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ISIS Lifetime Impact Study

Volume 1 – Full Report

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ISIS Lifetime Impact Study - Volume 1

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For the Appendix, please refer to the ISIS Lifetime Impact Report, Volume 2

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The ISIS Neutron and Muon Source at the Rutherford Appleton Laboratory: Lifetime Impact Study

1. Executive Summary

This report summarises our main findings from the ISIS Lifetime Impact study, which outlines the economic and social impact of the ISIS neutron and muon source, a major centre for research in the physical and life sciences (using data from 1985-2014). The ISIS Lifetime Impact study was commissioned by the Science and Technology Facilities Council (STFC) in response to the recommendations of the BIS "Big Science and Innovation Report"[1], to produce more ambitious and far-reaching evaluations of large- scale facilities. It is also part of STFC's ongoing programme of data capture and impact evaluation. For full analysis and discussion see our full report, the ISIS Lifetime Impact Study.

ISIS is funded largely by the UK Government and is operated by STFC on the Harwell Campus, near Oxford. The facility has been in operation since 1984, annually supporting a national and international community of 3,000 researchers from academia and industry. From the outset, it has been one of the most advanced spallation[2] neutron sources in the world, and has demonstrated to the global scientific community the feasibility and benefits of using a spallation source for the production of neutrons for science. The only facility of its kind in the UK, ISIS allows scientists to study materials at the atomic level using a suite of instruments. Research is undertaken in a wide variety of subjects including Physics, Chemistry, Materials Science, Geology, Engineering and Biology. The facility was originally expected to have an operational life of some 20 years (1985-2005), but its success has led to a process of ongoing refurbishment and further investment intended to advance the facility and extend the life of ISIS through to 2030.

In this ISIS Lifetime Impact Report we have estimated the immediate direct economic impact of ISIS over 30 years, and have also characterised the wider economic impacts among industry users and suppliers. To better assess the wider economic impact, we have gone beyond conventional approaches, in particular using research case studies and direct estimates of value from industry to estimate wider economic benefits. Using this approach we have estimated:

- **ISIS will deliver at least £1.4 billion in net economic impact, based on what has already been achieved up to 2014.** This total comprises £1.0 billion of past economic impacts estimated from the research, innovation and skills that have been generated by the facility and the direct impact to the local economy that comes from employment and supply chain effects. It also includes £0.4 billion of future economic impact up to 2025, generated from research and innovation already completed.

- **ISIS has delivered a healthy Return on Investment (RoI) of at least 214%**. Our conservative analysis indicates that ISIS has already paid for itself twice over, thus supporting the

[1] "Big Science and Innovation", Technopolis on behalf of BIS, (2013) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/249715/bis-13-861-big-science-and-innovation.pdf

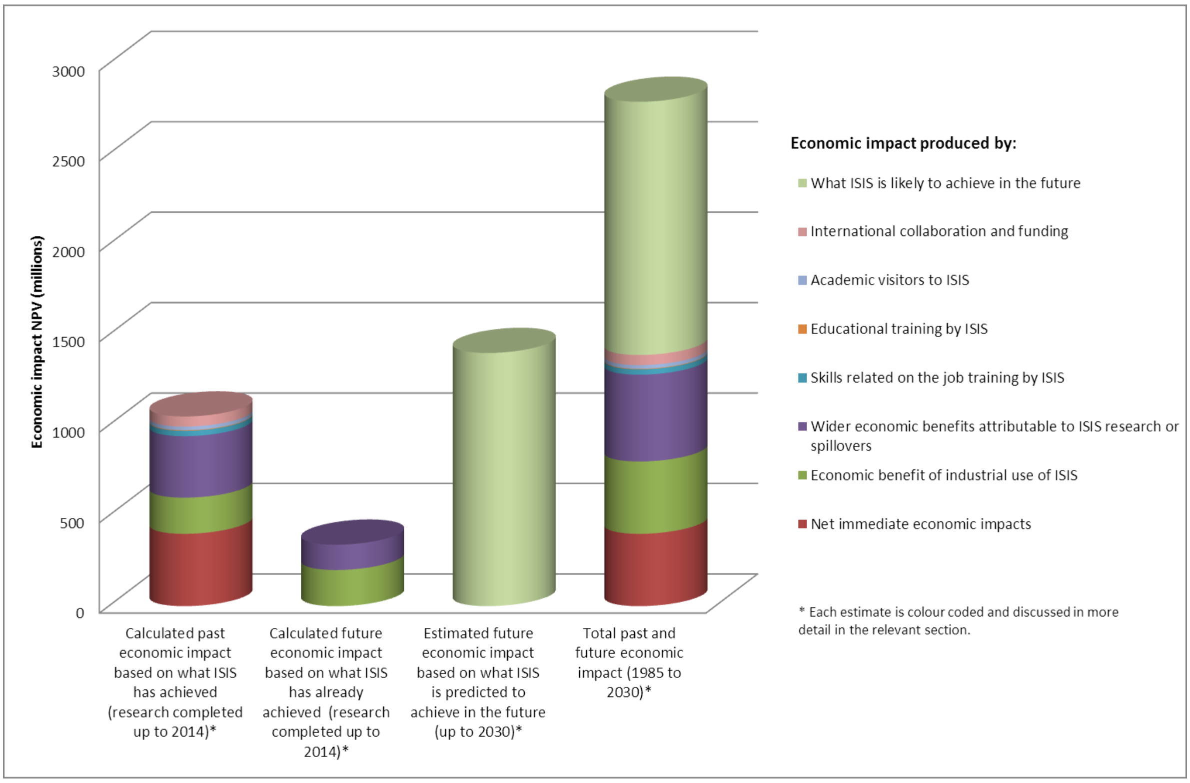
[2] Spallation is a process in which fragments of material are ejected from a body due to impact or stress. Nuclear spallation is one of the processes by which a particle accelerator may be used to produce a beam of neutrons.

understanding that publicly funded research and innovation is a key way to drive economic growth as outlined in the Government's Science and Innovation Strategy[3].

- **ISIS will generate a further £1.4 billion of economic impact, based on predicted future achievements up to 2030**. This includes what we expect ISIS to generate from likely new work in the future. With an expanding instrument set and a planned upgrade, we estimate that the next 15 years of ISIS operation could easily match the order of magnitude seen in the first 30 years. ISIS also remains as a capital asset worth £0.5 billion to the UK[4], with additional value in the associated skills base.

The numbers presented here are a conservative estimate of the impact of ISIS; this is due in particular to gaps in historical impact data as well as to the challenge of researching all impact case studies fully for a report such as this (with time and cost constraints). Therefore, this kind of study can only ever provide an outline of the impact that such facilities provide academically, socially and economically. Figure 1 represents all our estimates of the different types of social and economic impact which are attributable to ISIS. Further information on each aspect of the analysis is highlighted and colour coded throughout the report. Further information is also detailed in the Appendix.

Figure 1: Past and Future economic impact of ISIS



Other highlights from our study include;

- **ISIS research is world-class.** ISIS publications comfortably outperform the UK average and it is not uncommon for selected ISIS publications to achieve several hundred citations within a

[3] "Our plan for growth: science and innovation", HM Treasury and the Department for Business, Innovation and Skills, (2014)
[4] This is the estimated cost of totally rebuilding ISIS

three-year window. Academics using ISIS have produced more than 10,000 publications and our study has shown that research undertaken on the facility is world-class. ISIS allows scientists to work on the frontiers of biomedical research, chemistry, pharmaceuticals and fundamental biochemistry, for applications including clean energy, the environment, nanotechnology and materials engineering. For example, developing a new method of cleft palate treatment, or identifying better solutions for waste water treatment.

- **ISIS is an internationally recognized facility, attracting researchers from across the globe.** ISIS is renowned for the quality of its instruments, with its tradition of innovation and leadership in technical developments. The first facility of its kind in the world, ISIS has played a critical role in demonstrating the feasibility and benefits of spallation sources. This has helped to secure ISIS's highly regarded international reputation; its work has also changed the global landscape and opened up fresh opportunities internationally, with a number of neutron sources (such as the Spallation Neutron Source in the US, J-PARC in Japan and the European Spallation Source (ESS) currently being built in Sweden) that are based on ISIS developments.

- **The facility has long-established industrial links with more than 100 companies** including household names such as Rolls-Royce, Unilever, Airbus and BP. Over the past 30 years, UK and global industries have benefited through interactions with ISIS supporting advances in a wide range of products. Industrial products developed have included catalysts, aeroplane components, shampoos and lubricants to name but a few. For example, Unilever has developed personal care products, and UK start-up Orla Protein Technologies has developed new health diagnostics devices.

- **ISIS creates innovation impacts.** UK industry also benefits from being awarded contracts for the construction, maintenance and development of ISIS, benefiting sales, reputation and productivity. ISIS users and staff have also generated intellectual property including spin-outs, patents and licences. ISIS plays an important part in the local economy and is central to the success and attractiveness of the Harwell Campus.

- **ISIS nurtures scientific talent in the UK.** ISIS provides `on-the-job' training to 500-800 early career researchers each year, who go on to work in academia and industry. A large majority of ISIS users also consider that ISIS has helped them to make a significant contribution within their field, as well has having had a strongly positive impact on the skills of their research teams and their international reputation.

- **ISIS provides valuable skills to Industry.** Industry recruits staff with specialist skills developed from ISIS and also benefits directly from knowledge-exchange and collaboration activities. For example, the Siemens ONIAC (ONIon ACcelerator) facility was a collaborative programme with ISIS which aimed to test accelerators for medical isotope production.

ISIS has created substantial long-term impact. From the original vision over 30 years ago, ISIS has become one of the UK's major scientific achievements. As the world's leading pulsed neutron and muon source, ISIS has changed the way the world views neutron scattering and has delivered major social and economic benefit for the UK and global economies. Our study has backed up the findings of the 2013 international peer review of ISIS which stated:

"ISIS operations are providing an excellent capability to the user community, and are certainly world-class. ISIS has, since its creation, been able to create a culture of innovation that has had profound impact on, and will continue to change, the way neutron scattering is performed world-wide. Very

few research institutions have demonstrated similar drives toward innovation and spread of the resulting technological development."

2. Introduction

This ISIS Lifetime Impact Study was produced in collaboration with the evaluation team at STFC over the period January to October 2014.

In this report we explore the impact of the ISIS pulsed neutron and muon source facility over its lifetime and into the future to 2030. We detail the spectrum of impacts realized across ISIS, quantifying those benefits where possible, and summarising the overall impact. We provide both quantitative and qualitative evidence that demonstrates the wide range of impacts that ISIS has made possible over its lifetime.

In this report, we summarise our key findings under the STFC strategic themes of **Research, Innovation** and **Skills,** followed by sections on the **Economic Analysis** and the **Methodology** used. The ISIS Lifetime Impact Study Volume 2 contains the Appendices and includes further information on particular sections including, for example, bibliometrics, survey results and case study material. Where additional information is available, it is highlighted throughout this report.

2.1 Introduction to STFC

STFC's vision is to maximise the impact of its knowledge, skills, facilities and resources for the benefit of the United Kingdom and its people. In 2010[5], STFC set out its 10-year strategy to deliver this vision, through three strategic goals of delivering **world-class research**, **world-class innovation** and **world-class skills**.

STFC collaborates with industry and its long-term R&D underpins sectors which contribute to the UK economy in sectors including: space, pharmaceuticals, digital animation and communication, microelectronics and physics-based manufacturing. STFC is uniquely equipped to play an important part in supporting the UK's knowledge economy, creating jobs and generating growth by:

1. Supporting cutting-edge research with university partners, investing in world-leading research in particle physics, astronomy and nuclear physics.
2. Building and providing access to large-scale scientific facilities, fully exploiting opportunities and engaging in a wide range of discovery science.
3. Supporting businesses, promoting academic and industrial collaboration through all their programmes.

2.2 Introduction to ISIS

The ISIS pulsed neutron and muon source is part of the Rutherford Appleton Laboratory (RAL), which is at the centre of Harwell Oxford, one of the UK's science and innovation campuses. Owned and operated by STFC, ISIS is a world-leading international facility for research in the physical and life sciences.

The ISIS facility was developed at the RAL over 30 years ago, with the project being approved in 1977 and officially inaugurated in 1985. ISIS was originally expected to have an operational life of some 20 years (1985-2005), but its evident success led to further investment and a process of ongoing refurbishment. In 2015, it was announced that £150 million would be made available for the addition of a second target station (TS2), and a further seven beam lines (TS2 Phase 1). This, with the

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[5] To be updated in 2016

further expansion of TS2 in Phase 2, is intended to extend the life of ISIS for a further 20 years, through to 2025.

The ISIS facility produces beams of neutrons and muons that allow scientists to study materials at the atomic level using a suite of custom-designed instruments and analysis tools. It currently has a staff of around 370 people and hosts around 1,500 scientific visitors each year, carrying out more than 700 experiments entailing more than 3,000 user days annually. For more information on ISIS, including its history, usage and instruments, see Volume 2, Appendix A, The ISIS neutron and muon source.

2.3 Conceptual framework

Large research facilities such as ISIS make possible many different kinds of social and economic impact, both direct and indirect. The most extensive and important ***direct*** benefits include:

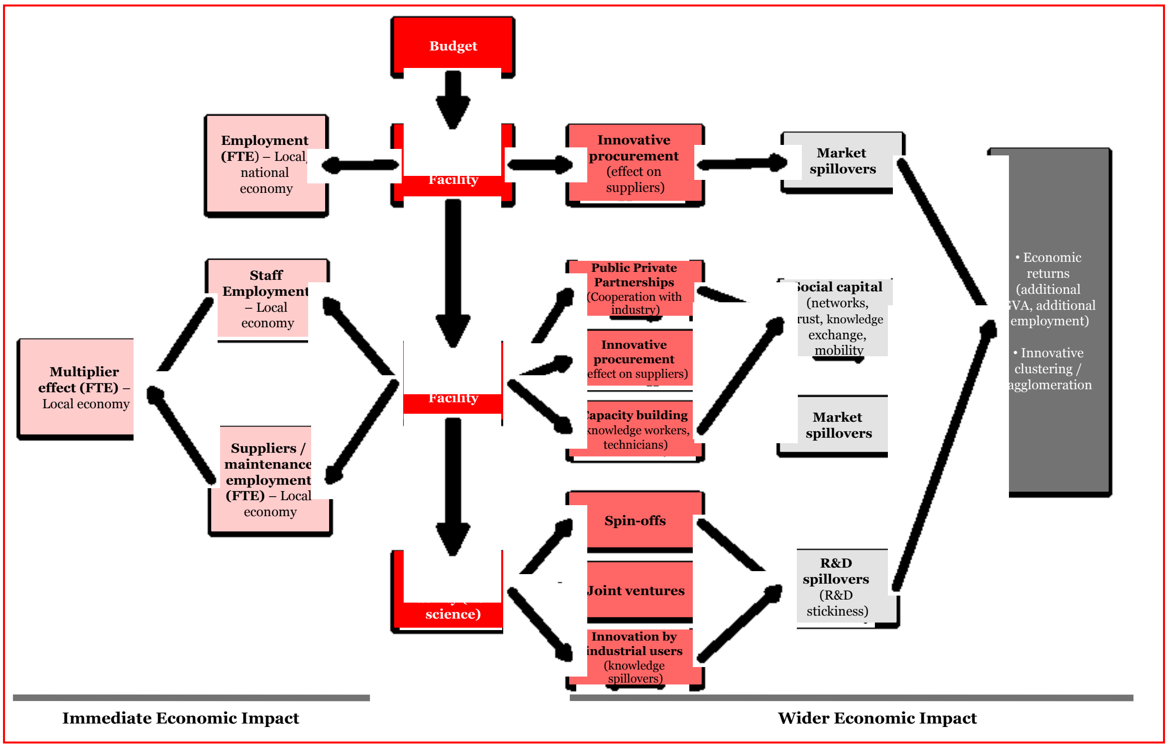
1. The advances in understanding that derive from the many thousands of scientific experiments made possible by the facility over its lifetime.
2. The scientific knowledge and technical developments in instrumentation established at ISIS that allows new research questions to be posed or existing research questions to be looked at in novel ways.
3. The wider developments in a facility's technologies and systems – from its detectors to analytical software tools that also improve the power of the science as well as deliver productivity gains (for researchers).
4. The industrial users who may either compete or pay for access to the facility to run more applied research or to work alongside academics on more fundamental use-oriented studies; in both cases, big facilities can deliver useful advances in know-how and technology.
5. The experimental skills developed on the facility by research students, post-docs and industrial users who go on to work as facilities scientists, academics and industrial engineers, amongst other things.

