Institution: Durham University		
Unit of Assessment: UoA8-Chemistry		
Title of case study: Applied Graphene Materials plc		
Period when the underpinning research was undertaken: 2009-present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Karl S. Coleman (KSC)	**Role(s) (e.g. job title):** Professor / Head of Chemistry Department	**Period(s) employed by submitting HEI:** 2004 to present
Period when the claimed impact occurred: August 2013 to date		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Durham Chemistry's development of a continuous synthesis of graphene nanoplatelets provided the intellectual property for the formation of the spin-out Durham Graphene Science (2010) which was listed on FTSE AIM index in November 2013 as Applied Graphene Materials plc (AGM). The IPO valued the company at GBP26.2m. AGM has raised over GBP29.3m in venture capital funding, has 33 employees (2020 payroll, GBP2.20m) and has invested GBP2.85m in infrastructure to supply graphene for products developed with commercial partners including Halfords, SHD composites, Airbus Defence and Space, James Briggs Ltd, Century, [redacted], Infinite Composites, Alltimes Coatings, Blocksil and Applied Nano Surfaces.

2. Underpinning research

Graphene is a single layer of graphite (first isolated in 2004 using the Scotch tape method) and is a continuous network of hexagonally arranged carbon atoms which gives rise to high carrier mobility, exceptional mechanical strength and high thermal conductivity. However, in the early years, commercialisation was limited by material availability and difficulty associated with product formulation. Solvent exfoliation of graphite (Nature Nano. 2008, 3, 563) could achieve graphene concentrations up to 0.01 mg ml^{-1} in solvents such as N-methyl-pyrrolidone.

To address this challenge KSC, supervising EPSRC-funded PhD students Christopher Herron and Rebecca Edwards (2008-2015), devised a simple chemical vapour deposition/pyrolysis approach to synthesize graphene which was continuous, high yielding (gram scale) and easy to scale up [R1]. This methodology used a flow approach, assembling graphene from the simple molecular precursors; it had the added advantage that the by-products from the process were water-soluble sodium salts that were easily removed. Similarly, the process avoided the use of graphite which is difficult to remove from graphene products [R1,2]. This process was further developed to use solid sodium carbonate and ethanol spray in place of sodium ethoxide solutions [R2] and metal templates [R3]. The use of metal templates allowed the size and morphology of the graphene nanoplatelets to be controlled and tailored.

Following the successful synthesis of synthetically useful quantities of graphene [R1-3], Coleman has continued to innovate, elucidating the fundamental science and devising transformative preparative solutions for the generation of new graphene dispersions and nanocomposites suitable for applications [R4-6]. This is evidenced through the EPSRC funded project 'Engineering innovation in graphene nanocomposites for consumer product and packaging applications' (EP/K016784/1, GBP1,633,244) a collaboration between Durham University (DU), University of Sheffield, Applied Graphene Materials, Procter and Gamble and Dyson. This project explored the use of graphene in polymer composites for use in consumer products. Durham has been looking

at controlling the interfacial interaction between graphene and polymer and how this impacts formulation and melt processing [R4-6]. This research and understanding have been developed further and used by AGM for the development of new dispersion and formulation technology for graphene nanoplatelets.

In recognition of the work on the continuous synthesis of graphene and the establishment of AGM, Coleman was awarded the Royal Society of Chemistry (RSC), Chemistry World Entrepreneur of the Year 2011 and the RSC Materials for Industry - Derek Birchall Award 2017 for creativity and excellence in the application of materials chemistry in industry. Durham University Business and Innovation Services and Coleman were awarded the Times Higher Education Research and Innovation Award 2012 for the scale-up and commercialisation of graphene fabrication technologies.

3. References to the research

Citations according to Web of Science: as of 08/12/20

[R1] C.R. Herron, K.S. Coleman, R.S. Edwards and B.G. Mendis, 'Simple and scalable route for the bottom-up synthesis of few-layer graphene platelets and thin films' *J. Mater. Chem.*, **2011**, *21*, 3378–3383. DOI: 10.1039/c0jm03437a. **[39 citations]**

[R2] K. S. Coleman, 'Production of graphene from metal alkoxide', *Patent* WO2011012874A1, 3 February 2011. Assignee: Applied Graphene Materials. Priority Date: GB0913011A 27 July 2009. This patent is granted in Europe (EP2459484B1), Korea (KR101965882B1, KR101987390B1), Japan (JP5767218B2, JP5932090B2) and the USA (US9932227B2).

