Institution: Queen Mary University of London (QMUL)

Unit of Assessment: Physics B9

Title of case study: Let there be light: Commercial and cultural impact from optical spectroscopy

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

Research on the spectroscopy of materials conducted by Prof. Dunstan has led to novel innovations for the Renishaw Raman microscope that have been patented and marketed by Renishaw plc, a UK-based global instrumentation company, as part of their inVia microscope range in the form of the NeXT filter. These innovations have provided the company with significant commercial advantage over their competitors and allowed the pharmaceuticals industry to develop applications for this technology in the areas of amorphous drugs, stability testing and polymorph screening. Dunstan's spectroscopy research has also enabled him to work with Absolute Action Ltd, a company which provides bespoke lighting systems for museums, galleries, public spaces and homes. The commercial value of contracts won by Absolute Action between 2008/13 that relied on Dunstan's technical innovations is estimated to be £1m. Dunstan designed the lighting technology for the Hope Diamond displayed in the Smithsonian Institution (USA), the Memorial to Japanese-American Patriotism (USA), and the gemstone collection in the Natural History Museum (UK). These lighting systems have enhanced the viewing experience of the public and attracted new visitors to the museums throughout the REF assessment period.

2. Underpinning research (indicative maximum 500 words)

Prof. Dunstan joined QMUL's Department of Physics in 1996. His research is concerned with spectroscopic analysis of advanced materials under high-pressure, for which he designed and developed diamond-anvil high-pressure cells (DACs) that enable materials to be studied in the laboratory at pressures comparable to the those at the centre of the Earth [R1]. On his arrival at QMUL, Dunstan purchased a Renishaw Raman microscope for application to his high-pressure spectroscopic studies. It is this research, and the innovations in optical engineering that he developed to allow him to perform this research between 1996-2003, that have led to the impacts described in section 4.

Prof Batchelder's group at QMUL designed the Renishaw Raman microscope in the 1980s [R2]. Dunstan purchased one of these from Renishaw when he moved to QMUL. This instrument was the most advanced in the field, however it had limitations that restricted its use. The Raman signal is approximately 1 million times weaker than the normal scattered light from the laser source, and hence an extremely sharp filter is required to remove the scattered light in order to detect the weak Raman signal. In the original Raman microscope this was done using holographic filters, but these had two major drawbacks. First, they only worked with a single wavelength of light so resonant Raman spectroscopy, which greatly improves sensitivity, could not be performed. Second, the filters were insufficiently sensitive to allow measurements at wavelengths very close ($<100cm^{-1}$) to the original laser; this is the region where much useful information can be found.

From 1996 onward Dunstan applied high-pressure spectroscopy techniques to strained-layer semiconductor structures and carbon nanotubes to study their properties using DACs coupled to the Renishaw Raman microscope [R3, R4]. His results presented in [R4] showed that it is essential to select the right nanotubes for study by resolving the radial breathing Raman mode, as this characterises the diameter of the nanotubes. The strength of the signal depends critically on the wavelength of the exciting laser light, so that has to be tuned to pick out individual nanotubes. Furthermore this radial breathing mode is at low Raman shift, near the excitation light. These two issues were completely opposite to what the standard holographic filters were designed to provide, and as a result Dunstan had to develop a completely new approach to removing the tunable laser excitation, while maintaining the low Raman shift information required by his experiments. It was the need to address these two problems that led him to build the Near-eXcitation Tuneable (NeXT) filter that was published in 2002 [R5] and a patent granted in 2003 [R6]. The experimental set-ups leading to the results published in [R3, R4] required critical innovations in optical engineering using fibre-optics and other techniques to couple the light output from the samples contained in the DACs with the Raman spectrometer. The requirement for this coupling to be achieved with minimal loss is particularly severe because of the extreme weakness of the Raman signal. Dunstan's research requirements exposed other limitations in the Raman microscope. The use of a microscope to obtain the special resolution required generally limited its application to objects that could fit under a microscope objective. Dunstan invented an "Omni-directional beam steering unit" that could be fitted to any microscope and allows objects to be studied at any angle or distance from the microscope. He also invented a new grating turret and developed the interface software.

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

[R1] D.J. Dunstan and I.L. Spain, 1989, *Journal of Physics* E22, 913-923.
[R2] US Patent 5510894 (1996), D.N. Batchelder and G.D. Pitt
[R3] M.D. Frogley, D.J. Dunstan, 1998, Phys. Rev. B., 58, 12579-12582
[R4] J.R. Wood *et al*, *Physical Review* B, 62, 7571, 2000.
[R5] D.J. Dunstan, Frogley M.D., *Review Sci*. *Instrum.*, 73, 3742, 2002
[R6] US Patent 6657724 (2003), D.J. Dunstan and M.D. Frogley

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

The impact that has been generated by Dunstan's research includes: an increase in the commercial competitiveness of Renishaw plc resulting from his innovations to their inVia microscope range, allowing them to become the market leaders in Raman spectroscopy; the development of new analysis techniques in pharmaceuticals quality control; commercial contracts and revenues won by the SME Absolute Action Ltd between 2008/13 arising from consultancy work undertaken by Dunstan; cultural impact and improvements in the quality of life for the general public through innovative lighting of public displays; and enhanced sustainability of public museums through increased visitor numbers.