The ***indirect*** effects include the wider impacts of the knowledge and technology that derive from the experiments and measurements, which can take many forms in their own right, including:

1. From profound changes in the way we understand the world to new products or services built on technological insights.
2. Financial and technological benefits that arise from designing, building and operating these facilities, when first built as well as over successive generations of upgrades and expansions, and decommissioning.
3. The major market created for the global scientific instrumentation sector and the important niche markets created for suppliers of even quite generic products and services – demanding a level of precision and quality which is much more exacting than the majority of segments and which can provide positive spill-overs in reputation, processes and quality overall.
4. The impact on local innovation ecosystems and the regional science-based clusters.

Figure 2 presents a schematic of the kinds of social and economic impacts we believe can arise from investment in a large facility such as ISIS, and which we have used to organise our impact methodology.

Figure 2: Social and economic impacts flowing from large research infrastructures



Source: Technopolis (2014). Adapted from Big Science and Innovation (Technopolis, 2013)

For more information on the conceptual framework, see Volume 2, Appendix B, Conceptual Framework.

2.4 Overall approach

In this study, we have estimated the **immediate economic impact** of ISIS over the past 30 years, and also characterised the **wider economic impacts** amongst industry users and suppliers (as shown in the flow diagram above). To do this we have taken a broad approach, comprising in-depth research on the ISIS facility and its resultant social and economic impacts using both primary and secondary data gathered from a variety of sources. The methodology being employed involved close collaborative efforts by the study team at Technopolis and STFC / ISIS throughout. The programme of work included:

- An historical analysis
- The development of an analytical framework
- The compilation of the relevant financials
- A series of online surveys of university academics, companies and suppliers who use or work with ISIS
- Case study development highlighting key examples from a substantial archive of information from ISIS
- A bibliometric analysis

To better assess the wider economic impact we have gone beyond conventional approaches. In particular, in the research section, we have used 10 Extended Impact case studies to estimate the wider economic benefits attributable to ISIS research; and in the innovation section, we have taken advantage of companies' own estimates of value through proposals to the new Industry Collaborative Research and Development (ICRD) programme. This has provided the most comprehensive basis for estimating likely future benefits. It has also provided a means by which to extrapolate the likely impact of ISIS research and innovation over the facility's lifetime.

2.5 Challenges

Research impact assessment is widely understood to be a challenging field of social science research. The measurement challenge is all the more difficult when the question relates to research infrastructure which underpins thousands of experiments conducted by tens of thousands of scientists and engineers in universities, institutes and businesses throughout the UK and around the world. To enable us to carry out this study, we have taken a variety of approaches throughout this report. It is worth noting upfront that:

- We have been conservative in our estimation of likely impacts and our attribution of a share of those benefits to ISIS, in recognition of the high levels of uncertainty as regards the scale and duration of wider impacts, the scale and duration of any displacement or crowding out and the difficulty in determining a fair attribution for ISIS.

- Case studies remain the best means we have for tracing and estimating the social and economic impact of research. Grossing up individual cases remains somewhat problematic, but we feel confident in this study that we were able to come forward with a reasonable estimate using ISIS's case study archive. However, assessing case studies is a laborious and costly process, and it was thus outside the remit of this study to include any specific analysis on numerous examples of economic impact beyond the ten extended case studies.

- With no electronic record-keeping in the early days of ISIS operations, together with an historical UK culture where 'impacts' were not analysed or recorded, there will always be an issue as regards timing. Our primary research has produced wide-ranging evidence of substantial anticipated future benefits, but far less extensive / fewer data about past benefits. Therefore, in order to make estimations, we have often been forward-looking, with an informed extrapolation back.

- The intangible nature of many of the benefits means phenomena are quantifiable but are not necessarily monetisable and therefore cannot be aggregated. This is the area where we have found no agreeable solution, and have had to revert to a pragmatic presentation of immediate economic impacts and otherwise rely on a very much more qualitative overview of the many and various benefits delivered by ISIS over the past 30 years.

- Our Academic, Industrial and Supplier surveys provided valuable feedback but were variable in their response rates and in some cases fell somewhat short of a comprehensive response and, as a result, did not provide a statistically robust platform. This left the team with a tantalising glimpse of some really quite striking impacts, but with the small number of responses it was simply unreasonable to seek to generalise from the few to the many.

For more information on the challenges and our recommendations, see section 7, Methodology.

3. Impact from ISIS Research

3.1 Introduction

ISIS is a world-class scientific facility that has underpinned fundamental research in numerous fields throughout its lifetime, and has provided the platform for wide-ranging advances in our understanding of the world. In this section we explore the impact ISIS has had over its lifetime on research in the UK and, where it is possible to undertake an analysis, how research can lead to economic impact. From this, our main conclusions are:

1. **The economic and social benefits of ISIS research are wide ranging.** ISIS plays an integral role in advancing research in many areas and underpins a significant fraction of all science. ISIS research plays a key role in supporting all the 'big opportunities' (such as new technologies, advanced manufacturing and materials engineering) as well as contributing to the 'big challenges' we face (such as energy generation, antibiotic resistance and global warming).
2. **ISIS has played an essential and major role in global research endeavours that have and could have significant impacts world-wide.** The impact of these areas of long-term, fundamental research, are hard to quantify but have the potential to revolutionise technology and bring significant impact to global economies.
3. **ISIS research has and will continue to produce significant economic impact for the UK.** We conservatively estimate ISIS research has likely delivered a wider economic impact of around £340 million over the lifetime of the facility (1985-2013) and research already completed will deliver a future benefit of £140 million (up to 2025), totalling at least £480 million.
4. **ISIS publications outperform the UK average**. Analysis of ISIS's most-cited articles suggests it is not uncommon for selected ISIS publications to achieve several 100 citations within a three-year window.
5. **ISIS is critical to academic excellence and UK research quality.** The results of the academic user survey are conclusive and emphatically positive, with the majority of academic users rating ISIS as having been critical to their scientific understanding, research quality and experiment skills and that of the UK research field as a whole.
6. **Since its inception, ISIS has had an innovative approach to instrument design and technology development.** Without the existence of ISIS, numerous research applications and new technologies may have gone unexplored both in the UK and internationally.
7. **ISIS has been essential for the UK's international reputation.** Some 95% of academic users in our survey state that ISIS has played a significant role in the UK's international reputation. International collaborations and investment are significant; currently (2014) ISIS has 26 live international agreements across 12 countries and has received at least £56 million in international contributions over its lifetime.

3.2 Discussion

*3.2.1 **The economic and social benefits of ISIS research are wide-ranging***

Large research facilities such as ISIS are, as their collective name suggests, universal supports that underpin a significant fraction of all science. ISIS is not only providing significant economic and societal benefit to the UK through its research portfolio, but the breadth of research that ISIS supports has expanded rapidly over the past 30 years. ISIS has pushed forward the frontiers of knowledge in multiple fields, from advanced materials to biochemistry. It supports a national and international community of several thousand scientists from academia and industry, who use neutrons and muons for research in physics, chemistry, materials science, geology, engineering, biology and other fields. ISIS plays an integral role in advancing fundamental research in many areas and as a consequence the economic and social benefits of ISIS research are wide-ranging.

Case studies

The study team compiled several hundred examples of research or innovation outcomes from ISIS annual reports and case studies. To further illustrate both useful advances in knowledge and potential future applications in the UK's 'grand challenge' areas, such as energy generation and storage, the environment and human health, we have summarised 12 case study examples below. For more detail on each case study see Volume 2, Appendix C, Examples of academic and industrial impact.

The Environment

- **Landfill and water pollution:** There are several thousand landfill sites in the UK alone, handling millions of tonnes of waste annually. The potential contamination of groundwater and watercourses by toxic chemicals leaching from these sites poses a significant threat to public health. Research at ISIS is helping to understand this process and support the development of methods to safely contain waste leachate.
- **Nanoparticle pollution:** Nanoparticles are widely used in cosmetics and pharmaceutical products. These are routinely released into wastewaters through drains but there is currently no efficient way to remove them during sewage treatment. Research at ISIS is supporting the potential development of a sewage treatment process and is helping develop new environmental legislation to safeguard aquatic ecosystems and water supplies.
- **Atmospheric pollutants and climate change:** Whether or not a cloud releases rain can be affected by particles of material in the atmosphere and these affects are causing uncertainty in climate models. Researchers have used ISIS to understand the chemistry of the atmosphere and the work has provided an important discovery in the understanding of cloud chemistry, helping to improve climate modelling and weather prediction.

Energy generation and storage

- **Green solvents and oil recovery:** Carbon dioxide in its liquid form can act as an efficient, cheap, non-toxic and non-flammable medium for processing foods, drugs and chemicals, and is also being used increasingly to replace common petrochemical solvents. Research at ISIS has been looking at carbon dioxide solvents to improve their performance and has contributed towards the development of a new solvent (TC14) which can be used for enhanced oil recovery.
- **Printable solar cells:** The solar installation market is worth around £72 billion[6] world-wide. Several different strands of research relating to the development of thin film solar cells have been undertaken over the last ten years at ISIS. The most recent research, in collaboration with UK spin-out Ossila, has explored the development of polymer (thin film) solar cells, making the components more efficient and thus more competitive. Ossila has now (2014) secured funding to develop polymer technology for eventual use in devices such as thin-film solar cells, light-emitting diodes and low-cost printed electronics.
- **Nuclear waste:** Biominerals are particularly suitable for nuclear waste remediation and storage. Researchers used ISIS to better understand this mineral, which is produced from bacteria. Researchers are now working with the Japanese Atomic Energy Agency (JAEA) to develop a new method of decontaminating soils using biominerals.

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[6] Converted from $ to £ on 05/02/2015 using www.xe.com. Source Technopolis

Medical advances

- **Drug delivery:** An important research area for the global drug delivery industry (currently worth around £80 billion) is the development of new methods of administering medicine. One option is the use of nanostructured materials but scientists first need to learn more about these materials before they can be deployed safely and effectively. Researchers have used ISIS over many years to explore nanostructured materials with a range of applications including, for example, in-vivo drug release (a method now the subject to a patent application) and drug delivery for treatment of heart disease.
- **Lung health:** Inadequate surfactants and mucus in the lungs can cause many respiratory diseases. Surfactants are essential for the exchange of oxygen and CO_2 and form a protective barrier that traps dust and other particles. Researchers are using ISIS to better understand the chemistry of this layer, which will help to improve medical treatments and develop more effective inhaled drugs.
- **Tackling antimicrobial resistance:** Pathogens such as bacteria and fungi constantly evolve to keep the upper hand in the face of the antibiotics used against them. Researchers used ISIS to better understand the origin, spread, evolution and development of resistance, which will facilitate the rational understanding and design of new antibiotics. For example, researchers have used ISIS to determine precisely how penicillin and the antibiotic, colicin, interact and kill bacteria, aiding in the development of effective novel drugs.

Engineering and materials

- **New materials for sensor technology:** Researchers used ISIS to characterise piezoelectric materials that can operate in high temperatures, high pressures, under extreme shocks and high stress. This allows these high-performance materials to be used in sensors, actuators and transducers in extreme environments. The research led to a UK spin-out, Ionix Advanced Technologies. Initial target markets for these high-temperature devices include industrial plant processes, aerospace, oil and gas, and nuclear power, representing a total market potential in excess of £500 million per annum.
- **The effects of glass corrosion:** Glass corrosion from moisture can lead to the poor adhesion and performance of coatings. Researchers used ISIS to better understand this process and found that water could penetrate deep into glass, even in specially coated windows (such as in aircraft). These results offer valuable input for future improvements in glass and there is now (2014) significant industry interest in using these results to develop new products and techniques.
- **Bio-active glass bone replacement:** Bioactive glasses are of great interest for medicine, potentially replacing current implant materials used in the repair and replacement of diseased or damaged bones. Researchers used ISIS to develop and investigate the properties and reactions of Bioglass. This has helped in the development of mechanically stronger joint replacements, and clinical trials are expected shortly.

A case study on Engin-X is also particularly relevant here, see section 3.2.6. A wider variety of case studies are also available on the ISIS website.

3.2.2 *ISIS has played an essential and major role in global research endeavours that have and could have significant impacts world-wide*

ISIS advances fundamental research by means of its world-leading instruments. Research has looked at many areas ranging from quantum magnetism and superconductivity to the behaviour of surfactants and the mapping of residual stresses in materials. These fields are major, long-term and fundamental global areas of research in which ISIS plays a key role. Some examples of how ISIS has supported particular research fields over the longer term are given below:

- ***ISIS has played a important role in research on Magnetism; the use of magnets is essential for modern society and research is driving the development of new technologies***

  ISIS has enabled a wide variety of studies of magnetic materials since it opened in 1985. From electric motors to computer hard disks, we rely on magnetic materials to underpin much of modern technology. Magnetic devices, such as the light switch, electric motors, computers and even MRI scanners, are now so deeply integrated into everyday life that we take most of them for granted. The world-wide market for permanent magnets alone reached £7.5 billion in 2013 and is expected to grow to £10 billion by 2018[7]. Research on magnetism continues to be globally important, and is a key area of long-term and fundamental research at ISIS. A better understanding of magnetism will drive the creation of essential new materials and products, such as advanced applications in energy management, memory storage, and multifunctional devices. It also holds the potential to reduce the global demand for rare-earth elements that is currently outstripping supply[8].

  Research on magnetism is also very important for the development of theories on the main principles that govern physics. ISIS plays a significant role in continuing global efforts to understand these principles, with neutrons and muons being used to investigate a broad range of topics in magnetism, thereby facilitating discoveries of both theoretical and practical significance. Research at ISIS has also influenced other international facilities. Through improved detector technology and techniques, and the coupling of computer power and advanced visualisation software, instruments pioneered at ISIS have revolutionised the measurement of magnetism. The MAPS instrument, in particular, has been the template for a dozen or more instruments in facilities across the globe. See section 3.2.6 for more information on MAPS.