[R3] K. S. Coleman, 'Process for producing graphene', *Patent* WO2012172338A120 December 2012. Assignee: Applied Graphene Materials. Priority Date: GB201109962A, 14 June 2011. This patent is granted Europe (EP2720978B1), Korea (KR101717277B1), Japan (JP5860957B2) and the USA (US9440856B2).

[R4] S. C. Boothroyd, D. W. Johnson, M. P. Weir, C. D. Reynolds, J. M. Hart, A. J. Smith, N. Clarke, R. L. Thompson, and K. S. Coleman, 'Controlled Structure Evolution of Graphene Networks in Polymer Composites' *Chem. Mater.* **2018**, *30*, 1524−1531. DOI: 10.1021/acs.chemmater.7b04343. **[13 citations]**

[R5] M. P. Weir, D. W. Johnson, S. C. Boothroyd, R. C. Savage, R. L. Thompson, S. M. King, S. E. Rogers, K. S. Coleman, and N. Clarke, 'Distortion of Chain Conformation and Reduced Entanglement in Polymer−Graphene Oxide Nanocomposites' *ACS Macro Lett.* **2016**, *5*, 430−434. DOI: 10.1021/acsmacrolett.6b00100. **[24 citations]**

[R6] M. P. Weir, D. W. Johnson, S. C. Boothroyd, R. C. Savage, R. L. Thompson, Steven R. Parnell, A. J. Parnell, S. M. King, S. E. Rogers, K. S. Coleman, and N. Clarke, 'Extrinsic Wrinkling and Single Exfoliated Sheets of Graphene Oxide in Polymer Composites'. *Chem. Mater*. **2016**, *28*, 1698−1704. DOI: 10.1021/acs.chemmater.5b04502. **[19 citations]**

4. Details of the impact

The scalable route to graphene production [R1] was filed as patents by DU in 2009 and 2011 [R2,3]. To exploit this technology KSC formed the spinout company Durham Graphene Science (DGS) in 2010 (Company number 07330136) in collaboration with DU Business and Innovation Services who helped develop the business plan and patent strategy. Initial venture capital funding was secured from NorthStar Ventures (North East Proof of Concept Fund, GBP100K, 2010) and, subsequently, by IP Group as part of the North East Technology Fund (GBP600k, 2011 and GBP700k 2012). KSC was seconded from DU to the company for 2 days a week (2011–2014) as a Director and Chief Scientific Officer. DGS recruited an experienced management team and employees to establish a commercial-scale production facility at the Wilton Centre in Redcar, capable of producing graphene following the protocol developed at Durham [R1-3].

DGS was renamed to Applied Graphene Materials plc (AGM) [E1] and launched on the FTSE AIM stock market under the stock ticker AGM (IPO 20 November 2013). The IPO (through N+1 Singers) raised GBP11.0m in funding to allow expansion of infrastructure and increase staff to commercialise its graphene fabrication technology to the global market. This gave AGM an initial market capitalisation of GBP26.2m. Two additional fund raises of GBP8.5m (December 2015), GBP9.8m (October 2017) means AGM has raised over GBP29.3m (November 2013-2020) in funding from the financial markets (including institutional investors such as Eden Tree, Insight, Herald, Ruffer and Hargreaves Lansdown) to develop its graphene technology [E1]. In September 2017 AGM completed the construction of their new production facility for the new grade of material A-GNP 35 (to complement the original A-GNP10), which was fully operational in February 2018. AGM (2020) employs 33 people (80% listed as having a degree or higher-level qualification) based in Wilton, Redcar with a payroll of GBP2.20m (GBP17.44m 2014–2020). A full breakdown of funding, business engagements, income, salary costs, infrastructure investment and employees are provided in Table 1[E1].

