Institution: Durham University		
Unit of Assessment: UoA 9: Physics		
Title of case study: Kromek Group plc: Materials research underpinning the Stock Market flotation of a radiation detection company		
Period when the underpinning research was undertaken: Between January 2005 and April 2017		
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:**
Prof. Andrew Brinkman	Professor of Physics	1980 to 2010 (deceased)
Prof. Brian Tanner	Professor of Physics Emeritus Professor of Physics	1973 to 2016 2016 to present
Dr. Douglas Halliday	Associate Professor	1992 to present
Period when the claimed impact occurred: Between 1 August 2013 and 31 December 2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

Research in Durham on vapour growth of II-VI semiconductors developed a technique to grow large crystals of cadmium zinc telluride (CZT), used as the basis for sensitive X- and gamma-ray detectors. This process was exploited via a departmental spin-out company, Kromek Ltd, which developed these into full systems for security and medical applications. Their machine for identifying liquid explosives has been deployed at over 50 airports in 11 countries. Since 2017, Kromek has also won contracts for baggage screening worth USD17.1million, and medical imaging worth USD19.4million.

The Kromek Group plc market value in July 2020 was GBP58million, it employs over 100 staff in the UK and USA and had a turnover of GBP14.5million in 2018-19.

2. Underpinning research

Semiconductors based on compounds of group II-VI elements such as cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTe) can be used as the basis for X- and gamma-ray detectors. However, these are only commercially viable if the crystals can be grown to large diameter, and techniques to do this were not available until 16 years ago. The background to this case study is that the late Professor Andy Brinkman (member of Durham Physics department from 1980 to 2010) had been experimenting with crystal growth from vapour deposition, and, with Durham postdoctoral researcher John Mullins, had designed the *Durham Multi-Tube Physical Vapour Transport* (MTPVT) method. This thermally decouples the vapour source and deposition region, so the crystal is not heated directly by the source, allowing it to grow smoothly to a large diameter (patent WO9910571, granted 1999).

In 2005, Prof. Brinkman won an STFC PIPPS grant, for a collaborative programme of research to use the MTPVT method to grow bulk CdTe on top of substrates made from different materials (heteroepitaxial growth). Within the year, the group, which included Dr. Douglas Halliday (Durham Physics 1992 to present) and Prof. Tanner (Durham Physics 1973 to present), achieved successful heteroepitaxial growth of high perfection crystals of CdTe, with good electrical qualities, on gallium arsenide (GaAs) substrates [R1,P1].

$Cd_{1-x}Zn_xTe$ (CZT) gives superior performance to CdTe for detection of X-rays, but again, for commercial exploitation, growth of large area crystals is crucial. With further support from a GBP930,000 DTI basic technology award via EPSRC (2006 to 2010), the group successfully modified the MTPVT growth chamber to grow CdZnTe [R2] by controlled injection of ZnTe vapour [US patent US2016160385A1]. Despite the large lattice parameter mismatch between GaAs and CdZnTe, no cracking of the CdZnTe crystal occurred [R3] and the dislocation density, as determined by high resolution X-ray diffraction, fell rapidly away from the heteroepitaxial interface. Further research developed the process, enabling the growth of 100mm diameter CdZnTe crystals of high resistivity, good lattice perfection [R4] and carrier lifetimes comparable to melt-grown CdZnTe [R5]. Reproducible crystals could be grown to volumes of 275cc.

The research on heteroepitaxial growth described above was undertaken collaboratively between staff in the Physics Department (Brinkman, Tanner) and the spin-out company, Durham Scientific Crystals Ltd. (Basu, Cantwell), as seen directly in co-authored references which span 2008 to2016 [R1-R4].

3. References to the research

All journals are international and peer reviewed.

[R1] Crystal growth of large-diameter bulk CdTe on GaAs wafer seed plates. J.T. Mullins, B.J. Cantwell, A. Basu, Q. Jiang, A. Choubey, and A.W. Brinkman, *J. Crystal Growth 310 (2008) 2058* https://doi.org/10.1016/j.jcrysgro.2007.11.190

[R2] Vapor-Phase Growth of Bulk Crystals of Cadmium Telluride and Cadmium Zinc Telluride on Gallium Arsenide Seeds. J.T. Mullins, B.J. Cantwell, A. Basu, Q. Jiang, A. Choubey, A.W. Brinkman, and B.K. Tanner, *J. Electron. Materials 37 (2008) 1460-1464* https://doi.org/10.1007/s11664-008-0442-3

[R3] Growth by the multi-tube physical vapour transport method and characterisation of bulk (Cd,Zn)Te. A. Choubey, P.Veeramani, A.T.G. Pym, J.T. Mullins, P.J. Sellin, A.W. Brinkman, I. Radley, A. Basu and B.K. Tanner *J. Crystal Growth 352 (2012) 120-123* https://doi.org/10.1016/j.jcrysgro.2012.03.005

[R4] Twinning in vapour-grown, large volume $Cd_{1-x}Zn_xTe$ crystals. B K Tanner, J T Mullins, A T G Pym and D Maneuski, *J. Crystal Growth 448 (2016) 44–50* http://dx.doi.org/10.1016/j.jcrysgro.2016.05.011

[R5] Fluorescence lifetime imaging microscopy analysis of defects in multi-tube physical vapor transport grown $Cd_{1-x}Zn_xTe$. A. Schneider, M.C. Veale, S.J. Bell, D.D. Duarte, M.D.Wilson, P. Seller, S.W. Botchway, A. Choubey, and D. Halliday, *Physica Status Solidi A 211 (2014) 2121-2125* https://doi.org/10.1002/pssa.201300724

[P1] Semiconductor Device and Method of Manufacture Thereof, A. Basu, A. Brinkman, B. Cantwell, M. Robinson, European patent EP1969622A1, published 17/09/2008.