- ***Superconductivity research has had global impact, such as the development of the MRI scanner, but its future potential is even more significant***

  ISIS has played an important role in understanding superconductivity, providing the state-of-art instruments and the expertise necessary to support this important field of research. Superconductors are materials (such as aluminium and tin) that exhibit no electrical resistance below a certain critical temperature. This property leads to use in a number of

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[7] `Permanent Magnets – Types, applications, new developments, industry structure and global markets'. Innovative Research and Products (iRAP), Inc. Apr 2014. https://www.reportbuyer.com/product/2083787/permanent-magnets-types-applications-new-developments-industry-structure-and-global-markets.html#utm_source=prnewswire accessed 05/05/2015

[8] `Perspectives on Permanent Magnetic Materials for Energy Conversion and Power Generation'. http://rd.springer.com/article/10.1007/s11661-012-1278-2 accessed 05/05/2014

current industrial applications, including, for example, MRI scanners. According to estimates, the global market for MRI systems was worth around £4.3 billion in 2010, and is expected to grow to around £6.2 billion by 2015, equivalent to an annual growth of 7.7% a year[ii]. The MRI industry also supported 2,200 UK jobs in 2010[9]. Since it opened in 1986, ISIS has determined the structure of numerous superconductors and measured their properties. For example, the detailed crystal structure of the first high-temperature superconductor was successfully determined at ISIS in 1985, and ISIS has provided direct evidence of the strong connection between magnetism and superconductivity, which has helped refine theories about these important materials.

However, whilst conventional superconductors have been proven to have some important uses such as the MRI scanners, their wider application has been limited by the critical temperatures required and the expensive liquid helium needed to cool them sufficiently. There is, therefore, a global scientific effort to better understand unconventional or high-temperature superconductors which do not have these restrictions. ISIS has played and continues to play a key role in this research. The applications for high-temperature superconducting technologies are wide-ranging and may be used to overcome numerous global challenges. Promising technologies include high-performance smart grids, transformers, power storage devices, improved electric power transmission, advanced electric motors and magnetic levitation devices, to name a few.

- ***ISIS determined the unique structure of 'bucky balls', a new type of carbon, which has now created a global market expected to be worth £3 billion by 2015***

The crystal structure of C_{60}, the novel football-shaped form of carbon, also known as bucky balls, was first discovered in 1985 by researchers, Robert F. Curl, Harold W. Kroto and Richard E. Smalley. However, their initial discovery was not fully accepted until the early 1990s, when a method for producing bucky balls was discovered and their crystal structure was determined at ISIS by diffraction experiments. Bucky balls are now recognized as one example of a group of spherical and tube-like carbon forms called fullerenes. This created an entirely new branch of chemistry, with consequences in such diverse areas as astrochemistry, superconductivity and materials chemistry/physics. The journal `Fullerenes, Nanotubes and Carbon Nanostructures', dedicated to fullerenes, launched in 1993[10], and within just three years of their discovery, scientists had filed nearly 300 applications for new patent families relating to fullerenes with thousands more patents following[11].

Researchers call the 1985 discovery of bucky balls a once-in-a-lifetime breakthrough and, from the 1990s onwards, fullerenes have been investigated at ISIS to determine the structure and properties of these important forms of carbon. Currently, fullerenes are being utilised in high-performance lubricants, innovative fuels, new classes of superconductors and magnets, and polymers designed for data recording and storage. The global fullerene market posted total revenues of £200 million in 2008, a figure that is expected to rise to £3

9 Global market for MRI systems to grow to $9.7 billion by 2015. BCC Research Market Forecasting. Aug 2010. Estimates translated from $US terms to £ by Oxford Economics.

10 http://www.tandfonline.com/loi/lfnn19#.VR0R57FwaUk

11 European Patent Office. https://www.epo.org/learning-events/european-inventor/finalists/2010/kraetschmer.html

billion in 2015[12]. New products are also expected to be developed including lubricants slicker than Teflon, improved batteries and a new rocket fuel. The ability of fullerenes to become superconductors is only one reason their commercial uses could be substantial. They could also be the building blocks for a new generation of high-speed computers based on light waves instead of electricity, and for innovative telecommunications systems[13]. Researchers also hope to encapsulate drugs for cancer treatments and other therapies to preserve the drugs until they reach the intended parts of the body. For this work, in which ISIS's research played an important role, Robert F. Curl, Harold W. Kroto and Richard E. Smalley were awarded the 1996 Nobel Prize in Chemistry[14].

- ***ISIS research created a new approach to surfactant research, which has been and continues to be essential for industrial applications***

  Surfactants can be found blended with a range of ingredients in home and personal care products (e.g. detergents, shampoos, cosmetics, etc.), adhesives, coatings, drug delivery systems and pesticides. Their structure gives rise to a wide range of surface chemistry functions, which provide opportunities for improved materials and potentially a wider range of uses.

  Professor Jeff Penfold from ISIS, in a long-term collaboration with the University of Oxford and Unilever, has carried out research that provided new understanding in this field and provided new techniques to study surfactants, polymers and proteins at different interfaces. The partnership between ISIS and Oxford dates back to 1990 and has led to the development of major experimental techniques and the production of over 400 publications. These types of measurements were only possible at ISIS, and now the instruments in the second ISIS target station provide an even larger spectrum of opportunities for soft matter studies, many of which are industrially relevant.

- ***ISIS has led the way in the study of water, research that will have wide-ranging applications***

  Over the past 25 years, research at ISIS employing neutron scattering techniques coupled with computer simulation has made major contributions to the understanding of water structure. Much of this research has been driven by ISIS senior scientist and STFC Fellow Dr Alan Soper. In recognition of his contributions, Dr Soper was elected as a Fellow of the Royal Society in 2014 for leading research on the structure of water and for developing instruments, techniques and software that have revolutionised the field. Below are some examples on the applications of this research:

  - **The Environmen**t: More than 99% of water found on Earth is not 'pure' and instead contains significant quantities of dissolved salt. Research in this area at ISIS has implications for the development of new, environmentally friendly solvents.

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[12] European patent office. https://www.epo.org/learning-events/european-inventor/finalists/2010/kraetschmer.html. Converted to £ from www.xe.com 05/05/2015

[13] http://www.nytimes.com/1991/08/26/business/stampeding-a-molecule-to-market.html?pagewanted=1

[14] http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1996/press.html

- **Biology:** The central and peripheral nervous systems uses synaptic fluid. Neutron diffraction at ISIS has been used to investigate this area and research findings have yielded structural details important for biological and medical research.
- **Chemical manufacture:** A large number of commodities and industrial chemicals are currently obtained by catalytic synthetic processes. Researchers at ISIS are using neutron diffraction to study the internal reactions and mechanisms of how water interacts with catalysts. The research findings now serve as the basis for further catalyst development.

3.2.3 ***ISIS research has produced and will continue to produce significant economic impact for the UK***

In order to get a better sense of the scale of the wider economic impacts (spill-overs) associated with ISIS's many scientific achievements, the study team has looked in depth at a series of ten case study examples where advances in understanding made possible by ISIS are supporting technological innovation and commercial deployment beyond that. The numbers presented here are a conservative estimate of the impact of ISIS, in particular because of gaps in historical impact data as well as the impossibility of researching all impact case studies fully for a report such as this (with time and cost parameters).

However, taken together, these 10 case studies suggest that ISIS research will underpin a substantial increase in national economic activity over the next ten years (2015-2025). Using rather conservative multipliers (1-5%), we feel confident that ISIS should claim several millions of pounds sterling for that increased economic activity in every case. The summary of each case study details the estimated economic impact and what proportion of this impact we conservatively estimate should be attributed to ISIS research. This is followed by our economic analysis, which uses the insight gained from these case studies and ISIS's archive of material, to estimate the impact ISIS has had over its lifetime and will likely have to 2025. See Volume 2, Appendix D, Economic impact of ISIS research, for the full analysis and more information on each case study.

Case study 1: Improved orthopaedic implants could save NHS £200 million and support £20 million in additional UK sales to 2025

The global orthopaedic devices industry was worth an estimated £17 billion in 2012. However, its products still suffer from relatively high failure rates (around 18%).

Researchers used ISIS to study the effects of different treatment techniques and created a modelling system that, if widely adopted, could save the UK NHS more than £20 million a year by 2020 (up to £200 million in total between 2015-2025). There would be substantial quality-of-life improvements, too, for the thousands of people with implants who would no longer need to have repeat surgery.

We elected to 'claim' 5% of those savings for ISIS, or £10 million, due to the critical contribution of neutron scattering. The UK market share of NHS implants is perhaps 10% of a market worth £500 million a year and it could easily increase to £750 million by 2020. With as much as £20 million in additional sales between 2015 and 2025, we elected to 'claim' 5% of this projected additional economic activity for ISIS.

ISIS has also contributed to the creation of new, more durable, bioactive implant coatings, as well as an associated patent application that has strengthened the technology portfolio of a UK-based spin-out company, Taragenyx. According to Companies House, the company had an asset value of around £0.5 million at the end of 2013/14.

Type	Total	Attribution to ISIS	ISIS benefits
Savings for NHS	£200 million up to 2025	5%	£10 million
Additional economic activity in UK	£20 million up to 2025	5%	£1 million

Case study 2: Advances in spintronic materials could revolutionise a globally important industry that could be worth at least £100 million to the UK economy up to 2025

The ISIS WISH instrument is being used to characterise and design novel antiferromagnetic (AF) materials for application in computer storage, which could revolutionise the speed and environmental performance of electronic devices globally. A research team from the University of Nottingham working in collaboration with the Institute of Physics and Charles University in Prague, the University of California Berkeley, Universidad Complutense de Madrid, Oak Ridge National Laboratory, STFC and Hitachi Cambridge has been investigating new materials which could increase computing speed, efficiency and memory capacity. ISIS research with the University of Nottingham is a stepping stone towards functional antiferromagnetic spintronics (AF). This is a new material that is attracting a large and growing area of physics research and has applications in fields including mobile phones, healthcare, automation, IT and automotive industries.

> *"The field of AF spintronics is very active at present and the development of room-temperature working AF devices could bring about not only an increase in speed and efficiency of computing systems but also a change in the fundamental architecture of computing leading to further gains. The potential commercial impact of spintronic devices cannot be overstated, and the role for AF materials within this new field could be very significant."* Dr Peter Wadley, University of Nottingham

Assuming that there will be new IP and start-ups linked with UK research, future sales (turnover, royalties, shares) are likely to run into the tens of millions, given the critical role these technologies could play in what is an enormous and rapidly growing market globally. ISIS's contribution is hard to determine, as there is a very substantial research effort under way internationally and many other neutron sources and other large research facilities (e.g. Diamond) are actively involved. However, if we assume the UK may see up to £100 million in income of one kind or another related to AF spintronics over the next 10 years, it is arguably reasonable to claim perhaps £5 million of that new economic activity as being attributable to ISIS, which has had a long-term influence on this developing field. The global industry will derive substantially larger benefits from ISIS's work.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity in UK	£100 million up to 2025	5%	£5 million

Case study 3:UK spin-outs are developing spider silk worth a potential £150 million to the UK economy to 2025

Spider silk is light, thin, flexible and strong. The production of a synthetic version of spider silk in commercial quantities could have a wide range of potential uses in military, industrial and consumer applications. A team of researchers from the Oxford Silk Group (University of Oxford) have been using ISIS over the past decade and this has increased understanding of the complicated silk spinning process, which is of fundamental importance for future applications.

The Oxford Silk Group recently created a company, Oxford Biomaterials Ltd (OBM), to develop silk technologies for commercial application. According to Companies House, OBM has an asset value of nearly £0.5 million. It has also spun out a further two companies: Neurotex Ltd and Orthox Ltd.

Both Orthox and Neurotex technologies show great promise in early trials, and should soon (as of 2014) enter full clinical trials. We estimate a £50-60 million annual economic output for Spidrex® products by 2020, perhaps £150 million through to 2025. We have elected to attribute 2% of this figure to ISIS (£3M) because of the long-term use of the facility by the Silk Group that has helped establish these companies.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£150 million to 2025	2%	£3 million

Case study 4: Patented technology helps meet the UK's greenhouse gas emission targets and grow a market worth a potential £3 billion a year to UK business by 2030

Currently, the major source of emissions in the UK is power stations, which generate over a quarter of CO_2 emissions (145 Mt of 464 Mt in 2013). If the UK is to meet its legally binding targets to reduce emissions, it will need to achieve near-zero emissions from its power stations by 2030. Carbon capture and storage (CCS) is seen as a cost-effective and affordable way to help countries to secure low carbon energy supplies. However, several challenges must be overcome before CCS can be deployed on a large scale.

Failure to deliver CCS as a key mechanism for cutting carbon emissions will have profound implications for the UK economy. Estimates show that the costs of a low-carbon energy mix in 2050 could be around £30 billion (1% of GDP) per year higher without CCS and possibly £10 billion by 2025. World-wide up to £25 billion has already been committed by governments to support CCS projects. There is a potential market worth over £100 billion per year from 2020, in particular in the US, China, India and other coal- and gas-dependent nations. This offers substantial export opportunities for UK businesses. It has been estimated, that if CCS opportunities develop as anticipated internationally, UK-based engineering and manufacturing firms could benefit from additional income of more than £3 billion a year by 2030.

The University of Nottingham has developed and patented[15] NOTT-300, which adsorbs large amounts of CO_2 and other acidic gases. The structure of NOTT-300 was determined from data gathered at ISIS. NOTT-300 is cheaper and more efficient than existing materials at capturing polluting gases from flue gas and could lead to innovative technologies to tackle global warming. Work at Nottingham and elsewhere may help this huge global market become a reality earlier, and generate additional income for the UK specialty chemicals sector. Materials like NOTT-300 might ultimately be addressing a global market valued in the hundreds of millions sterling annually, perhaps £2 billion in total through to 2025.

[15] Covered in patent application UK 1205365.8 and published in `Nature Chemistry', 2012, 4, 887–894

If UK companies can maintain a 10% share of the global market, NOTT-300 could yield £200 million in additional economic activity for the UK through to 2025, as well as royalties for the University of Nottingham. Given the critical role played by ISIS in the design of NOTT-300, we believe it is reasonable to claim a conservative multiplier of 1% applied to the anticipated £200 million in net additional income to the UK economy through to 2025.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£200 million to 2025	1%	£1 million

Case study 5: Reducing damage accumulation in train wheels, worth £50 million in savings to the UK economy by 2025

The UK passenger rail industry currently replaces approximately 20,000 wheelsets every year, at a typical cost of £6,000 each (including purchase, fitting, etc.). Wheel-tread damage is often the dominant factor controlling wheel life, so even a modest 10% life extension to wheelsets could bring savings to the UK rail industry worth £12 million annually. A recent US rail research presentation[16] estimated the annual costs globally at around £460 million.

Research is being carried out by the University of Huddersfield, the Institute of Railway Research (IRR), Siemens (train manufacturer), Lucchini UK (wheel manufacturer) and ISIS to investigate how the residual stresses change through the life of the wheels. The ISIS ENGIN-X instrument is one of the few facilities world-wide capable of measuring stresses in such large and heavy samples. A better understanding of the triggers of residual stress should lead to further optimisation of wheel maintenance, and might justify the use of different (more costly) materials or a smaller minimum wheel diameter. It could also identify opportunities for changes to wheelset manufacturing processes or materials to further improve through-life performance.

