Institution: Lancaster University

Unit of Assessment: 9, Physics

Title of case study: Increasing commercialisation and public awareness of ultralow-temperature technologies.

Period when the underpinning research was undertaken: 2000 to 2019

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. Richard Haley	Professor of Low Temperature Physics	15/11/1997 to present
Prof. George Pickett FRS	Distinguished Professor	01/08/1970 to present
Dr. Jonathan Prance	Reader in Low Temperature Nanoelectronics and Director of IsoLab	17/9/2012 to present
Dr. Dmitry Zmeev	Lecturer and EPSRC Research Fellow	01/10/2010 to present

Period when the claimed impact occurred: 2015 to 2020

Is this case study continued from a case study submitted in 2014? N

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

Research from the Low Temperature Group (LTG) at Lancaster University has led to commercial impact and increased public understanding of ultralow temperature physics and technology. Between 2015 and 2017, they collaborated with Oxford Instruments NanoScience (OINS) to produce a low-cost, portable refrigeration platform for quantum technologies, generating commercial benefits for OINS, with sales of GBP1.692 million. They also collaborated with OINS in public engagement, exhibiting at a national science exhibition with a footfall over 12,000 people in 2019. Media coverage of the exhibit included an article in The Times and an interview on The World at One, with a combined reach of more than 3.0 million people. A short, multi-internationally-award-winning, documentary film about Lancaster research on the low temperature properties of acrylonitrile butadiene styrene (ABS), in the form of LEGO®, has been viewed over 448,000 times, and received international media attention from several hundred outlets spanning 60 countries and 31 languages, with a total audience reach in excess of 275 million.

2. Underpinning research (indicative maximum 500 words)

Lancaster University's LTG is a world leader in ultralow-temperature physics and technology [3.1, 3.2, 3.3, 3.4]. At present, temperatures of around 0.01K can be readily accessed using commercially-built dilution refrigerators. These use helium-3 in superfluid helium-4 as their refrigerant, and the physics of liquid and superfluid helium is fundamental to their operation. Dilution refrigeration was first demonstrated in the 1960s and commercialised shortly afterwards. Over the past 20 years, the technology has advanced significantly in terms of reliability and ease of use. In the same period, dilution refrigerators have become a ubiquitous tool for a range of quantum technologies including superconducting qubits developed by IBM, Google and others, and semiconducting and hybrid qubits pursued by Intel, Microsoft and others. Such solid-state devices must be operated at low temperatures, usually near 0.01K, to enter the quantum regime. In comparison, the work at Lancaster is driven by the challenge of reaching temperatures significantly below 0.01K, and uncovering novel physics accessible in this range. The LTG have developed pioneering techniques and built new equipment in order to reach these temperatures. For example, custom-made dilution refrigerators, built in-house, achieve world-record low temperatures of 0.0016K. LTG researchers also continue to explore the application of new manufacturing techniques and materials, and in 2019 demonstrated that ABS, which is 3D-printable, could be used to construct parts of a dilution fridge [3.4].

While the physics of liquid and superfluid helium underpins the operation of dilution refrigerators, it is also a topic of fundamental interest that lends itself to inspiring public interest. The LTG is active in this area and its research includes, for example, breakthrough studies of turbulence [3.1], and simulations of cosmological phenomena [3.2] using superfluid helium-3. This work often requires temperatures that are out of reach for even the best dilution refrigerators. To

reach below 0.001K, the LTG adds a stage of magnetic refrigeration (adiabatic demagnetisation) to cool pieces of metal into the microkelvin range; a technique that was established at a similar time to dilution refrigeration.

The scope of research in the LTG also includes new techniques that are directly applicable to the growing fields of quantum materials, engineering and technology. In general, it is a significant challenge to cool most materials or devices below 0.01K. While the refrigeration technology exists to reach lower temperatures, it becomes extremely difficult to make effective thermal contact to anything other than liquid helium or bulk metals. In 2016, the LTG succeeded in cooling electrons in an on-chip device to a record low temperature (at the time) of 0.0037K by immersing the device inside the refrigerant of a dilution refrigerator [3.3]. Subsequently, they led an international collaboration within the European Microkelvin Platform, an H2020-funded consortium of 17 universities and companies, to demonstrate a new technique to cool devices using on-chip magnetic refrigeration. They were able to reach a device temperature of 0.002K and, as with conventional magnetic refrigeration, the technique has the potential to reach far below 0.001K.