Improvements to the Raman microscope give Renishaw plc competitive advantage
Between 1996-2002, Dunstan developed the numerous improvements to the Renishaw Raman microscope described in section 2. Renishaw incorporated these into their new inVia range of Raman microscopes, with the Near-eXcitation-Tuneable (NeXT) filter being the primary innovation. The Design Manager in Renishaw's Spectroscopy Products Division writes: *"… Renishaw started collaborating with Prof Dunstan at Queen Mary on the development of a number of modifications to the Raman microscope which were incorporated into the design of the inVia system*" [1].

The design of the NeXT filter in particular has given Renishaw a distinct competitive edge, and the inVia Raman microscope has become the world's best selling research Raman system. According to the Design Manager at Renishaw the NeXT filter has enabled them *"to become market leaders in the area of low wavenumber Raman microscopy"* [1]. Raman spectroscopy is "*the predominant income source*" in Renishaw's healthcare section, which contributed £29m to their revenue in 2013. This is a rapidly growing area for the company with 11 percent growth since 2012 [1, 6]. Their main competitor in the field of Raman microscopes, Horiba, use a triple spectrometer coupled to their microscope to achieve similar performance. As has been stated by the Science & Technology Lead at AstraZeneca plc, the NeXT filter had: "*the distinct advantage over triple monochromators of lower cost and vastly increased throughput. It was a major step forward giving industrial labs access to a traditionally difficult spectroscopic region. It was routine, relatively easy to maintain and provided invaluable insight into polymorph structure and formulation behaviour including polymorph stability.*" [2].

New industrial and pharmaceutical applications
The introduction of the NeXT filter has allowed for the development of new industrial applications of Raman spectroscopy using the inVia microscope. The Design Manager at Renishaw writes: "*This filter … has allowed us to expand our sales into new areas, such as polymorph screening in pharmaceuticals, graphene and related carbon materials*" and *"…the development of the NeXT*

filter has provided our customers with a powerful high-throughput technique that has benefitted their industries." [1]. The Science & Technology Lead at AstraZeneca states: "*Prior to the introduction of the NeXT filter, the challenges from an industrial perspective largely resulted from limitations in the capability of the instrumentation and not the science. The NeXT technology opened up opportunities for solving industrial problems needing a solution from low frequency mode measurements.*" [2]. One particularly important use of the NeXT filter has been in the pharmaceutical industry, where: "*These low frequency modes were invaluable in supporting the characterisation of drug polymorphs and formulations. They helped define both the properties of these polymorphs and their behaviour. To address the challenge of probing this spectral region, I evaluated industrialized and research solutions in Fourier Transform far-infrared, Terahertz and Raman spectroscopies. The two former were shown to be of limited value. Raman spectroscopy clearly was the technology of choice.*" [2].

A considerable amount of research has been undertaken into drug polymorphism by the pharmaceutical industry – partly because polymorphs (different structural forms of a given molecule) are patentable, and this can have advantages for industry in extending the patent lifetime of the drug, but also because of the risk polymorphism poses to the effectiveness of a drug. According to the Chief Scientific officer at pharmaceutical research company SAFC-Pharmorphix: *"The worst that can happen for a pharmaceutical company is if a new polymorph suddenly appears in the temperature and humidity conditions of a blister-pack when a compound is actually on the market"* [7]. This is because new polymorphs can alter the bioactivity of a drug, for example through changes in solubility. A number of techniques have been used to study polymorphism such as X-ray diffraction and optical spectroscopy, but given that polymorphs can be formed by subtle changes in crystallisation due to solvent, temperature, cooling rates, etc, there is an active market in high throughput characterisation techniques. Attempts have been made to use other techniques such as FTIR (Fourier Transform Infrared) and Terahertz spectroscopy, but these have proved ineffective and the introduction of the NeXT filter to Raman microscopes added significant value as the low frequency modes "*helped define both the properties of these polymorphs and their behaviour*." [2]. This was in part due to the fact that "*it was routine*" and "*relatively easy to maintain*" [2], but also the removal of a large scanning triple spectrometer meant that spectra can be collected on a CCD array with fast integration times (due to the higher light throughput). "*It was a major step forward giving industrial labs access to a traditionally difficult spectroscopic region.*" [2]