Overall we would expect this ongoing research involving ISIS to lead to practical changes in design, which should begin to be implemented in the next few years, and could give an average 20% extension to the average life of a wheelset. We estimate there could be as much as £50 million in savings to the UK economy by 2025. It may also reduce imports, with a reduction in the numbers of wheelsets being purchased from predominantly overseas manufacturers.

International research is feeding into design and operating principles, so while the neutron diffraction experiments have provided unique insight into the failure modes, the practical response to that research is broadly based. For this reason, we elected to allocate 1% of those benefits to ISIS.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£50 million to 2025	1%	£0.5 million

[16] Scott Cummings from the TTCI research centre in the US estimated that wheel damage globally was costing around $675 milion for wheelset replacement and a further $35 million a year relating to derailments and slowdowns. These figures were set out in a presentation given to the 18th AAR Annual Review Conference, hosted by the Transportation Technology Center, Inc. (TTCI is the research and testing centre of the Association of American Railroads). Converted to £ at www.xe.xom accessed 05/05/2015

Case study 6: UK spin-out created with new hydrogel worth an estimated £50 million to the UK economy

Cleft palates are the most common birth defect in Britain, with one in every 700 babies affected. In severe cases, radical surgery is required, taking up to 10 expensive operations to correct the problem, and future complications can occur as the child grows.

A team from the University of Oxford[17] used ISIS to develop an intelligent hydrogel, which encourages skin growth. In early 2011, Oxtex Limited was created as a spin-out to further develop the technology. Within a short period of time, the company attracted over £500,000 of seed funding from investors and won several awards. In 2012, Oxtex secured another £65,000 of funding from Innovate UK to scale up its manufacturing process and have now launched their product range (in 2013) for medical, dental and veterinary use.

Market research data suggests the global market for an intelligent hydrogel for reconstructive surgery could run into the many tens of millions, replacing the use of current devices in more severe cases, but also accelerating growth in the market overall as a result of its greater applicability and improved health outcomes. The future potential for hydrogels must run into the many hundreds of millions globally, within 10-20 years, as they displace older technologies. In the UK, the cumulative value of the market might easily reach £100 million between 2015 and 2025, of which perhaps 50% might be additional and not substituting for existing devices.

Oxtex itself is a small medtech company. However, it is already a well-regarded business with a list of impressive research and trial partners. It seems highly likely the business could attract a trade sale with a price running into the millions, and perhaps as much as £5 million. Given the critical importance of a definitive understanding of the material's properties to the success of the hydrogel, we elected to claim for ISIS 5% of our estimated £5 million company valuation and 2% of our estimate of £50 million in additional economic activity (to 2025).

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£50 million by 2025	2%	£1 million
New business	£5 million in 2015	5%	£0.25 million

Case study 7: Research at ISIS may enable next generation of high-tech displays and touch screens, a market worth an estimated £0.25 billion to the UK economy by 2025

Transparent Conductive Films (TCFs) are used in more than 90% of high-tech displays and touch screens in the electronics industry, with the global TCF market estimated to be worth more than £1.3 billion (2012)[18]. However, this is not an ideal material for touch screen devices and it is expensive to produce. Carbon Nanotubes have been proposed as an ideal alternative but their use has been limited by production and manufacturing methods.

[17] Together with the John Radcliffe Hospital in Oxfordshire, working in collaboration with colleagues from the Georgia Institute of Technology (GIT) in the US

[18] Converted by www.xe.com accessed 05/05/2015

Using ISIS, a new innovative production method was originally developed by the London Centre for Nanotechnology (LCN). ISIS was critical to this research and the findings were very important in the subsequent decision by The Linde Group[19] to commercialise the technology, for which they gained an exclusive licence in 2011. The Linde Group's first nanotube product, SEER^{e-} Ink, was launched in 2013.

This market is likely to grow so vigorously and be so large that there will be good opportunities for businesses in the UK. Capturing even 1% of the global market for novel TCFs could add £50 million a year to the UK economy by 2020, and perhaps as much as £0.25 billion between 2015 and 2025. Taking 1% of that figure to reflect the contributions of ISIS to the development of this novel technology is reasonable, and would give an estimated financial value of £2.5 million.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£0.25 billion by 2025	1%	£2.5 million

Case study 8: ISIS has contributed to world-class research in organic electronics, with a global market value over £13 billion

Organic semiconductors are an important new class of semiconductors, combining the virtues of plastics with the electrical properties of semiconductors, creating the potential for novel low-cost applications (e.g. in solar panels or display screens). The global organic electronics market is around £13 billion (2013), with sales growing strongly over the past five years and forecast to strengthen further, increasing to £60 billion by 2020.

To realise the full potential of organic semiconductors, the fundamental physics of these materials needs to be better understood. ISIS facilities have been used to contribute to world-class research in this field. The UK is among the world's leading players in plastic electronics research, with large, world-leading groups at the University of Cambridge, Imperial College, and activity at ISIS. There is potential for the UK to contribute to the development of the global organic electronics market through research (including the experiments done at ISIS) and there is a great potential for new IP as well as new company creation in the sector. However, translating this academic capacity into new industries and jobs is proving challenging, in large part because of the smallness of the UK industrial base in the area and the dominance of global players in the Far East.

The overall future revenue (licences, funding brought in through new start-ups as well as trade sales, etc.) for the UK (domestic and international) is likely to run into the many tens of millions of pounds, and may be as much as £500 million over the next 10 years through to 2025. We believe ISIS's contributions to our understanding of these materials has been and will continue to be critical and as such believe it is credible to assign to ISIS 1% of our estimated total future economic output for organic semiconductors in the UK and we estimate the value of the contribution of ISIS over the next 10 years may be as much £5 million.

[19] The Linde Group is a Munich headquartered multinational specialised in industrial gases and engineering with more than 60,000 staff in 100 countries. The Linde Group UK is a significant operation and includes much of the former operations of the BOC Group, which Linde acquired in 2006

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity in UK	£500 million up to 2025	1%	£5 million

Case study 9: ISIS enables advances in forensic science which could help reduce the cost of crime, currently more than £124 billion a year in the UK

Fingerprints are unique impressions which, when left on an object or at a crime scene, can link a suspect to the crime. In practice, so-called latent (non-visible) fingermarks are the greatest source of evidence, since they are not visible to the naked eye and therefore commonly left unnoticed by a criminal.

Although research over many decades has resulted in a diverse range of reagents, only approximately 10% of latent fingerprints detected are developed to a level that is considered adequate proof of identity in court. Using ISIS instruments, the University of Leicester has developed a new fluorescence technique to address this important challenge. This has the potential to partially replace conventional fingerprint detection powders, with an estimated annual global market value of around $90 million in 2013. However, it is most likely to be used as a complementary technique for analysis in more difficult cases, so expanding rather than reducing the market value.

The major benefit for the UK would be improved forensics and more effective criminal prosecutions. Crime costs the UK economy more than £124 billion a year, or 7.7% of GDP[20]. If the UK overall could lower its crime rate to match the average level for the South East of England, for homicide and violent crime, the Institute for Economics and Peace estimates there would be an expansion in economic activity for the UK of £23.4 billion up to 2025.

A 1% improvement in the cost-effectiveness of the national criminal justice system would amount to £20 million-plus in direct savings over ten years. If we further assumed a 0.1% reduction in national crime rates attributable to this technique, this would yield a further £23.4 million in savings. The contribution of ISIS to the evolution of the new technique has been reasonably important, and might credibly claim 5% of the anticipated future UK social and economic benefits.

Type	Total	Attribution to ISIS	ISIS benefits
Savings for public sector	£22 million up to 2025	5%	£1.1 million
Reduced crime	£23.4 million up to 2025	5%	£1.2 million

Case study 10: Energy generation – maintaining safety at nuclear power plants

Given the harsh conditions of power plants, coupled with an absolute requirement for safe containment of radioactive material, procedures for assessing the structural integrity of plant components are strictly regulated and nationally codified. A 2001 survey of weld-repair technologies

[20] “The Economic Cost of Violence Containment”, a report written by Institute for Economics and Peace in 2013 [Font]

used by utilities in the US found that 40% of all repairs resulted in subsequent cracking.[21] This led to a programme of investigation involving researchers at the Open University and British Energy (now part of EDF Energy).[22] The researchers used neutron diffraction at ISIS to directly measure residual stress in weld repairs. These were the first measurements of their kind and revealed the surprisingly severe nature of residual stress fields associated with repairs. As a result, EDF launched a multi-million pound programme of weld-modelling development and validation, carried out across the period 2001-2010, to underwrite safety cases for repaired Advanced Gas-cooled Reactors (AGR).

The improved awareness of the risk of weld-induced residual stresses has resulted in the development of new repair procedures that have a very much lower failure rate (validated through experiments at ISIS) and, as a result, the UK regulator is allowing plant owners to extend the lives of these hugely costly pieces of infrastructure through major refurbishment programmes. With each of these reactors generating around £700,000 of electricity per day, these life extensions represent a major contribution to the UK economy, affecting jobs and the security of electricity supply. It also deferred the need for decommissioning and replacement of the two nuclear power stations at a cost of £1.5 billion pounds each.

EDF has calculated a wide range of benefits for (five-year) plant life extensions to the 15 reactors in the UK's nuclear fleet, including 30 million tonnes of CO_2 emissions, at £650 million a year in contracts for mostly UK-based businesses to carry out the repair and upgrading work associated with the extensions and the safeguarding of 2,000 jobs in the power industry. As most existing nuclear power stations are scheduled to close by 2023, the government has identified eight sites as potentially suitable for the deployment of new nuclear power stations in England and Wales before the end of 2025. Insights from research conducted at ISIS will help optimise the lifespan and safety of new nuclear builds.

The role the Engin-X instrument at ISIS was clearly critical in confirming the nuclear industry's hypotheses about residual stress. However, the power industry has been researching this issue for more than a decade along with multiple research groups, and the development of improved simulation tools and welding procedures has also been carried out by others. As such, we argue ISIS should claim a small share (1% attribution) of the very large amount of additional economic activity that will result from this major refurbishment work over the next decade.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£6.5 billion or £650 million a year up to 2025	1%	£65 million
Savings in terms of tonnes of carbon dioxide	300 million (30 million tonnes of carbon dioxide emissions saved each year up to 2025)	1%	3 million tonnes of carbon dioxide up to 2025
Jobs safeguarded	2,000 power jobs safeguarded, up to	1%	60 jobs safeguarded

[21] Gandy D. W., Findlan S. J. and Viswanathan R., 2001, `Weld repair of steam turbine casings and piping – an industry survey'., ASME J. Pres. Ves. Techn. Vol. 123, pp 157-160

[22] http://ec.europa.eu/research/brite-eu/thematic/html/2-3-03.html

	2025 4,000 jobs supported in the contracting industries		

Economic analysis

Taken together, these 10 Extended Impact case studies suggest that ISIS research will underpin a substantial increase in national economic activity over the next 10 years, running into the hundreds of millions of pounds sterling and possibly billions, were we to extend our geographical scope to the global scale. These figures have been arrived at through consideration of various global market research data as well as consideration of UK markets and industries, in order to arrive at estimates of likely *additional* economic activity for the UK; we have attempted to determine net effects. Using rather conservative multipliers (1-5%), we feel confident that ISIS should claim several millions of pounds sterling for that increased economic activity in every case, and possibly as much as £85 million in total future benefits across the 10 cases. That amounts to a value of around £70 million in net present value (NPV) terms, using an inflation rate of 3% over the 10-year period to 2025.

There is no definitive means by which to relate this group of 10 cases to ISIS's total research endeavour over the past 30 years. We have come to a view, however, based on the size of the archive of case studies. Our group of 10 Extended Impact case studies was identified following consideration of the 50 most promising examples selected from within a larger catalogue of 150 cases. If we work with the kind of Pareto (skewed) distribution derived from consideration of various other empirical studies of research impact, we would expect to see 20-30 examples of major impacts within the 150. Given this, and the fact that the feedstock of 150 cases accounts for perhaps a third of all possible cases, the £85 million might reasonably be doubled to account for our under sampling of high-impact case studies within the 150 and then trebled to account for the fact that this group of 150 cases amounts to around one-third of all cases that might have been captured and profiled had the impact agenda been as prominent across the past 30 years as it is now.

We also need to keep in mind the importance of time. The 10 Extended Impact case studies have produced very little economic impact to date, and are expected to deliver the bulk of the very substantial projected benefits over the next 10 years through to 2025. Hence the decision to apply an NPV adjustment to that future cash-flow projection (£85 million becomes £70 million). So, we estimate total *future* benefits at £140 million, up to 2025. Using the extended impact case studies to guide our thinking about past wider benefits, we assume the £85 million can be doubled to approximate for the larger number of high-impact cases and doubled again to account for the previous 20 years' of ISIS research outputs, giving a total estimate for past wider economic impact of around £340 million.

3.2.4 ISIS publications outperform the UK average

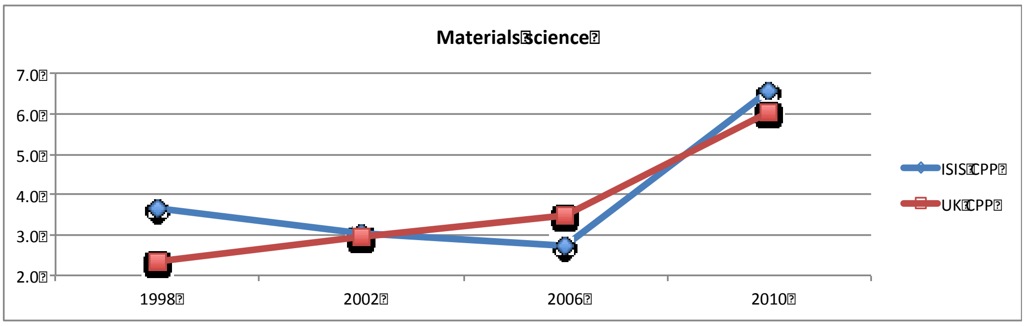
Summary of the bibliometric analysis

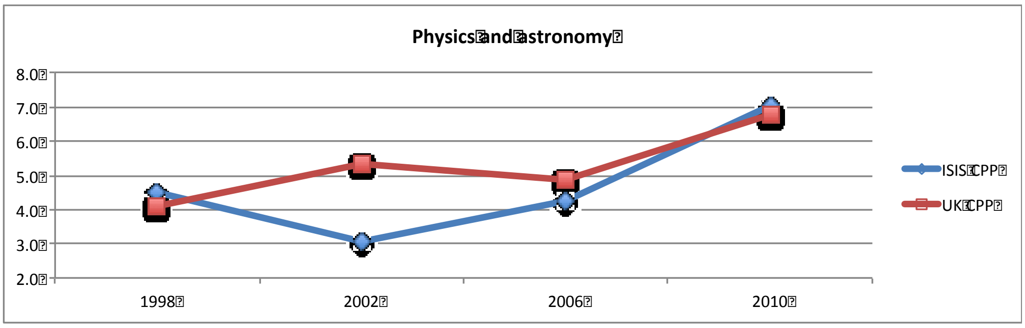
Our bibliometric analysis indicates the research undertaken at ISIS results in the publication of some 400-500 articles annually, and more than 10,000 recorded publications in total. Analysis of citation counts in selected years show ISIS publications receive around four to eight citations within a three-year window, while just 20-30% go un-cited. For comparison, Materials Science and Physics papers globally have both achieved around five citations per publication on average within a three-year window (2007-2010)[23].