Grants to Prof. Brinkman:
PIPPS PP/C503470/1 GBP152,545 2005-06. Evaluation of Foreign and Hybrid crystal growth.
EPSRC EP/DO48737/1 GBP931,012 2006-10. New Materials for High Energy Colour X-ray Imaging

4. Details of the impact

Durham Scientific Crystals Ltd spun-out of the Physics Department in 2003 with venture capital funding to commercialise the MTPVT process. The aim was to fully control the exploitation of the processes by building integrated detector systems, as well as providing the large crystals for other companies. The first staff members, Arnab Basu and Ben Cantwell, had both just completed PhDs with Prof. Brinkman and continue in leading roles with the company today. The company was renamed Kromek in 2010 and by 2013, had approximately 50 employees. In October 2013, Kromek floated on the London AIM Stock Exchange with a capitalization of approximately GBP55million.

The impact of Durham Physics Research on the underpinning basis of the company is explicitly stated on p.11 of the Placing Document for the flotation: "*In addition to more established liquid phase growth methods, the Group has developed a patented vapour phase growth technique capable of producing CZT with good structural integrity, uniform composition and purity, on a* *commercial scale. The Directors believe that it is the only vapour based bulk growth method developed worldwide, it is critical in relation to its non-recurring engineering offering, and is an enabling technology for future products. Kromek has an intellectual property portfolio of more than 70 granted patents and 110 pending applications*." [E1].

Kromek's CEO, said "*The MTPVT capability and its associated Intellectual Property was an enabling part of the value proposition, underpinning the Initial Public Offering of Kromek and its subsequent business expansion.*" [E2].

As a result of the October 2013 flotation, underpinned by the Durham University research programme, Kromek has been able to continue its investment and expansion from a turnover of GBP2.7million in 2012-13 to GBP14.5million in 2018-19 [E3]. The year 2018-19 saw an EBITDA profit of GBP1.9million (EBITDA earnings before interest, tax, depreciation and amortization – a recognised indicator of company health). The company raised GBP11million in August 2015, and GBP21million in February 2017 through share placement in order to fund the capital development programme necessary to break into the medical imaging market. Kromek signed multi-year contracts totalling approximately GBP100million in the three years to 31 October 2019 [E4].

An AIM news release in 2019 states, "*The Group's business model provides a vertically integrated technology offering to customers, from radiation detector materials to finished products or detectors, including software, electronics and application specific integrated circuits ("ASICs"). The Group has operations in the UK and US (California and Pennsylvania), and is selling internationally through a combination of distributors and direct OEM [Original Equipment Manufacturer] sales. Currently, the Group has over one hundred full time employees across its global operations*." [E5a].

Kromek has developed products based on the large crystal detectors in three main areas.

Fig 1. Liquid identifier scanner

1: Security

Since flotation, the company has made significant strides in the field of security systems. Its CZT-based airport security bottle scanner (Fig 1) for detection of liquid explosives is now installed in 50 airports in 11 countries around the world, supporting the safe journeys of millions of people. In 2017, it announced agreements, worth USD5million, with two Original Equipment Manufacturers (OEMs) to incorporate Kromek's CZT technology into baggage screening systems for luggage. Similar contracts, worth USD1.5million and USD7.8million, were announced in July and November 2018 [E5c, d]. An extension worth USD2.7million was won in May 2019 [E5e]. The new generation of baggage scanners, in which Kromek detectors are incorporated, are predicted to ease restrictions on carriage of liquids through airport security.

Fig 2: Kromek D3S radiation monitor

2: Nuclear radiation detectors

Customers of Kromek's nuclear radiation detectors include the United Kingdom Ministry of Defence, the United States Defence Threat Reduction Agency and Defence Advanced Research Projects Agencies (DARPA) SIGMA programme. Kromek has delivered over 10,000 units of its hand-held, networked D3S neutron and gamma radiation detectors. These detectors, which are capable of accurate isotope identification, enable a dynamic network of measurement points to be monitored from a central server. They are deployed in the Port of New Jersey for cargo screening and in other US cities to protect against the "dirty bomb" terrorist threat. Although causing few fatalities, such an attack would have huge economic impact, for example, making Manhattan uninhabitable for very many years. The D3S-ID was deployed during the NATO Security Summit and Donald Trump's European visit in May 2017. Kromek also sells detectors to OEM customers, for example, an USD1.4million contract in February 2019 [E5f], a further GBP1.6million contract to US and European government-related bodies in July 2019 [E5g] and a further extension of GBP1.6million in September 2019 [E5h]. DARPA awarded Kromek an USD5.2million contract for bio-security devices in May 2020 [E5i].

