled HALO, in March 2019, to secure significant VC investment [text removed for publication] from venture capital firm Midven Ltd and the Midlands Engine Investment Fund (**S5**, **S6**). The Director of Midven wrote, "*The Company* [HALO] *is founded on patented next generation X-ray technology developed by Paul Evans, Head of Imaging Science Group at Nottingham Trent University … Indeed, it is fair to say that without this IP the investment would have been unlikely to proceed*" (**S6**). The HALO CEO confirmed that, "*This and other funding enabled HALO to move in 2020 to Castle Park Industrial Estate, Nottingham, providing greatly increased floor space required for the ongoing expansion in their development and testing facilities. HALO also used part of this funding to establish a U.S. Office in 2020*" (**S2**).

4.4. HALO has developed products, is funded by international industrial product development collaborations, and has generated revenue from product sales

HALO X-ray Technologies Ltd. has created a new range of scanner technologies, *HXT132, HXT264*, *HXT364*, and *HXT464 XRD* (**S7**). The HALO CEO wrote (**S2**), "*together with high-energy hold and cargo screening variants, which incorporate Evans' and Rogers' Patented focal construct X-ray diffraction and absorption techniques. HALO are integrating, combining and co-tuning these technologies with a range of different scanners produced by globally leading security scanner manufacturers. These collaborations have or are funding the combination of HALO's HXT264 technology*", with: Rapiscan's 620DV to form a HXT364 system (under DoHS contract 70RSAT18CB0000038); Leidos Clearscan CT scanner, to form a HXT464 system (Department of Homeland Security Contract HSHQDC15CB0036); [text removed for publication]; and Integrated Defence and Security Solutions (IDSS) DETECT1000 CT system to form a HXT464 system (projecting beyond the REF period, $3.7 million total under DoHS contract 70RSAT20CB0000025, 29 Sept 2020 to 28 June 2023). These development programmes allow liquids and laptops to remain in the bag. Such industrial product development collaborations are essential in the highly regulated aviation security sector to enable HALO scanners to obtain ECAC Standard 3 approved and U.S. Transportation Security Administration certified explosives detection system status (**S2**).

The HALO CEO wrote (**S2**), "*Products developed by HALO have been sold to customers and have also been delivered to Contracting organisations.* [text removed for publication]*"* (**S2**).

5. Sources to corroborate the impact (*participant in the process of impact delivery)

S1.* Web-link: https://find-and-update.company-information.service.gov.uk/company/08020147 HALO X-ray Technologies Ltd Company number 08020147, Companies House
S2.* Testimonial letter: CEO, HALO X-ray Technologies Ltd.
S3. Web-link: The Opioid Detection Challenge, hosted by NASA Tournament Lab website, https://www.opioiddetectionchallenge.com/
S4.* Testimonial e-mail: CEO, HALO X-ray Technologies Ltd.
S5. Web-link: https://midven.co.uk/nottingham-firm-lands-meif-investment-for-next-gen-x-ray-technology/, Investment Announcement news item, Midven Limited, Birmingham, UK
S6.* Testimonial letter: Director, Midven Limited, Birmingham, UK
S7. Web-link: HALO X-ray Technologies Ltd products, Technical Specifications and Brochures https://www.haloxray.com/products