Analysis of the most cited ISIS journal articles in selected years suggests that it is not uncommon for selected ISIS publications to achieve several hundred citations within a three-year window[24]. These papers often appear within higher-impact journals, such as `Nature', `Science' or the `Journal of Applied Crystallography'. The top 10 journals for ISIS publications also fall into the SNIP band 1.0-2.0, with a small number of exceptions, notably the journal of Physics Conference Series (lower influence at 0.2074) and Acta Materialia (higher influence at 2.858). In three of the years considered, the top eight papers have all amassed more than 100 three-year citations. The top 10 have all passed 50 citations. We feel these are deeply impressive statistics.

Overall, ISIS publications outperform the UK average for the fields in question. Figure 3 demonstrates that ISIS has shown an increase of 0.5-2 citations per publication over the UK average depending on the year and subject.

Figure 3: ISIS and UK publications – citations per publication for selected fields and years





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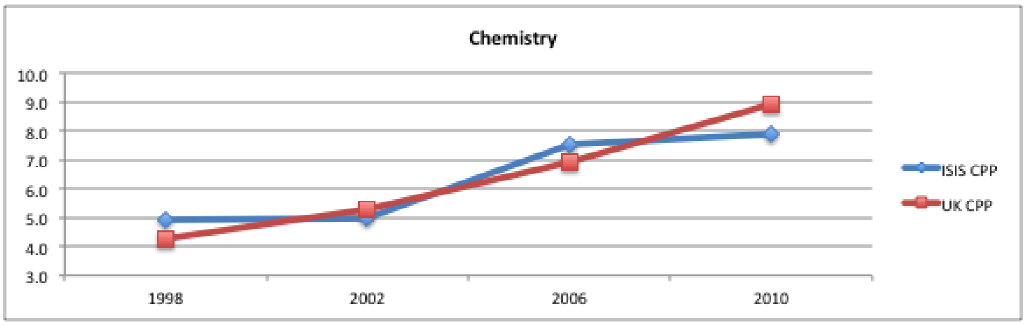
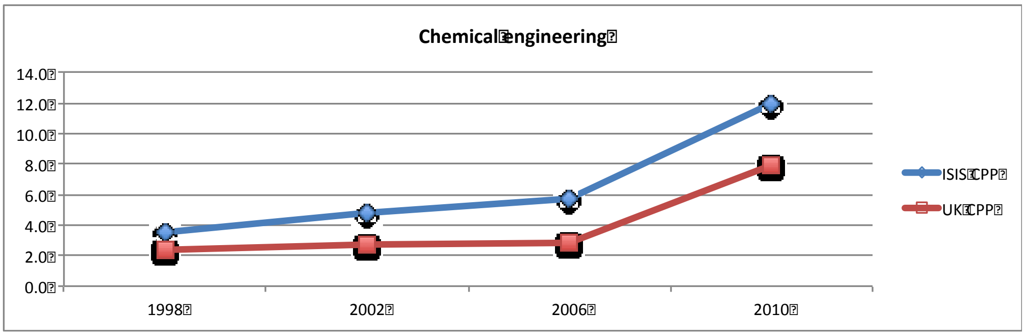
[23] *Source: Thomson Reuters' Essential Science Indicators database, 1 January 2000 -31 December 2010. http://www.timeshighereducation.co.uk/415643.article*

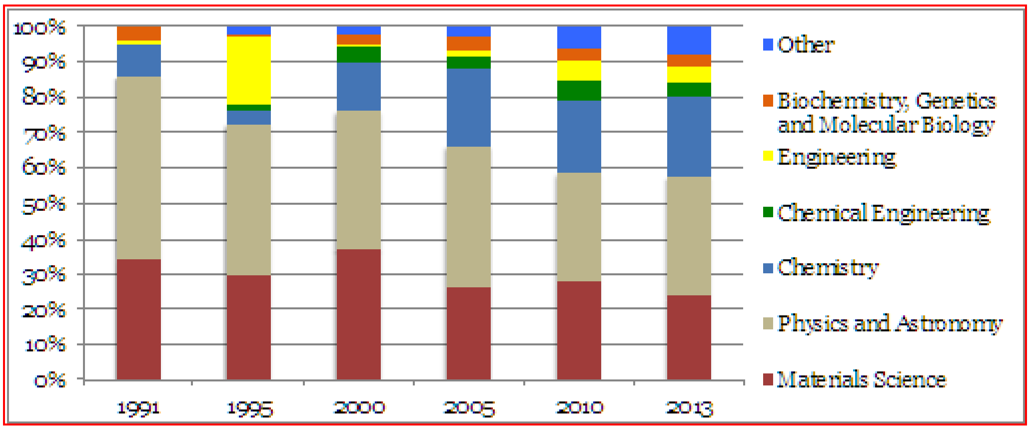
[24] A 'highly cited paper' (as defined by Thompson Routers) is a paper that belongs to the top 1% of papers in a research field published in a specified year. The 1% is determined by the highly cited threshold calculated for the research field in the specified year. Usually 100 citations over three years is considered significant and would usually class the research paper as 'highly cited' in a physics field although this may vary. Reference: http://ipscience-help.thomsonreuters.com/incitesLiveESI/glossaryAZgroup/g2/8251-TRS.html Accessed August 2016





The study team used bibliometric data in an attempt to better understand the distribution of activity across scientific fields. This indicated that Physics and Materials Science have dominated ISIS research. There is a clear increase, however, in the diversity of publications over time. In particular, Chemistry has seen a rapid rise, and now accounts for over 20% of all ISIS publications. Other areas (e.g. Energy, Medicine and Mathematics) are also increasing strongly, reflecting the growing relevance of neutron science to very many disciplines, with growing numbers of researchers supported by each of the UK's research councils.

Figure 4: Number of publications in different Scopus subject areas



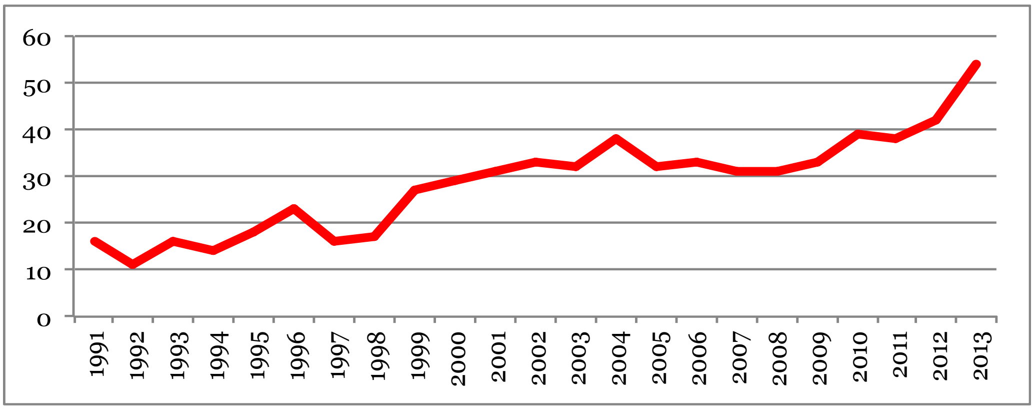
Access to the ISIS facility for universities and academics has enabled and will continue to enable high- quality, world-leading research in the UK. UK universities appear to rely heavily on access to the ISIS facility. ISIS runs two proposal rounds in most years, each of which attracts 400-500 proposals. Almost 75% of all ISIS usage (i.e. of all allocated beamtime) is accounted for by UK resident applicants, with the top five UK universities that use ISIS from the esteemed UK Russell Group universities, including the University of Oxford, University College London, the University of Edinburgh, the University of Warwick and Queen Mary University.

Figure 5: Top 20 UK universities, by number and share of ISIS experiments (2010-13)

Rank	Institution	Grand Total (days)	%	Cum %
1	University of Oxford	703	10	10
2	University College London	412	6	16
3	University of Edinburgh	406	6	21
4	University of Warwick	304	4	26
5	Queen Mary University of London	291	4	30
6	University of Bristol	242	3	33
7	University of Bath	241	3	37
8	University of Durham	217	3	40
9	University of Manchester	176	2	42
10	University of Cambridge	175	2	45
11	University of Glasgow	160	2	47
12	University of Nottingham	152	2	49
13	University of Sheffield	147	2	51
14	King's College London	143	2	53
15	Imperial College London	113	2	55
16	University of Liverpool	110	2	56
17	University of Birmingham	96	1	58
18	Queen's University of Belfast	87	1	59
19	The Open University	80	1	60
20	Royal Holloway University of London	78	1	61

While in the early 1990s ISIS publications tended to involve just one or two countries, for the past decade they have tended to involve two or more. There has also been a significant increase in the number of countries affiliated to ISIS publications each year, from just 10-20 countries in the early 1990s, to over 50 in 2013 (see Figure 6 below). Across the full 1991-2013 period, the authors of ISIS publications represent 66 different countries in total – most commonly France, the US, Germany, Italy, Japan, Australia and Switzerland (affiliated to at least 5% of publications each). This is a good indication of ISIS's growing international reputation and the global reach of its publications and research.

Figure 6: Total number of countries affiliated to ISIS publications each year



For the full bibliometric analysis see Volume 2, Appendix E, Bibliometric analysis of ISIS papers.

3.2.5 ***ISIS is critical to academic excellence and UK research quality***

ISIS research covers a wide range of scientific fields with numerous applications, enabling the advancement of science for the entire community. From our analysis of bibliometrics and the responses to our academic user survey, the importance of ISIS to UK science and UK academics is abundantly clear. This facility plays a critical role in enabling the UK to maintain its world-leading position.

Academic user survey

A clear indicator of the quality of ISIS research is our survey of 200 ISIS academic users that provided our team with an excellent profile of benefit types as well as long lists of specific research, skills and application-related outcomes. The results are conclusive and emphatically positive, with users rating ISIS as having been critical to their scientific understanding, research quality and experimental skills and that of the UK and international research field as a whole.

More than half of respondents rated the ISIS contribution as 'absolutely essential' to both UK and international communities (as well as their own research), and over three-quarters rated it at 4 or 5 (where 5 is critical and 1 has no importance) for all three communities.

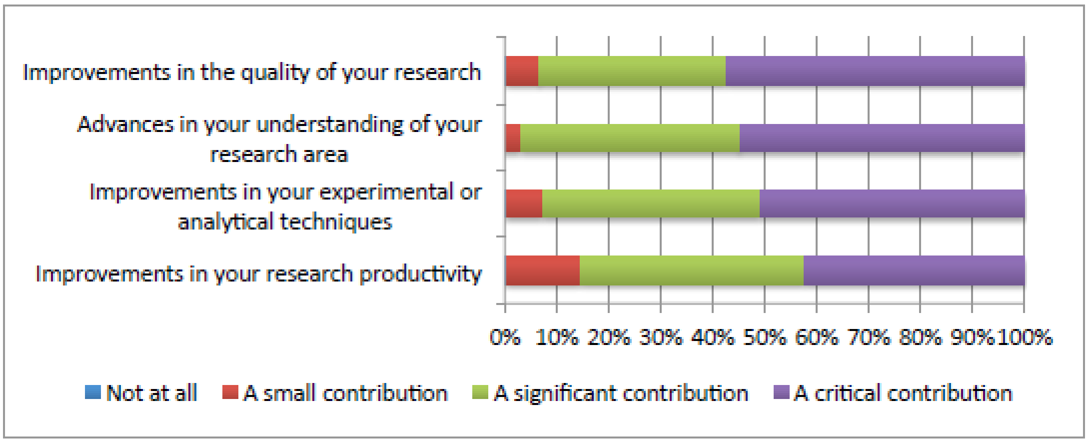
For full results from the survey see Volume 2, Appendix F, Survey of Academic users.

Figure 7: Importance of ISIS to research communities

Importance to:	1	2	3	4	5
Your research	0%	5.6%	12.2%	26.7%	55.6%
Your research community in the UK	0.6%	6.7%	12.8%	24.4%	55.5%
The international community in your field	0.6%	4.5%	13.6%	31.1%	50.3%

ISIS users were asked about the contribution ISIS has made to the quality of their research and any advances in techniques or understanding. The analysis shows that ISIS is widely regarded as having had a very positive impact; with respondents saying that ISIS played a critical or significant role in improving their research productivity (over 85%) and the quality of their research (over 90%) (see Figure 8 below).

Figure 8: Contribution of ISIS to users' own research (n=192)



ISIS users were also asked about specific aspects of the impact of ISIS on their expertise and that of their students, their opportunities to collaborate and the breadth of the methods they use. All these aspects, which are critical to the quality of research, were deemed to have been supported by ISIS to a large extent e.g. ISIS was deemed critical in providing opportunities to collaborate (over 83%). Over half of respondents also stated that their work at ISIS had provided some opportunities for working with industry, with almost 20% reporting a strongly positive impact on their industrial collaboration.

Figure 9: Impact of ISIS on aspects of research experience

Aspect	Not at all (%)	To a small extent (%)	To a large extent (%)
Opportunities to collaborate	0.0	17.0	83.0
Your domain knowledge	1.1	21.7	77.2
The breadth of your experimental experience	0.6	22.7	76.8
The skills of your research students	9.9	21.1	69.0
Opportunities to work with international partners	7.1	25.3	67.6
The breadth of analytical methods you use	1.1	37.0	61.9
Opportunities to work with industry	49.2	33.5	17.3

The ISIS facility provides a unique resource for its users, which enables research that would not otherwise be possible. Our user survey indicates the value of ISIS as a powerful, unique, research facility. Examples of these include:

'The ability to perform high-pressure in-situ neutron measurements is unique to ISIS and critical to my research group …'

'ISIS has some of the best-engineered instruments in the world (low background, high-resolution) and several of the neutron scattering experiments we have successfully performed at ISIS and have obtained extremely high-quality data would simply not have been possible anywhere else in the world.'

'The large facility offers a unique place for performing studies impossible elsewhere.'

3.2.6 *Since its inception, ISIS has had an innovative approach to instrument design and technology development*

A large number of instruments built and developed at ISIS are world firsts. ISIS has consistently taken the lead over the last 30 years, achieving a world-leading innovative approach to instrument design internationally. This is proven by the numerous examples of ISIS instrument design being adopted at facilities world-wide that were once operational here, and the influence the ISIS facility has had over a number of research fields, in many cases creating new areas of research or techniques previously unknown. Without the existence of ISIS and the instrument development work undertaken here, numerous potential new technologies and applications may have gone unexplored. For example:

- **ISIS Muon Facility:** The ISIS Muon Facility is unique in Europe, and one of only four muon facilities available world-wide. Muons detect information at the atomic level, with applications in materials science, condensed matter physics and chemistry. The ISIS muon facility first began in 1987, with the building of the first muon instrument in the UK, MuSR. This instrument was developed in collaboration with the European Community and demand for experimental time quickly increased. In the 1990s the 'European Muon Facility' was created, including two new muon instruments, EMU and DEVA, quickly followed by the 'RIKEN-RAL facility', an international collaboration between Japan and the UK (see section 3.2.7 for more information). Research using the ISIS Muon Facility includes, for example, work by Toyota on Li-ion batteries. Batteries have global use in smartphones, home appliances, electric vehicles and airplanes. However, current batteries are limited in terms of their performance. Jun Sugiyama, Toyota Central Research & Development Laboratories, and Dr Martin Månsson, EPF Lausanne, Switzerland state: `*Although Li-ion batteries are one of the great achievements of modern materials electrochemistry, we are currently reaching the limits in performance. In order to build better batteries, a breakthrough in science and technology is needed. Technical developments at large-scale experimental facilities such as ISIS have opened up new possibilities for studying such material's properties in a straightforward manner.'*

- **Pearl:** The development of the Paris-Edinburgh cell, which was incorporated into the ISIS Pearl Instrument for the first time, enabled a new understanding of materials at high pressures and opened up a new area of research. This is important for industry in the study of high-pressure, high-temperature systems such as those found in engines or in particular manufacturing processes, for example. The international significance of the Paris-Edinburgh cell is now demonstrated by its proliferation – there are now ~90 world-wide, as well as in other applications beyond neutron and X-ray scattering. The multi-million dollar high-pressure neutron diffraction facilities recently developed in the USA and Japan are directly inspired by Pearl, and ISIS will now also be closely involved in the development of similar capabilities at the European Spallation Source.