AGMp plc*	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
VC funding (GBPm)	11.0	8.5	-	9.8	-	-	-
Active Business engagements	-	120	300	100	120	101	109
Income (GBPm)	00.2	0.10	0.25	0.27	0.20	0.12	0.08
Salary costs (GBPm)	1.12	2.61	2.91	2.65	2.85	3.10	2.20
Infrastructure & equipment investment (GBPm)	0.29	0.39	0.99	0.68	0.26	0.19	0.05
Employees (FTE)	30	33	42	45	44	43	33

*Table 1: *Financial year runs 01 August to 31 July. Annual reports are published in Oct/Nov of the same year calendar year. VC funding is listed in year raised.*

AGM's customer base is seeing extensive growth in the coatings, composites, lubricants, adhesives and energy sectors in the short timeframe since production began (all products containing AGM manufactured graphene use original DU research and IPR [R1-3]). The business is currently focused on building business engagement for long-term partnerships and has 109 active business engagements (FY2020). Formulated products are supplied under the Genable® family, a fully characterised product platform specifically designed to a standard formulation to enable graphene technology to be delivered easily into existing manufacturing processes, enabling customers to consistently access the performance attributes of AGM's A-GNP graphene nanoplatelets [E1].

Coatings and Adhesives: In October 2019 Halfords (FY2019, turnover GBP938m) the UK's leading retailer of motoring, cycling and leisure products and services, with over 465 retail stores, launched a Graphene Primer containing an AGM graphene formulation [E1]. In the same period, James Briggs Ltd, JBL, (part of the Tetrosyl Group, the largest supplier of car care, parts and accessories in the UK, FY2018, turnover GBP144m) launched its Hycote graphene anti-corrosion primer, developed in collaboration with AGM [E2]. [redacted] Since July 2020, Kent Europe GmbH in Duisberg, Germany have been launched Genable® graphene-based aerosol primers [E1]. Applied Nano Surfaces (Sweden) uses AGM formulations for its innovative graphene-fortified low friction coating Tricolit®-GO; [redacted] [E3].

In July 2019 Alltimes Coatings Ltd, a leading specialist in the supply and application of protective coatings for buildings, launched (Advanced Materials Show https://advancedmaterialsshow.com, with approximately 4,000 visitors) the Advantage Graphene liquid coating roofing system (with formulated AGM graphene), with significantly enhanced anti-corrosion performance and life

expectancy, for industrial and commercial roofs [E4]. In July 2020 Blocksil Coatings launched a high-performance graphene anti-corrosion coating for industrial applications that has been approved by Avanti (the leading provider of Ka-band high-throughput satellite capacity in Europe, Middle East and Africa) for application on its large satellite communications dishes [E1,E4].

The coatings area is complemented by high-performance thermal paste adhesive materials. [redacted] Since 2016 AGM has been working on the qualification of a thermal paste adhesive product TP300 and TP400 with Airbus Defence and Space. These novel epoxy adhesive systems exhibit high levels of thermal conductivity (3 and 6W m-1 K-1 respectively), combined with excellent mechanical, adhesive and outgassing performance [E5]

Composites: In October 2016 Century Composites Ltd (40 years of manufacturing fishing rods) began sales of the Tornado Graphex sea rod range which uses carbon fibre with AGM graphene resin technology. AGM manufactured graphene now features in the new Century SGR (Stealth Graphene Reinforced) range. The graphene resin matrix used in the production of the carbon fibre prepreg carries the loadings generated on the rod and allows for the production of lighter rods with high strength and toughness. It is also used to minimises twist in the tip section which Century has called Generation 2 Anti-Twist Technology (Gen 2 AT-T) [E6].

Infinite Composites (October 2019) has successfully incorporated AGM's graphene technology into two resin systems for cryogenic pressure vessels being tested for use in multiple NASA spaceflight missions, including materials on the International Space Station Experiments (MISSE), Artemis, and Lunar Gateway [E7].

In March 2017, SHD Composites Ltd launched a range of AGM graphene enhanced epoxy component prepreg resin system (MTC9800 and now MTC9810) for use in applications as varied as automotive components, sporting goods and artificial limbs. MTC9800 graphene-enhanced product has been used in the award-winning Sit-Ski project run as a technology demonstrator by the High Value Manufacturing Catapult. In March 2018, AGM announced a collaboration with Magna (largest automotive part manufacturer in North America with a turnover of GBP40.8bn, FY2018) and SHD Composites on the W Motors Fenyr SuperSport tailgate using MTC9810 [E8]. The Fenyr Supersport and Sit Ski were launched at JEC 2018 in Paris with approximately 40,000 visitors from over 100 countries [E8].