Optical-engineering gives Absolute Action Ltd a competitive edge
Dunstan began his consultancy with Absolute Action Ltd in 1996/97 when they approached him with the challenge of illuminating the Hope Diamond in the Smithsonian, which is often quoted as being the most viewed museum artefact in the world. The diamond is set in a ring of brilliant white diamonds and visitors were frequently disappointed because the original lighting caught the white diamonds so much that the blue diamond appeared dull in comparison. Dunstan used his research expertise in optical-engineering, developed through his experimental research in coupling samples contained in Diamond Anvil Cells to the Renishaw microscope, to design a lighting system that used fibre-fed imaging optics coupled with a graticule to provide as much light as possible on the Hope Diamond while minimising the light level on the surrounding diamonds. This resulted in the current display where the Hope Diamond "sparkles, dazzles and glows" [*The Times,* reference 8]. The curator of the National Gem and Mineral collection at the Smithsonian stated that: *"annual viewing figures since 2008 have been approximately 5 million, compared to only about 3 million before this lighting was installed*" [3].

In 2003 Dunstan designed the lighting for the Memorial to Japanese-American Patriotism and the lighting system that illuminates the paintings in the British Embassy in Paris. The key knowledge transfer from the experimental research was developing the ability to place light, at whatever intensity or colour and at whatever place, with whatever variation over time, that may be desired by a lighting designer or client. The design rules and computer software developed by Dunstan to achieve this were given to Absolute Action Ltd, allowing them to use this technology in many subsequent contracts [4].

This has given Absolute Action Ltd a distinct competitive edge. Although there is no IPR protection or patentable technology in the designs Dunstan has given the company, the know-how and confidence to tender for commissions that competitors cannot meet has led to many top-end contracts and a very strong reputation. Absolute Action Ltd states that this technology "*enables us to secure projects of elevated intrinsic value, to satisfy the kind of clients who will come back for more, and to reinforce our Company's status as providers of unique services in high-profile projects*." [4]. They estimate that these high value projects have accounted for ~£1m in revenue since 2008, which is "*not an insignificant contribution to the commercial health of a small entity such as we are*". It has also "*elevated our company to the status of Lighting Specialists of Choice for some of the Smithsonian Institution's most vaunted exhibitions- including inter alia the illumination of the Dresden Green Diamond, the Wonder of Pearls exhibition and the Fancy Diamonds Exhibit.*" This status and the reputation that goes with it helps them to continue to secure high prestige projects such as illuminating the exclusive Carnet jewellery store in Hong Kong and Carnet exhibition in London (2010), and a commission from Foster & Partners to illuminate Buddhist sculptures in the Kamakura private residence in Japan (2010). Bespoke lighting design companies who have partnered Absolute Action Ltd have also received commercial benefit through utilisation of these technologies [5].

Museums and art galleries

The impact of this work is currently on display around the world in both public and private permanent collections. The initial work on the Hope Diamond has led to a number of contracts for exhibitions. For example, the Vault at the Natural History Museum in London displays the institution's most valuable collection of gemstones and minerals in a permanent exhibit. The approach is being increasingly used in art galleries where there is a need to have very discrete luminaires which place light (with no damaging UV component) solely onto the artwork to be displayed. By removing the light overspill the painting or sculpture appears to stand out from the background, greatly enhancing the impact on the viewer. This technology has now been used for displaying artwork in locations as varied as Cliveden, The Van Loon Museum in Amsterdam and The Garrick Club in London, as well as the British Embassy in Paris.

Secondary impact is generated by the enhanced viewing experience of the public provided by these lighting systems. The resulting cultural capital leads to improvements in the quality of life. The increased interest and engagement of the general public has a positive impact on the sustainability of public museums through increased visitor numbers, as evidenced by the increase from three to five million visitors to the Hope Diamond after the new lighting was installed [3].

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

[1] Renishaw plc, Design Manager, Spectroscopy Products Division. Corroborates commercial advantages gained by Renishaw plc from Prof. Dunstan's innovations to inVia microscope.
[2] AstraZeneca plc, Science & Technology Lead. Corroborates impact of NeXT filter on industrial and pharmaceutical applications for the Renishaw Raman microscope.
[3] Smithsonian Museum of Natural History, Curator Gem & Mineral collection. Corroborates impact of Dunstan's lighting design on Hope Diamond display and subsequent increase in visitors
[4] Absolute Action Ltd, Managing Director. Corroborates commercial benefits received by Absolute Action Ltd from Dunstan's lighting designs.
[5] Cannon-Brookes Lighting Design, Managing Director. Corroborates impact that Dunstan's lighting designs have had on SMEs other than Absolute Action Ltd.
[6] Renishaw Interim Report 2013:
www.renishaw.com/en/financial-reports-and-presentations--18962
[7] S. Aldridge, Chemistry World, p. 66, April 2007.
[8] The Times, London, 20th September 1997.