Realising the commercial and scientific benefits of ultralow-temperature technology requires expertise and insight into its practical applications, and the LTG works extensively with academic and commercial collaborators. Two examples are their longstanding research cooperation with OINS, and a more recent collaboration with the National Graphene Institute (NGI). Since 2015, they have worked with these two partners to develop a deeper understanding of the environmental requirements of certain quantum devices operating below 0.1K. Initially, building on the experimental know-how of the LTG, and in collaboration with the NGI, they found a new physical phenomenon in superconducting graphene, only observable at temperatures close to 0.01K [3.5]. As a result of this discovery, a superconducting quantum interference device (SQUID) magnetometer based on graphene was developed [3.6]. This work, at the forefront of research on new materials for quantum technology, provided a valuable insight into how the cryogenic industry can support emerging quantum technologies. Ultimately, the LTG took the graphene SQUID devices to the OINS factory and used them to test the capabilities of a new dilution refrigerator platform being developed.

Through the research described above, the LTG continues to push the boundaries of ultralow-temperature technology, while also applying its expertise to current applications. They continue to study the fundamental physics of helium at the lowest possible temperatures, whilst also working to bring other devices and materials into the same temperature range. All of this work underpins the impact they generate through public engagement and commercial partnership.

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

[3.1] D. I. Bradley D. O. Clubb, S. N. Fisher, A. M. Guénault, **R. P. Haley**, C. J. Matthews, **G. R. Pickett**, V. Tsepelin, and K. Zaki, "Decay of pure quantum turbulence in superfluid ^{3}He-B", Phys. Rev. Lett. 96, 035301 (2006).115 citations (Web of Science).

[3.2] D. I. Bradley, S. N. Fisher, A. M. Guénault, **R. P. Haley**, J. Kopu, H. Martin, **G. R. Pickett**, J. E. Roberts and V. Tsepelin, "Relic topological defects from brane annihilation simulated in superfluid ^{3}He", Nat. Phys. 4, p46 (2008). 28 citations (Web of Science).

[3.3] D. I. Bradley, R. E. George, D. Gunnarsson, **R. P. Haley**, H. Heikkinen, Yu. A. Pashkin, J. Penttilä, **J. R. Prance**, M. Prunnila, L. Roschier and M. Sarsby, "Nanoelectronic primary thermometry below 4 mK", Nat. Commun. 7, 10455 (2016). Altmetric – 89 (91st percentile of similar-aged articles in Nature Communications).

[3.4] J. M. A. Chawner, A. T. Jones, M. T. Noble, G. R. Pickett, V. Tsepelin and **D. E. Zmeev**, "LEGO® block structures as a sub-kelvin thermal insulator", Sci. Rep. 9, 19642 (2019). Altmetric – 897, article accessed 118k times, a Springer Nature "top downloaded article" of 2019.

[3.5] M. Ben Shalom, M. J. Zhu, V. I. Fal'ko, A. Mishchenko, A. V. Kretinin, K. S. Novoselov, C. R. Woods, K. Watanabe, T. Taniguchi, A. K. Geim and **J. R. Prance**, "Quantum oscillations of the critical current and high-field superconducting proximity in ballistic graphene", Nat. Phys. 12, 318-322 (2016). 127 citations (Web of Science).

[3.6] M. D. Thompson, M. Ben Shalom, A. K. Geim, A. J. Matthews, J. White, Z. Melhem, Yu. A. Pashkin, **R. P. Haley** and **J. R. Prance**, "Graphene-based tunable SQUIDs", Appl. Phys. Lett. 110, 162602 (2017). Joint publication with OINS and the National Graphene Institute.

Quality Indicators:

"Development of a cryofree ultra low temperature environment for quantum enhanced sensors" (CUE-QS) GBP103.091, EPSRC (EP/M508354/1EP/M508354/1) and the Technology Strategy Board (49735-370170), May 2015 to April 2016.

"Prototype cryofree ultra low temperature environment for quantum enhanced sensors" (CUEQS2) GBP177,551, Innovate UK (70971-492147), September 2016 to August 2017.

"European Microkelvin Platform", EUR1,289,157.00 (project total EUR9,984,192.66). H2020-EU.1.4.1.2. - Integrating and opening existing national and regional research infrastructures of European interest (824109), January 2019 to December 2022.

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

The LTG engages with a full range of stakeholders who are interested in their work, from the general public to commercial partners. Their goal is to inspire others and to drive the uptake of new technologies. They are motivated by questions of fundamental physics, as well as the promise of specific applications.