In May 2017 AGM launched their Structural Ink® technology platform to deposit AGM manufactured graphene resin on a structure in a targeted manner using 2D industrial inkjet printing. As part of the Nano Enhanced Aerospace Interiors (NEAT) project (MAA243, GBP149k), funded under the National Aerospace Technology Exploitation Programme (NATEP), AGM working with Composites Tooling Engineering Services (CTES), SHD Composites Ltd, Composites Evolution Ltd, Coventive Composites and GKN Aerospace (a multinational automotive and aerospace company with over GBP9bn revenue) demonstrated that graphene and Structural Ink® can enhance structural, fire, smoke and toxicity performance in composite parts for the aerospace industry. Several materials are currently undergoing field trials [E1,9].

Policy and Regulation: AGM have been actively involved in determining European health and safety regulation. AGM is the lead partner and founding member of a REACH consortium that will enable graphene to be used in commercial products in the European Union (EU). REACH requires all companies manufacturing or importing chemical substances into the EU in quantities of one tonne or more per year to register these substances with the European Chemicals Agency (ECHA). As part of this AGM (with KSC) and the consortium, have been identifying the risks

associated with graphene manufacture, graphene dispersion and the use of graphene in commercial products [E10].

In summary, AGM and all products arose from the new method for producing graphene on a large scale invented at DU [R1,2,3]. AGM graphene materials are used by third parties who supply products to end-users and consequently detailed sales figures for some products are currently unavailable.

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

[E1] Applied Graphene Materials plc, (http://www.appliedgraphenematerials.com), UK registered company 08708426; Launch announcement 20 November 2013 – RNS Number 4548T; Fundraise 18 December 2015 – RNS Number 4948J; Fundraise 08 January 2016 – RNS Number 3108L; Fundraise 30 October 2017 – RNS Number 9897U; AGM company reports (2014-2020) filed at UK Companies House (https://beta.companieshouse.gov.uk/company/08708426/filing-history) and published each year on the AGM website (https://www.appliedgraphenematerials.com/reports-and-presentations/)
[E2] Graphene enhanced anti-corrosion aerosol primer paints: James Briggs Ltd and Halfords branded primer
[E3] Tricolit GO coating http://appliednanosurfaces.com/products/ans-tricolit/; AGM Annual Report 2019, page 11
[E4] Alltimes Coatings (http://www.alltimescoatings.co.uk); http://www.alltimescoatings.co.uk/our-products/metal-roof-repair/, RNS announcement 09 July 2019 – RNS Number: 9642E. Blocksil (https://blocksil.co.uk/news); AGM Annual Report 2020, page 12
[E5] Graphene adhesives: [redacted] AGM Annual Report 2019, page 13; Airbus partnership AGM Annual Report 2020, page 15
[E6] Century (http://www.century.uk); Tornado Graphex sea fishing rods and the stealth graphene reinforced range now available widely (e.g http://www.centurycarp.co.uk/carp-rods/century-stealth/ and https://www.anglingdirect.co.uk/century-tip-tornado-graphex-sport-rod, retailing at approximately GBP520 each), RNS announcement 14 October 2016 – RNS Number 5109M
[E7] Infinite Composites (www.infinitecomposites.com/), RNS announcement 03 October 2019 – RNS Number 5887O; Graphene Info (https://www.graphene-info.com/agm-and-infinite-composites-develop-graphene-composite-material-space)
[E8] SHD Composites Ltd (https://shdcomposites.com); SHD MT98100 used in tailgate of Fenyr cars (https://www.wmotors.ae/the-fenyr-supersport.php), RNS announcement 08 March 2018 – RNS Number 045OH, and MTC9810 in sit-ski (https://hvm.catapult.org.uk/news/taking-technology-off-piste/) and http://www.jeccomposites.com/knowledge/international-composites-news/sit-ski-made-graphene-enhanced-epoxy-component-prepreg; JEC 2018 Paris (http://www.jeccomposites.com/events/past-events/jec-world-2018), approximately 40,000 visitors from over 100 countries.
[E9] National Aerospace Technology Exploitation Programme (NATEP), RNS announcement 30 May 2019 – RNS Number 5324A.
[E10] Graphene: EC number: 801-282-5 | CAS number: 1034343-98-0 (https://echa.europa.eu/registration-dossier/-/registered-dossier/24678/1)