- **MAPS***:* When MAPS was commissioned in 2000, it was a pioneering instrument which set the direction for future spectrometers both at reactors and spallation sources. It was game-changing in terms of the science it allowed researchers to carry out, changing the way the neutron community now thinks about inelastic neutron scattering. As described in the independent ISIS `International Beamline Review' in September 2013: `*The MAPS instrument is delivering an impressive breadth and depth of science. Over the years MAPS has been highly successful in mapping excitations in cuprate- and iron-based superconductors and exploring quantum magnetism and model systems for precise testing of theories. Remarkably, it has proved effective for measurements of catalysts, providing a complementary role to TOSCA. This strength was completely unforeseen when MAPS was* *originally conceived and we offer our congratulations for the ability of the ISIS scientists to accommodate new directions. Although the number of MAPS publications is not high, we note however that they are exceptionally highly cited. We are also impressed by the strong national and international user base of MAPS.'*

- **Engin-X**: This is the first dedicated neutron engineering instrument in the world, and has defined the frontier of stress measurements. This was funded by the EPSRC in 1999 at a cost of £2.5 million and was built in 2002. Engin-X can precisely map out the stress distributions and can be used to predict the integrity of engineering designs. Our surveys and case studies suggest ISIS's support for in-situ studies of residual strain and internal stresses is both state-of-the-art and hugely valuable to industry. These applications can be particularly important for safety critical applications in sectors like aviation and nuclear power, which is evident in the ICRD projects for the likes of Rolls Royce and EDF. Mike Johnson, a researcher from ISIS, was one of the first materials scientists in the world to realise the potential of large-scale neutron beams for engineering research, and led early development work, building the world's first dedicated engineering instrument Engin, the predecessor to Engin-X. ISIS engineers were also part of a world-wide team that drew up Standards for Residual Stress Measurement by Neutron Diffraction under the auspices of the Versailles Agreement on Advanced Materials and Standards (VAMAS).

- **ChipIR**: This instrument is also currently being developed (2014) specifically to mimic damage to electronic systems caused by cosmic rays. This will enable researchers to investigate a major social and economic issue: the failure in safety critical IT systems due to cosmic rays, such as airplane failure in flight for example. This instrument development has involved an industry-ISIS collaboration that will be able to `certify' devices and systems against possible catastrophic failure. It is clear that the ISIS instrument will be an important addition to international capabilities in this field, and will be the first dedicated facility outside of the US. The ISIS Muon Facility will be complementary to ChipIR, with industry already interested in how muons will also affect microelectronic devices.

ISIS instrument timeline
A timeline of the internationally leading instruments developed at ISIS over the last 30 years, often the first built of their kind in the world.

- **1985-1995:**
  - **HRPD**, built 1986, is the highest resolution 'neutron powder diffractometer' of its type in the world.
  - **CRISP**, built 1987, was a world first and one of the best instruments in the world for 'spin-polarised neutron scattering'.
  - **LOQ**, built 1987, is the most successful 'time-of-flight SANS instrument' in the world.
  - **ISIS Muon Facility**, built in 1987, included the UK's first Muon instrument, MuSR.
  - **SURF**, built 1994, is one of the leading instruments in the world for 'liquid interface research'.
- **1995-2005;**
  - **RIKEN-RAL**, built in 1996, is a highly regarded international collaboration between Japan and the UK.
  - **PEARL**, operational since 1998, was a world first. It opened up a new area of research in 'high-pressure neutron diffraction studies', enabling a new understanding of materials at high pressures.
  - **GEM**, operational in 2000, is a world first and creating new generation 'neutron diffractometer'.

  - **MAPS,** operational in 2000, is a world first and advanced the research field considerably, setting the direction for future spectrometers both at reactors and spallation sources.
  - **Vesuvio**, operational in 2001, is the only instrument of its type in the world, and pioneered 'inelastic neutron scattering at eV energies'.
  - **TOCSA**, operational in 2002, is a world leading 'indirect geometry spectrometer' that currently supports a thriving scientific community of academics and industrial users.
- **2005-2015**
  - **SANS**, operational in 2009, is a world-leading instrument which enables research on nanomaterials.
  - **Engin-X**, opened in 2003, is a world first. It is optimised for engineering measurements and has a strong research programme, including industrial users such as Rolls-Royce, Airbus, TWI and Tata Steel amongst others.
  - **HiFi**, operational in 2009, is the only instrument of its kind in the world and has opened up new science areas for the muon technique.
- **2015 - Under construction**
  - **IMAT**, under construction in 2014, is the world's first combined imaging and diffraction instrument, used for applications in materials science, materials processing and engineering.
  - **ChipIR**, under construction in 2014, is one of the first dedicated facilities to look at how silicon microchips respond to cosmic neutron radiation, essential for industry and the safety testing of electronics.

*3.2.7 **ISIS has been essential for the UK's international reputation***

ISIS has always had an international outlook, with access to its instruments awarded through open competition to the best scientific proposals. Now, international use of ISIS is increasing substantially, as shown by our bibliometric analysis but also confirmed by other indicators detailed below (see section 3.2.4 Publications outperform the UK average, for more information)

Academic user survey

In our academic survey, over 70% of respondents stated ISIS was critical in improving the international reputation of their own research group. The most widely perceived 'big impacts' relate to the UK's international reputation, attractiveness to students and international cooperation. In particular, 94.9% of respondents to our survey stated that to a large extent ISIS has been critical to the UK's positive international reputation.

Figure 10: Impact of ISIS

Aspect	Not at all	To a small extent	To a large extent	No view
The UK's international reputation	0.0	3.4	94.9	1.7
The field's attractiveness to students	0.0	15.3	83.1	1.7
International cooperation/networking	0.0	15.3	78.0	6.8
International partnerships	0.0	18.6	78.0	3.4
Employability of researchers/students	0.0	20.3	71.2	8.5

Survey quotes regarding international collaborative also highlight the international importance of ISIS:

'Being from Australia, the international collaborations with Europe that have come from using ISIS have been highly significant.'

'Our access to ISIS has led to several collaborations with international groups whose expertise lies in areas other than neutron diffraction.'

'The opportunity to collaborate with the ISIS staff members, who are some of the finest scientists in the world.'

International agreements

ISIS is actively supported financially and in-kind by the international community. ISIS currently (2014) has 26 'live' international agreements with research institutes, laboratories, academies and Government departments in 12 countries. Most recently, new agreements have been signed with Italy, Sweden and India. International receipts amount to £2-3 million a year between 1987-2009. In total, ISIS has **received approximately £56 million** in international contributions (some 14% of total income).

Four of the largest and longest-standing international collaborations are summarised below:

- **Japan**: The RIKEN institute (Japan) and ISIS have collaborated for over 20 years (up to 2014), resulting in tens of millions of pounds in investment by Japan in a new ISIS facility (the RIKEN-RAL Muon Facility). The facility is unique and has been used to undertake research that would not otherwise be possible. It has involved researchers from over 50 Japanese institutes and resulted in around 300 published papers. In 2010, Japan and STFC signed their third 10-year international collaborative agreement, under which Japan provides funds and staff to operate, maintain and upgrade the facility, its instruments and beamlines.
- **USA**: ISIS has had a long-term relationship with the US, through various agreements and financial contributions to the facility. For example, in 2004 the US Department of Energy provided $2 million to the MAPS instrument and a further $2 million to other projects, and approximately 10% of all ISIS beam-time was used collaboratively between the US and UK. ISIS has also strongly supported the development of the $1.4 billion US nuclear spallation source, which is under construction and will incorporate design features specifically developed at ISIS.
- **Australia**: ISIS has had an agreement with Australia for more than 20 years and over the years Australian users have accounted for an increasing proportion of beam-time. Australia has also held specific contracts with ISIS since at least 1995, worth approximately £450,000 per year, and has supported specific instruments through direct investment. ISIS has also played a supportive role in the development of the case for an Australian facility.
- **Italy**: Italy is one of ISIS's longest-standing international partners, with a collaboration extending over nearly 30 years. Typically Italy contributes 3-4% (€1 million-€2 million) of ISIS's annual costs in return for Italian scientists accessing 4% of ISIS' beam time. In addition, Italy has typically contributed a further 1% of annual costs each year in support of the development of mutually beneficial instrumentation and techniques. In the past five years alone (up to 2014), over 300 Italian scientists have produced 200 publications based on research undertaken at ISIS. Continuing this long-standing collaboration, it was recently announced (March 2014) that STFC and Italy have signed a further agreement worth €15 million to further develop collaboration between the two countries.

3.3 Summary

ISIS is arguably the world's most successful pulsed spallation neutron source. The facility has supported key advances in many areas which affect people's lives underpinning significant developments in a wide range of research fields, advancing our knowledge and improving our understanding of the world.

ISIS has made neutron scattering an indispensable analytical technique, contributing numerous advances in instrumentation and analytics. The facility has also made substantial contributions to neutron scattering itself, creatively pushing the boundaries world-wide with novel target materials, new instrumentation and next generation software. ISIS is also at the cutting edge of muon science and is the world's most intense source of pulsed muons for condensed matter research.

As the world's first short-pulse neutron spallation sources, ISIS attracted international interest from the outset, with many international investments having been agreed over the years. ISIS has a number of formal international partnerships, some of which have been active for over 20 years. These agreements provide for direct or indirect (i.e. in-kind) contributions to ISIS instruments, providing benefit to the whole user community.

As detailed above our main conclusions on the impact ISIS has had on research are as follows:

1. The economic and social benefits of ISIS research are wide-ranging.
2. ISIS has played an essential and major role in global research endeavours that have and could have significant impacts world-wide.
3. ISIS research has and will continue to produce significant economic impact for the UK, totalling at least £480 million.
4. ISIS publications outperform the UK average.
5. ISIS is critical to academic excellence and UK research quality.
6. Since its inception, ISIS has had an innovative approach to instrument design and technology development.
7. ISIS has been essential for the UK's international reputation, with ISIS leveraging £54 million in international funding.

In support of our conclusions, ISIS was also recently subject to a separate international peer review in 2013, which was undertaken by the ISIS International Review Committee, chaired by Professor Joël Mesot, Director of the Paul Scherrer Institute (PSI), Switzerland's largest research institution. The committee concluded ISIS was one of the most productive research centres of its type in the world, benefiting from experience, skills and knowledge developed over three decades of operation:

`ISIS is serving one of the largest and most productive neutron communities in Europe. Most UK research-intensive universities have research groups using ISIS and the best international neutron scatterers and muon users are making use of the unique capabilities offered by ISIS. With the initiative to reach out to engineering and industry, the community will become in future even more diverse, which is an excellent development.'

4. ISIS Innovation impacts

4.1 Introduction

ISIS has been used by industry since it first opened and has wide-ranging and long-established industrial links with a wide range of businesses, from large multinational companies to small local companies and start-ups. In this section we explore the industrial use of ISIS and its impact on innovation in the UK. From this, our main conclusions are;

1. **Industrial use of ISIS is significant; research with an industrial link now account for 10-15% of total ISIS beam-time.** ISIS has a number of 30-year-plus collaborations with companies, with records suggesting a significant expansion in industrial engagement in the recent past. The great majority of the top industrial users of ISIS are large multinational companies, underlining the significance of ISIS globally.
2. **The types of benefits that ISIS provide industry are wide-ranging and across multiple applications**. Industry uses ISIS for a broad range of purposes, including technology development, safety testing, product design, improving manufacturing techniques and pioneering the use of new materials.
3. **Companies who use ISIS report increased productivity, competitiveness and share value.** Industry also reports positive impacts on its technology partnerships and innovativeness generally.
4. **The industrial use of ISIS has and will continue to directly benefit the UK economy.** We conservatively attribute around £200 million of net economic impact directly to ISIS over the lifetime of the facility, and a future net economic impact of £200 million (up to 2025).
5. **ISIS suppliers derive substantial benefits in manifold areas of their business.** Suppliers reported working with ISIS had increased sales, increased the quality and productivity of their business and had helped them grow both nationally and internationally.
6. **There are numerous examples of the successful commercialisation of ISIS research.** Successful new technologies, patents and spin-outs have benefited or arisen as a result of ISIS, with 10% of academics asked reporting commercialisation linked to ISIS research.
7. **ISIS plays an important role in the Harwell campus.** ISIS is at the centre of an evident and strengthening community of researchers and industrialists. ISIS's success over 30 years has supported the creation of this successful and growing UK science and innovation campus.

4.2 Discussion

4.2.1 ***Industrial use of ISIS is significant; research with an industrial link now account for 10-15% of total ISIS beam-time.***

Companies now account for a significant proportion of total ISIS beam time; the most frequent users are almost all are household names. There are 111 companies mentioned in some form in ISIS records where a link to proposals has been identified over the full 1986-2014 period. There are five companies where links have been identified clearly since the opening of ISIS; these include **Unilever, ICI, Rolls-Royce, BP** and **Kodak**, indicating that ISIS has always been of benefit to industry and 30-year-plus collaborations with a number of important industries have been established from the opening of this UK facility. A wide range of industries has made use of ISIS instruments over the years through a number of different modes of access. We examined the impact of each of these below. For more information see Volume 2, Appendix A, The ISIS neutron and muon source (section A.5 ISIS and industry).

Main user programme

This is the principal access route, accounting from more than 85% of ISIS beam time in a typical year. External researchers, from the UK and abroad, access ISIS via one of the Facilities Access Panels, which assess proposals on their scientific merits. The great majority of industrial engagement with ISIS has come through this route, with companies working closely with university academics. The ISIS user office estimates that 10-20% of mainstream experiments through the main user programme include some industrial component, whether that is direct involvement in the experimental work or indirect support. The nature of the involvement of industrial partners is most commonly the funding, or part-funding, of students involved in the proposal (in the experiment or wider project). Companies can also be listed as the principal investigator (PI) or co-investigator on the ISIS proposal, or they coordinate the wider project that the experiment relates to. Through this route businesses need to publish their work in scientific journals, making it publicly available.

In 2013, academic-led applications to ISIS's main user programme included more than 50 individual companies; the most frequent users are almost all household names, and include BP, Rolls-Royce and Unilever. The great majority of the top 15 industry users are also large multinational companies, many of which are headquartered in other countries elsewhere in Europe or the US, underlining the importance of ISIS on the one hand and the quality of UK science on the other (see Figure 11 below).