The LTG's track record in ultralow-temperature physics and technology (including [3.1, 3.2, 3.3, 3.4]) underpins a long-lasting collaboration with OINS, a world leader in the development and manufacture of nanoscience tools and systems for industry and research. As stated in the testimonial from OINS [5.1] *"[o]ur close and ongoing collaboration has been in operation for many years*". OINS is the largest manufacturer of dilution refrigerators in the UK and one of the top two manufacturers worldwide. The LTG's efforts to close the gap between fundamental, ultralow-temperature physics and practical technologies enables them to collaborate with, and influence, this major commercial producer of ultralow-temperature research tools. In the opinion of OINS, Lancaster's research involvement *"has been pivotal in maintaining direction and vision for the low temperature research goals of UK physics"* [5.1]. Research on superconducting devices [3.5, 3.6] combined with LTG expertise [3.3] provided the basis for a multi-year collaboration (2015 to 2017) with OINS to develop a new portable refrigeration product. Together, *"a market requirement for a low-cost, portable refrigeration unit to support solid-state quantum technologies in applications such as sensing and metrology"* was identified [5.1]. Pre-existing systems made by OINS could cool devices to slightly below 0.01K, but at a significant capital cost, around GBP500,000 to GBP1.0 million. These platforms also have large physical footprints, require significant support facilities and are relatively complex to operate. In cases where liquid cryogens are used there is also a safety risk in maintaining and using the equipment. Working together within the framework of two Innovate UK grants (CUE-QS and CUEQS2) LTG and OINS developed a prototype, cryogen-free, ultralow-temperature environment for quantum-enhanced sensors. The end result was a new product, the "Io", which was significantly cheaper, more compact, and easier to operate than other systems – the first such compact system marketed by OINS [5.2]. It offers a low-temperature environment that reaches 0.05K, suitable for many commercially-ready sensors and devices, but at a significantly lower capital cost than existing systems, i.e. around GBP150,000 to GBP200,000. Testing of the prototype, including critical parameters such as its cooling performance and internal vibrations, were undertaken using superconducting magnetometers developed in Lancaster [3.6] as reference devices.

Photograph of an Io compact ultralow-temperature refrigerator [5.2]. The cold volume of the refrigerator is contained within the cylindrical white can, suspended from the frame on the left. In previous products, both this can and the support apparatus (right) would be roughly double the size.

The Io was actively marketed by OINS until 2019. During that time, nine Io systems were sold *"generating commercial product revenues of £1,692,000"* [5.1]. OINS have predicted, based on their market analysis, that *"the demand for cryogen-free systems for quantum technology applications is growing and we anticipate the total market for ultra-low temperature systems to be in excess of £80M by 2022"* [5.1]. OINS historically captures a significant fraction of this market with ultralow-temperature products covering a range of capability and cost. The Io sits at the cheapest end of the range. The LTG's work with OINS allowed them to explore this part of the market and their competitors developed comparable offerings. Although the market has currently shifted in the opposite direction towards larger and more expensive products, as a result of the collaboration, OINS are ready to respond quickly if it moves towards a more widespread adoption of ultralow temperature technologies.

The partnership with OINS also includes working together on public engagement and educational outreach activities. In 2019, Lancaster academics, including Prance and Haley, were invited to contribute an exhibit at the Royal Society Summer Science Exhibition (SSE) [5.3, 5.4]. A major element of the 2019 Lancaster exhibit was a visual demonstration of the operation of a dilution refrigerator. The demonstration was built at Lancaster University using components of a real dilution refrigerator, on loan from OINS, and was used to educate school students, teachers and members of the public about the future of low-temperature physics and quantum technologies. Visitors to the week-long event numbered 12,653, of which 187 were teachers and 1,518 students from around the UK [5.3]. The SSE was also a high-profile opportunity to showcase OINS products to politicians, policymakers, industry stakeholders and other invited VIPs at the 'soirees' with 1,140 in attendance. Official feedback on the event, collected by the Royal Society, demonstrates how the SSE can influence students in particular [5.4]. For example, 98% of teachers agreed that by attending the exhibition their students gained a greater understanding of the relevance of science to the world around them, and 98% of teachers agreed their students had gained a greater understanding of the range of scientific careers [5.4]. The Lancaster exhibit, including the dilution refrigerator demonstration, also generated significant media attention. Coverage included a piece in The Times and an interview on The World at One, with a combined reach of more than three million people [5.3]. Social media engagement comprised 350,200 impressions across a range of twitter accounts and 30,466 views of the videos related to the exhibit [5.5].