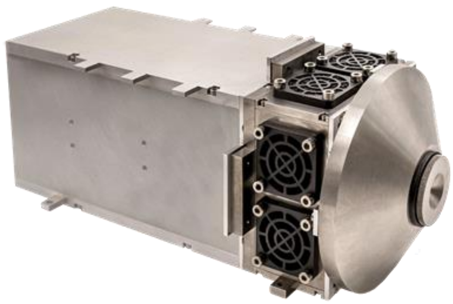

Fig 3. Kromek gamma camera module

3: Medical Imaging

In the medical imaging market, Kromek has substantially expanded sales of CZT detectors for bone mineral densitometry (BMD). These OEM sales are of both imaging and non-imaging assemblies, the unique feature of CZT being that the detectors are sensitive to X-ray energy and hence changes in bone density and porosity can be independently determined. This is now established clinical practice [E6]. In 2017, Kromek commenced delivery on a USD12.6million contract and won another of USD5.38million [E5b]. It announced a further USD1million BMD contract in August 2018 [E5j].

Kromek shipped its first CZT-based gamma-camera for single photon emission computed tomography (SPECT) medical diagnostics in 2017. These imaging modules give much higher resolution and allow lower patient dose than standard scintillator-based cameras and are now competitively priced due to CZT production improvements within the company. The higher resolution gives better diagnosis than with scintillator-based cameras, as discovered by one of the first volunteer patients, who had an asymptomatic kidney stone unexpectedly diagnosed (and subsequently treated). SPECT forms the basis, for example, of Myocardial Perfusion Imaging, a now routine procedure for monitoring heart muscle blood flow [E7].

In January 2019, Kromek was awarded a USD58million contract to supply CZT medical imaging detectors to an OEM customer [E5k]. To support this growth, Kromek raised a further GBP21million in a Placing and Open Offer to shareholders in February 2019 [E8]. Kromek's market value in July 2020 stood at GBP58million [E5].

In April 2020, in response to the equipment crisis of the Covid19 pandemic, Kromek began manufacturing medical ventilators under licence from Metran (Japan).

Recognition

Kromek won two innovation awards in 2016 from the Institution of Engineering and Technology (IET) [E9] and an Institute of Physics Business Innovation Award. In 2017, Kromek was named in the UK Tech List of the 35 companies showing best innovation and technology in the UK, alongside Rolls-Royce, Bombardier and Airbus. In 2019 it was appointed one of 170 “UK Export Champions” [E10] that gave support and advice to other companies in export development. Kromek’s CEO, Arnab Basu, also received the 2019 UK Institute of Directors ‘*Director of the Year Award for Innovation*’, recognising a leader who has “*developed and implemented innovative or transformational ideas*” [E11]. In April 2020, Kromek received a Queen’s Award for Enterprise in recognition of its outstanding contribution to International Trade. These are the most prestigious awards for UK business, and Kromek was recognised in the International Trade category for its outstanding growth in overseas sales. In the three years up to 30 April 2019, Kromek’s non-UK sales grew by 52% to make up 84% of all sales, exporting its radiation detection technologies and products around the globe to over 40 countries in Europe, North America, Asia and Australasia [E5].

Critically, the contracts and developments described here have only been possible because Kromek is a financially strong, public company. The impact of its products is felt, indirectly, by millions of people throughout the world. Without the technology developed by the collaborative research programme, the flotation, growth and subsequent contracts would not have been possible.

5. Sources to corroborate the impact

[E1] Kromek Group plc, *Placing and Admission to trading on AIM* document, October 2013 (second paragraph of the Information on the Company) (http://www.kromek.com/images/investor/Kromek_admission_doc.pdf)
[E2] Emails confirming quotation from Kromek CEO (dated 23 September 2020).
[E3] Kromek Group plc, Annual report and accounts for the year ended 30 April 2019 (https://www.kromek.com/wp-content/uploads/2019/09/2019-Kromek-Annual-Report-Accounts.pdf).
[E4] Kromek Group plc, Interim Results H1 2019, dated 11 December 2019 (https://www.londonstockexchange.com/exchange/news/market-news/market-news-detail/KMK/14343503.html)
[E5] Shareholder information all available at https://www.kromek.com/investor-relations/shareholder-information/ including all announcements of contracts which for ease are available on file under E5a-k.
[E6] Advice to patients concerning dual energy densitometry from RadiologyInfo.org
[E7] British Heart Foundation guidance to patients
[E8] London Stock Exchange, *Firm placing and open offer and Notice of AGM*, 7 February 2019
[E9] Article on IET Innovation Awards 2016 from IET website, published 18 November 2016.
[E10] Press release from gov.uk, *Liam Fox launches new export champion community*, published 28 February 2019.
[E11] Kromek news article, *Director of the Year, Innovation*, dated 21 October 2019