Figure 11: Top 15 industry users (2011-2013 user programme)

	Company	Field	Allocated days
1	Unilever	Consumer goods	138
2	Toyota	Automotive	57
3	BP	Oil & Gas	47
4	Johnson Matthey	Industrial technologies	42
5	Rolls-Royce	Aerospace	40
6	Merck	Pharmaceuticals	38
7	General Motors	Automotive	35
8	Sasol Technology	Oil & Gas	31
9	MI Swaco	Oil & Gas	19
10	EDF	Power and energy	18
11	Syngenta	Agrochemicals	18
12	Aqua GMBH (Evonik Industries)	Specialty chemicals	12
13	Borealis	Chemicals	12
14	European Thermodynamics Ltd	Electronics	11
15	Cella Energy	Energy / advanced materials	10

Paid proprietary access

In addition to the main user programme, ISIS provides third parties with the option to pay a commercial rate to gain access to beam time and to use particular instruments. Proprietary access provides companies with a means of using ISIS privately. This allows them to keep results out of the public domain when commercially sensitive. Currently, a small amount of proprietary work is undertaken at ISIS, with individual clients paying for 24-hour access period. Although the number of companies accessing the facility in this way is small and variable; 1% of ISIS funding is usually accounted for by industrial contributions. This provides a notable, if variable, additional funding stream for ISIS and provides companies with a means of using ISIS privately, allowing them to keep results out of the public domain when commercially sensitive, helping UK business remain competitive.

The Industry Collaborative Research and Development (ICRD) programme

A third, more recent, mode of access is the newly created ICRD programme, which was introduced in 2011. This is an option which allows businesses to choose whether or not to publish their results publically (combining the main user and paid proprietary type access). This has broadened the use of ISIS by industry, and has quickly developed into the main route through which industry gains direct access to the facility. It also provides business with a fast-track means to access ISIS and in its first two years (up to 2013) more than 20 individual companies including Rolls-Royce, Unilever, Infineum and Schlumberger (to name a few) have been approved to run close to 40 experiments (150 allocated days).

With the creation of the ICRD programme, industry has a more 'flexible' means by which to access the ISIS instruments directly. It has also generated a new proposal system which has provided comprehensive data for this study, as ISIS requires industry applicants to estimate the proposed experiment's likely future benefits to their business. These projections provide a window onto industry users' view of the benefits of ISIS to their business. These are summarised below in Figure 12.

Figure 12: Potential benefits deriving from ISIS ICRD experiments

Company no.	Experimental days at ISIS	Title	Quantifiable benefits	Other benefits
C1	5	Residual stresses in an aircraft structure	Savings in manufacture and operation	Reduced emissions. Exploitation by others / other sectors
C2	3	Residual stress in weld specimen	Reduction in repair time	Improved safety
C3	4	Residual stress in machined aluminium		Cost savings through increased component life. Benefits transferable to range of sectors
C4	5	Residual stress in turbine housings	Savings for company	
C5	7	Structural studies of oil lubricant additives	Increased income	
C6	3	Polyelectrolyte surfactant complexes	Increased income	
C7	4	Testing welded plate samples		Supports measurements that enable five-year extension to life of reactors
C8	1	Residual stress of alloy parts built using electron beam melting powder process		Reduced material use, lower machining. 30% weight reductions and lower emissions
C9	4	Analysis of positive electrode for Li-ion battery	Increased jobs	
C10-1	2	Particle formation mechanism for particles stabilised by surfactant	Savings for company due to reduced waste	
C10-2	4	Structural studies of anti-wear and friction reducing layers	Savings for consumers / businesses	Reduction in CO2
C11-1	9	Characterisation of metal hydrous oxide and hydroxide compounds	Savings / new business for company	
C11-2	3	Neutron scattering analysis of automotive enamel glasses	Increased turnover company	
C11-3	4	Lithium conduction mechanisms in Lithium metal triphosphate compounds		Reduced emissions. UK economic benefit
C12	6	Residual stress in marine welds		Savings to company from reduced maintenance cost and lifetime extension.

Company no.	Experimental days at ISIS	Title	Quantifiable benefits	Other benefits
				Potential in other sectors
C13-1	3	Residual stress in compressor discs	Savings for company through reduced material, employment, energy.	
C13-2	2	Deformation and recrystallization studies of specialist steels	Savings due to improved manufacture process	Other benefits on-top expected in future
C13-3	6	Surface defect formation during the processing of engine components	Savings from reduced repair work	
C13-4	2	Residual stress in bolts in superalloy	Savings to company	
C13-5	3	Residual stress at surface of a superalloy	Savings to company due to increased life	Wider employment / economic benefits to UK
C13-6	6	Formation of a Surface Defect during heat treatment of a superalloy	Savings to company due to reduced defects in manufacture	
C14	5	Residual stress in wheels	Savings to UK industry, due to increased lifespan	Benefits to wider industry. Environmental benefits
C15	10	Residual stress in the seam weld of a UOE line pipe	Savings and increased revenue for company	Additional jobs. National energy security. Environmental protection
C16	2	Analysis of lithium ion conduction in glassy and ceramic alloys		Reduced emissions
C17-1	8	Residual stresses in pipeline girth welds	Savings to UK companies due to reduced cost of repairs.	
C17-2	7	Hydrogen embrittlement of dissimilar joints for subsea applications	Cost of delay to companies	Environmental benefits
C18	166	Seven experiments over three years (INTER) Three experiments over three years (SANS2D)		New / improved products, resulting in market share and profitability

Using the ICRD scheme information, we also carried out an economic analysis on the industrial use of ISIS. This is described in section 4.2.3.

4.2.2 The types of benefits that ISIS provide industry are wide-ranging and across multiple applications

ISIS has a substantial and rather diverse evidence base of case studies (see ISIS website for more information). We have chosen industrial case study examples to illustrate the types of benefits that ISIS often provide e.g. enabling technology development, improving manufacturing and pioneering new applications for materials and compounds. ISIS has also directly provided some of these case studies. To note: when asked, contributors highlighted the critical role played by ISIS, but went on to say that they could not attribute a monetary value to their ISIS experiments, sometimes because the development work was ongoing, but often because of the amount of subsequent investment / development work and or the commercial sensitivity of these statistics.

Unilever

Unilever has been using ISIS regularly for more than 30 years and has purchased beam-time for commercial purposes (e.g. looking at perfume molecules in shampoo). The company works closely with ISIS staff on a number of research programmes. Unilever often plays a significant role in fundamental research looking at surfactants. Experiments at ISIS have yielded significant cost savings for Unilever, allowing them to better understand and manipulate the surfactant-based mixtures used in fabric / hair conditioners, paints, coatings, cosmetics, foodstuffs and drug delivery systems.

For example, Unilever carried out work looking at the formulation of their detergents. As a result of the understanding gained from ISIS experiments, Unilever was able to change its formulation and production methods. This research fed into the development of products, and led them to launch their products in the EU for the first time.

`Neutron scattering measurements are used to optimise processing conditions, reduce process time and energy and improve product quality.' Dr Ian Tucker, Unilever

In 2006, Dominic Tildesley, Chief Scientist at Unilever, also wrote a letter to the Government in support of ISIS, detailing the importance of the facility to their business, describing strong academic links with ISIS staff and confidentially giving an example of some research which has delivered £millions in additional turnover[25]. Although, for reasons of commercial sensitivity, the exact details and value of ISIS research is not available from Unilever, the value of this research can be indicated by the fact that Unilever is still the heaviest industrial user of ISIS and has used ISIS regularly since it was first opened in 1986. For example, during 2011-2013, Unilever was allocated 138 experimental days (equivalent to over two2 months a year of continuous instrument time assuming a normal 40 hr working week).

Rolls-Royce

Rolls-Royce has been a regular user of ISIS for many years, having first used ISIS when it was opened in 1986, and has co-authored a number of scientific publications involving ISIS. Rolls-Royce also has a long-established and award-winning global network of University Technology Centres (UTCs) in the UK, with the first formal UTC collaborations being signed in 1990. Many of the UTCs that carry out research on materials and engineering are regular users of ISIS, capitalising on the instruments and expertise this facility provides, including the Universities of Manchester, Cambridge, Oxford, Birmingham and Imperial College London.

Currently, the mostly heavily used instrument by Rolls-Royce is Engin-X. In order to stay competitive in a world market, Rolls-Royce is under constant pressure to develop new engines which demonstrate dramatically improved fuel efficiency, improved cost of ownership, and reduced environmental impact. Engin-X enables residual stress to be mapped in three dimensions and Rolls-Royce has used this technique to study the structural integrity and performance of new engine components, and in the testing of new materials and manufacturing methods.

For example, modern aircraft incorporate a range of high-performance alloys. However, these new materials often cannot be welded by traditional techniques. Rolls-Royce and the University of Manchester used Engin-X at ISIS to test and develop new welding techniques. This allowed Rolls-Royce to use inertia friction welding to build the Trent 900, 1000 and XWB engines, which now power the Airbus 380, Boeing 787 and Airbus A350 respectively. More than 1,500 of the Trent XWB engines[26] (exceeding a list-price value of £60 billion) have been so far ordered (2014), including an order from British Airways worth more than £1 billion to power a fleet of 18 Airbus A350 aircraft[27].

[25] A copy of this letter to the Government may be made available on a confidential basis on request to STFC

[26] http://www.rolls-royce.com/customers/civil-aerospace/products/civil-large-engines/trent-xwb/trent-xwb-infographic.aspx

[27] Impact case study (REF3b). University of Manchester. UoA13a Metallurgy and Materials. Friction welding for aeroengine applications. REF2014

Airbus

Since 2006, Airbus has used ISIS to continuously develop product innovations to meet its customers' needs, ensuring the company's full range of jetliners remains at the cutting edge of performance. In particular, neutrons can be used to measure stress in engineering structures. Experiments at ISIS have enabled Airbus engineers to adjust the manufacturing process and produce safer aircraft parts at a lower cost. The process has been integral to the development of welding techniques and has confirmed the integrity of aircraft parts.

Neutron diffraction is also enabling measurement of new production processes at Airbus. For example, aluminium is very difficult to weld, which is why aircraft are traditionally riveted. Friction Stir Welding is of great interest to the aircraft industry to replace riveting both to reduce weight and remove the holes from which cracks can form. Airbus has worked with UK academics to use neutron diffraction at ISIS to reduce the weld stresses. This has allowed Airbus to make lighter large aircraft-wing test panels and assess their suitability for future aircraft programmes.

`Residual stress measurement at ISIS has been invaluable in researching and developing existing and novel material manufacturing and processing techniques. The fact neutron diffraction is a non-destructive technique means it can even be used to improve component performance in manufactured parts.' Richard Burguete, Experimental Mechanics Specialist, Airbus

BP

BP is a long-term user of the ISIS facility, having first used it in 1987. Since then, BP has used the facility regularly and is, after Unilever, the heaviest industrial user of ISIS over the three years to 2014, requesting the most experimental time on instruments via academic collaborations. Recently, BP has used ISIS through the BP Institute, one example of which was when ISIS was used to look at lubricant additives. Lubricants reduce friction and wear, and are essential for the functioning of moving parts in a wide number of applications from internal combustion engines to gearboxes, and turbines to hydraulic systems. ISIS instruments were able to provide a unique insight, with the ability to 'see' the surface of this engineering material in its working conditions.

`The lubrication of surfaces by oils is a key aspect of many industrial problems with significant financial implications to industry and the economy generally. This area of science is growing in importance. We have advances in engine technology combined with lower emission requirements, and also the demand for fuel efficiency, improved friction reduction and the desire for longer oil change intervals. Hence, understanding the role and adsorption of lubricant additives at the oil metal interface [at ISIS] is essential.' Dr Stuart Clarke, University of Cambridge BP Institute

In 2004, 37.4 million tonnes of lubricants were consumed world-wide. The top 1% of the world's manufacturers account for more than 60% of sales and one of the world's largest manufacturers is BP. Research has shown that 0.4% of GDP across Western industrialised countries could be saved if new knowledge on friction, wear and lubrication from scientific research was applied across this industry[28], which means this research at ISIS is very relevant for the European and UK economy.

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28 `Lubricants and lubrication'. 2nd Edition. Edited by Mang, T. and Dresel, W.

Schlumberger

ISIS has so far supported Schlumberger in a key area of research, understanding exactly how and why oil pipes become blocked by substances called asphaltenes. Schlumberger had previously recognized the problem, and had known that these substances can cause problems in all stages of production, for example, transportation and processing, causing the loss of efficiency in equipment used to produce crude oil. In the reservoir rock, it can also partially or completely block pores, resulting in the loss of oil recovery[29]. The cost associated with deposition during production and refining operations is in the order of billions of dollars a year. For this reason, the prevention or minimization of this problem is an important goal for oil companies.[30] As Schlumberger has stated: `*Most oils contain asphaltenes – a solid phase precariously suspended in liquid hydrocarbon phases. Asphaltenes out of solution can form solid deposits in wells, flowlines, surface facilities and subsurface formations. In extreme cases, blockages can completely halt production*.'

However, until recently, scientists knew very little about the structure of asphaltenes and why they form blockages. By using neutron beams at ISIS, Schlumberger and a team of researchers from University College London were able to see in real time how they behaved in different circumstances. Small-angle neutron scattering at ISIS enabled scientists to observe for the first time how they aggregate in the presence of clay surfaces.

*`The work at ISIS allowed us to understand more clearly how the asphaltenes aggregate,*' says Edo Boek, a senior research scientist at Schlumberger Cambridge Research. `*This is an important observation from a flow assurance point of view and should allow more efficient extraction of hydrocarbons in the future.'*

INEOS ChlorVinyls

INEOS ChlorVinyls is Europe's largest manufacturer of PVC and chloromethanes, which are important components of many everyday products, from window frames to pharmaceuticals. Production of these substances creates unwanted by-products, representing a waste of materials and energy, and causing undesirable effects in later stages if not removed. Research at ISIS led to improvements in manufacturing and a significant reduction in the unwanted side product. The new approach has now been used successfully at INEOS' Runcorn site now for 10 years (as of 2014).

The methodology has since been further developed and applied to other systems, for example in the Fischer-Tropsch process. Sasol Ltd – an international energy and chemical company that uses Fischer-Tropsch – has also now been working with ISIS to look at the process it uses.

4.2.3 The industrial use of ISIS has and will continue to directly benefit the UK economy

The best available information with which to estimate the economic impact of the industrial use of ISIS was that provided by companies who are currently using the ICRD scheme. As described in section 4.2.1, all ICRD proposals are required by ISIS to include a description of anticipated applications. This gave us good information to work with, with 15 of the 36 proposals from companies including estimates for the future benefits to their business. Taken together, these forecast more than £500 million in additional income or savings for the participating companies and

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[29] `Asphaltenes – Problems and Solutions in E&P of Brazilian Crude Oils'. Erika Chrisman, Viviane Lima and Príscila Menechini
[30] `Asphaltene Stability in Crude Oils and Petroleum Materials by Solubility Profile Analysis'. Estrella Rogel,* Cesar Ovalles, and Michael Moir. Energy&Fuels. 2010

their supply chains. In several cases, benefits are foreseen each year, many years into the future, suggesting that this group of current ISIS experiments may help secure or expand national economic activity by several billions over the next decade.