Since the end of the exhibition, the dilution refrigerator demonstration built by LTG academics, continues to be used by OINS "*to build knowledge and interest in STEM as part of [their] outreach programme to great success"* [5.6]. Relocated to the OINS factory at Tubney Woods, it is used to advertise the work of the NanoScience division and to help educate staff in the science that underpins their ultralow-temperature products. The Director of Human Resources at OINS said the *"[t]he model has been an excellent source of learning within NanoScience for those of us who need visual aids to understand how the helium flows…", and "[t]he idea of demonstrating it so visually is really creative and has been having a significant impact."* [5.6].

In 2019, LTG member Zmeev seized the opportunity offered by a particularly appealing piece of research to generate significant online engagement with low-temperature physics. Group members worked with Hamster Productions to make a short documentary film [5.7] explaining the results of their recent research on the assessment of ABS as a construction material at low temperatures [3.4]. This is of broad interest as ABS is a base material for 3D printing and is also the material used to build LEGO® bricks. The film was titled "The World's

The stills above are taken from an educational documentary that introduces concepts from low temperature physics and talks about some of the group's research [3.4]. Upper: a LEGO® "cryonaut" emerges from their journey to millikelvin temperatures. Lower: Distinguished Professor George Pickett FRS explains the Kelvin scale and the concept of absolute zero temperature.

Coolest LEGO® Set! (Literally)". Through interviews with academics and stop-motion LEGO® animation, it described the results of the group's research and explained fundamental concepts such as absolute zero temperature The documentary has been viewed over 448,000 times across several platforms. It won "Best Science Movie" at the Vienna Science Film Festival (2020) and the "Science Fact (Amateur)" category of the Bristol Science Film Festival (2020). It was selected for the Scinema International Film Festival and the China International Conference of Science and Education Producers, and was a finalist at the "#LabMeCrazy!" Science Film Festival, all in 2020 [5.8]. LTG members gave a number of interviews about their work to outlets including CNN (USA), The Times (UK), NBR.nl (Netherlands), ACS Chemical & Engineering News (USA) and the Physics World "Everyday Science" podcast (UK). The publication was discussed widely on Reddit where two posts generated over 44,900 upvotes and were in the top 50 posts of the month on the subbreddits r/science and r/Futurology, which have around 40 million subscribers combined. The story was covered by hundreds of news outlets worldwide, spanning 31 languages and 60 countries. Notable outlets included MSN online, The Times of India, New York Post and BBC's Science Focus. A news report about the film aired on CNN (26th December 2019) reached an expected 1 million live viewers [5.8]. A sample survey of physics departments at UK schools revealed that 21 out of 22 (95%) agreed that the film could be a useful tool for their teaching, and 18 out of 22 (82%) agreed that they plan to use it. Teachers' comments included *"A really interesting video and a nice way to lead into the thermal properties of polymers",* and *"The experiment was a useful starting point for discussion about insulation at ultra-cold temperatures"* [5.9]. In total, the audience reach of media coverage was over 275 million people [5.10].

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

[5.1] Letter from Strategic Business Development Manager, Oxford Instruments NanoScience (25th November 2020) corroborating impact of the research on their organisation.

[5.2] Oxford Instruments Product brochure (2018) showing technical details of the "Io" compact cryogen-free, ultralow-temperature refrigerator.

[5.3] Royal Society Summer Science Exhibition (2019). Individual exhibit feedback report corroborating visitor numbers, breakdown of demographics and media coverage.

[5.4] Royal Society Summer Science Exhibition Review of 2019. Corroborates the impact of this event, particularly on teachers and students.

[5.5] Press report (compiled by Lancaster University), December 2020. Corroborates coverage of the RSSE 2019 exhibit in print and online social media.

[5.6] Letter from the HR Director of Oxford Instruments NanoScience and Magnetic Resonance (26th September 2019) confirming the impact of the dilution refrigerator in their training and outreach activities.

[5.7] Hamster Productions documentary "The World's Coolest LEGO® Set! (Literally)" , December 2019. Copy available on request.

[5.8] Press report (Lancaster University, November 2020) corroborating publicity relating to output [3.4].

[5.9] Results of Lancaster University Public engagement teacher survey (August 2020) corroborating impact of RSSE 2019 event and video relating to output [3.4].

[5.10] Audience reach report (Lancaster University, December 2020) corroborating online media coverage of video relating to output [3.4].