Adjusting these gross estimates of increased sales in line with likely displacement of economic activity elsewhere in the UK economy, depreciation over the 10 years to 2025 and conversion to GVA, we arrived at an estimate of future net economic impact of between £330 million and £660 million. Given the critical contribution of ISIS to the realisation of those future benefits, we attributed 30% of the higher bound to ISIS, or **£200 million**.

The ICRD programme is a reasonable approximation to the close working relationship that the facility has had with a core group of industrial users across its 30-year life, and we have used these detailed financial projections as the basis for estimating historical benefits to industry users. We assume 20-30 companies have seen similar benefits from a sub-set of their ISIS experiments across a 20 year period (allowing for ISIS start-up and commercialisation time lags), the ICRD projections suggest that ISIS will have made possible new sales on the order of £500 million a year, or around £10 billion overall, which when adjusted for additionality, displacement and attribution, as previously described, produces an estimate of total net economic impact of somewhere between **£200 million** (lower bound) and £750 million (upper bound). Given our use of the ICRD projections as the basis for these estimates of likely historical benefit, we elected to include the most conservative figure in our summary and overall estimate of ISIS's total economic impact.

Figure 13 - The estimated socio-economic impact of industrial use of ISIS

Type of socio-economic impact	**Estimated ISIS lifetime (1985 to 2013)**	**Estimated future impact (2014 to 2025)***	**Total estimated impact (1985-2025)[31]**
Impacts on industry (ICRD programme)	-	£200 million	£200 million
Impacts on industry (main user programme)	£200 million	-	£200 million

4.2.4 *Companies who use ISIS report increased productivity, competitiveness and share value*

Several hundred companies are known to have been involved with ISIS through the mainstream user programme; however, just 10 industry responses to our survey were received in total. The companies that did respond have been making use of ISIS for anything between two and 22 years, with an average of 1- years' experience of the facility across respondents. The respondents came from companies (including both SMEs and large multi-nationals) that are active in a range of different sectors, including:

- Energy (3)
- Chemicals (2)
- Aerospace (2)

31 *Based on projects and research already done now. Excludes any new work ISIS will do in the future

- Automotive (1)
- Materials (1)
- Micro/nanotechnology (1)

The 10 responses received cannot be compared with the size or features of a total population, but feedback was instructive and suggests a number of important conclusions:

1. A majority of respondents reported a *large* impact in both domain knowledge and the ability to work successfully with academia, resulting in impacts such as improved product safety and a better basis for making commercial decisions.
2. Industry users report positive impacts on their company's approach to R&D, their technology partnerships and innovativeness more generally. Impacts on the company approach to R&D stand out, with two-thirds of respondents providing a high rating.
3. More than two-thirds of survey respondents reported ISIS had a positive impact on their productivity, competitiveness and share value. The most significant impacts (ratings of four or five) were most commonly reported in relation to competitiveness (56%) and productivity (38%).
4. Respondents were also asked to estimate the total value of additional sales underpinned by their use of ISIS. For some, it is too early to put an estimate on the value; while for many, it is difficult to attribute a value to the use of ISIS within their wider research and development endeavour. However, four respondents did estimate a value (£5 million on additional sales, ~£500,000 over three years), and two respondents suggested the value to their companies would be in the millions of pounds per year.

Example quotes from the survey include:

- *`An example of important advances made possible by the use of ISIS is the effect of residual stress on the service integrity of inflexible pipes, an issue that was not properly understood. This became an obstacle in developing new pipes for high-pressure, deep-water applications. Work at ISIS will help to understand this effect and to design future pipes with high confidence of integrity'*

- *`ISIS provides the advanced technologies for evaluating residual stress in manufactured products that could not be evaluated by other means. These evaluations are extremely useful for us to increase the utilisation of current materials and the capability of our products without compromising safety.'*

For full information on the Industry user survey see Volume 2, Appendix G, Questionnaire survey of ISIS Industry users.

4.2.5 ***ISIS suppliers derive substantial benefits in manifold areas of their business***

Big science facilities constitute a major market for the global scientific instrumentation sector of course, but big facilities are also important niche markets for suppliers of even quite generic products and services, demanding a level of precision and quality that is very much more exacting than the majority of segments and which can provide positive spill-overs in reputation, processes and quality overall.

Supplier survey

In order to investigate this further, organisations that have supplied ISIS during the design and construction of Target Station 2 (TS2) were used for our survey of ISIS suppliers. Some 47 responses were received and this provides a snapshot on supplier interactions with ISIS. We cannot assume that the responses provided can be simply extrapolated to a wider population but the results do provide insight into the experiences of a meaningful number of different sorts of suppliers, whose aggregate responses concerning the impact of ISIS can be assumed to constitute the lower bound as regards the benefits realized across the full portfolio of suppliers.

The main conclusions are as follows:

1. The survey results show that ISIS suppliers derived substantial benefits in manifold areas of their business. A majority of suppliers suggested that their sales to ISIS had had some impact on new products or services (83%), increased domestic sales (73%), increased quality (71%) and increased productivity (62%). Around 40% of the 46 responding suppliers reported some degree of positive impact on third party sales of products/services originally developed for ISIS, 30% report an increase in international sales and 20% report an increase in employment.
2. Suppliers were asked what the implications would have been if their contract(s) with ISIS had not been awarded. Just over half highlighted that there would have been a significant loss of direct revenue (with implications for employment, growth and profitability), and a quarter went as far as to suggest that there would have been wider implications (in terms of business growth and market position, which had been aided or enabled by ISIS sales).
3. Comments from suppliers show that while for some ISIS has been most important simply as a customer providing revenue (direct benefits), for many suppliers the capabilities, products and reputation developed has been most important – often leading to wider opportunities and sales (indirect benefits). This kind of reputational benefit – a kind of accreditation by the market – is widely reported by large international scientific facilities like CERN.

Example quotes on the benefits of working with ISIS include:

`Increase in sales turnover'

`Employment of more people within the company.'

`The most important factor for us is the ability to develop new products and resolution for problems we may not face in normal industry."

`ISIS as a customer is a prestigious organisation and is good to have within our customer portfolio; ISIS is a well-known company and hence a valuable reference for us when trying to find new customers.'

For full information on the Supplier survey see Volume 2, Appendix H, Survey of suppliers to ISIS Target Station 2 (TS2).

Case studies

We have also chosen a series of supplier case study examples to illustrate the types of benefits that ISIS often provide for these industries, creating long-term beneficial relationships. These include examples from multinationals to local businesses, and these case studies provide a snapshot of examples of how suppliers can benefit.

For full information on supplier case studies see Volume 2, Appendix I, ISIS supplier case studies.

Edward Vacuum Pumps

ISIS has close links with several leading vacuum pump manufacturers based in the UK, including Edwards Vacuum Pumps. This is a large international company and a leading developer and manufacturer of sophisticated vacuum pumps. The relationship between ISIS and Edwards started when ISIS was first opened in 1986, with ISIS buying several hundred vacuum pumps and other items each year with a value in excess of £1 million, about 300 products a year, priced at £3,000-£4,000 per product.

While ISIS constitutes a tiny fraction of Edwards' total annual sales, business development is important, with ISIS's challenging requirements providing a valuable input for Edwards's more general ambitions in growing its position in the scientific instrument / R&D sector internationally.

Applied Scintillation Technologies

Applied Scintillation Technologies (AST) is a UK SME employing around 45 staff (2014), which has been supplying ISIS for more than 25 years. It provides specialist scintillator materials for use in detectors of 17 of ISIS's current 26 neutron scattering instruments.

AST's close relationship with ISIS scientists has helped it to remain at the forefront of neutron detection technologies and contributed in no small measure to the company's five-fold increase in employment over the last 15 years (up to 2014). As a direct result of supplying ISIS, AST now supplies scintillators to neutron scattering research centres in Japan and the US. The substantial history of sales and development work with ISIS helped to provide a respected track record of success for their products which is underpinning sales internationally. Working alongside ISIS and the wider neutron scattering community helps drive AST's product development and opens new doors, through direct introductions or indirectly through citation in academic papers.

Prototech Engineering

Prototech Engineering is a small precision engineering company set up in 1991, based in Oxfordshire, a mile or so away from ISIS. In 2009, Prototech was awarded a four-year, £400,000 contract to manufacture the neutron moderators for ISIS TS2. The moderators are critical to the performance of the facility; they cost approximately £50,000 each and must be replaced approximately every six months.

Prototech's proximity to ISIS enabled the incredibly complex manufacturing process to be carried out more economically and with a higher quality result than may have been possible without the ability for the facility scientists to sit with the manufacturers. Prototech has benefited from what is a large contract for them with a long duration that has given the company the cash-flow, confidence and reputation to bid for large contracts with other large facilities.

Oxford Instruments

Oxford Instruments and STFC (and its predecessors) have collaborated over many decades on topics including superconducting wire and magnets, particle accelerators and applications of cryogenic technology. Oxford Instruments executives estimate the company has gained a cumulative financial benefit in excess of £100 million (2014), although it could be considerably higher, from this longstanding relationship. Sales of superconducting magnets and associated equipment directly supplied to ISIS, SRS and Diamond has amounted to more than £2 million.

Building on the success of the sales to ISIS, Oxford Instruments has supplied similar equipment to comparable research institutions overseas, with benefits to Oxford Instruments' revenue stream and the UK's balance of trade. ISIS has also collaborated with Oxford Instruments to design and test dry cryostat technology. As a result, Oxford Instruments released a product in 2013 called ISISstat, which is being marketed for other neutron scattering experiments globally.

For full information on Oxford Instruments see Volume 2, Appendix J, Oxford Instruments and STFC.

4.2.6 There are numerous examples of the successful commercialisation of ISIS research

ISIS consciously pursues an open access strategy in order to maximise social benefit for the UK, requiring all users – public and private – to publish as a matter of priority. This policy is in place for a good reason but can pose a challenge for any formal protection of IP for ISIS. Nevertheless, there are numerous examples of technologies, patents and spin-outs that have benefited or arisen in part as a result of work done at ISIS. This can either be directly by ISIS staff, or through the work of ISIS users who are based at universities across the UK.

University commercialisation of research

As a user facility, ISIS mainly supports the generation of technology, intellectual property and spin-outs via the researchers who visit the facility to carry out experiments. Any intellectual property linked to ISIS research would then be likely to be owned by the university or company in question and would not necessarily be known to ISIS. Case study examples of technology and spin-out creation have been mentioned throughout this report as an example of research or innovation impacts. However, we also carried out an academic survey to more directly investigate this area. See Volume 2, Appendix F, Survey of Academic users for full information.

We asked respondents to our academic survey to estimate the number of knowledge-transfer-related outputs (for their research group) that are linked to research done at ISIS. Out of the 200 researchers who completed the questionnaire, 20 indicated that patents had been applied for. This survey therefore suggests that around 10% of ISIS users may apply for patents linked to the research they have carried out at the facility.

Some research groups are more active in this area than others, and this is always likely to be the case given the variety of research being carried out at ISIS and the varying interests of different university departments. Certainly in this survey, of the 28 cases of IP that were cited, 10 were from one research group. The values of these 28 research contracts are uneven – but five significant groups are holding contracts with a total value exceeding 1 million euros. See results of the academic survey below:

Figure 14: Knowledge-transfer outputs

Output category	Number or value
Number of industry research contracts	128
Approximate value of this contract research	>£5 million
Patents applied for	28
Licence agreements entered into	4
Number of these licences that have generated income	1
Start-ups launched	18

Collectively, these IP and licensing cases and start-ups reported by 10% of survey respondents indicates a relatively high knowledge exchange and commercialisation rate and ISIS is playing a key role in the research. For example, users gave the following quotes:

`Studies on energetic materials have been of significant benefit to UK MOD/DSTL and have provided the UK Government with leverage in exchanging information with US and other NATO partners.'

`Establishing that we could produce individual single-walled carbon nanotubes in metalammonia solutions was patented, and led to a licensing agreement with Linde.'

`Transferring neutron Compton scattering knowledge to the European NMR community, resulting in a series of common papers with the use of both techniques.'

There are also 18 start-ups companies mentioned in this survey, spread between 12 research groups. It is outside the remit of this report to give a full summary of all of these, but to give an example, see the case study on Orla Protein Technologies detailed below:

Orla Protein Technologies

Orla Protein Technologies has been developing protein surfaces suitable for use in biosensor devices since 2002. ISIS was critical for the company in addressing two essential steps in technology development – the optimisation of the orientation of antibody molecules on the biosensor, and validation of the reproducibility of the manufacturing process. Tweaking this technology to optimise the process, the company established a suitable manufacturing method.

In 2009 Orla established a spin-out company with a multinational electronic communications supplier, and created a miniature wireless sensor that can rapidly detect infectious diseases and send information using a smart phone. This low-cost device could be used for consumer diagnostic applications in remote or rural areas, and the technology is now ready for pilot production. The parent company Orla has also now secured £500,000 in funding from business angels to expand its activities in advanced protein technology and mobile medical diagnostic applications. OJ-Bio is also attracting separate inward investment from Japan worth $2 million.

`In 2002, I co-founded Orla Protein Technologies with D. Dale Athey and also got a BBSRC fellowship to study bionanotechnology, which enabled me to start research work at ISIS. Orla designs proteins for the creation of biocompatible surfaces and in 2009 we started a joint venture, between Orla and the Japan Radio Company, called OJ-Bio. This is developing hand-held point-of-care devices which use engineered protein layers upon electronic chips to detect signs of disease. The very thin protein layers we make are impossible to see by most methods and neutron reflection at ISIS offers a unique way to define their structure. This data helped convince our electronic engineer partners that we had a robust and reproducible technology upon which to base the joint venture.' Professor Jeremy Lakey, Professor of Structural Biochemistry, University of Newcastle

Commercialisation of ISIS research

ISIS also employs researchers directly: these researchers, as well as supporting ISIS users, undertake experiments either in collaboration with external researchers or on their own (applying for beam-time through the same routes as external users). ISIS scientists are encouraged to maintain various external links and a substantial proportion of staff hold visiting fellowships at leading universities. Therefore, there are examples of technology, IP and spin-outs generated directly from the research of ISIS staff. Below are some case studies describing the latest highlights:

Patents: ISIS has developed a new cost-effective way to run hydrogen fuel-cell vehicles

Researchers from ISIS have developed a new cost-effective way to run hydrogen fuel-cell vehicles by filling the cells with ammonia. Major car manufacturers including Toyota, Honda and General Motors have committed to launch hydrogen cars by 2015 and have already invested over £3.7 billion in their development. The hydrogen car market is predicted to be worth £161 billion by 2050. However, there are high manufacturing costs and safety concerns with the storage of hydrogen gas. Ammonia can be transported and stored easily, and can be manufactured cheaply. This research at ISIS offers a solution to some of the major challenges in harnessing the power of hydrogen as a fuel source, and could address some of today's transportation issues. Several patents have been filed by STFC for the use of ammonia as fuel and its storage.

Technology: ISIS has taken a world lead in the development of software used to manage data

The 3D visualisation of data is essential for the state-of-the-art instruments at ISIS, and computer simulation of neutron and X-ray scattering data is a field in which ISIS has taken a world lead. MANTID software, developed by in-house by ISIS, has been rapidly adopted by other facilities across the world including Oak Ridge National Laboratory in the US. ISIS has now set up a collaboration with Tessella, an IBM spin-out, to distribute this software and provide data and software support services while ISIS keeps control over the software development.

The value of this approach and its results cannot be overstated. The International Review Committee concluded that ISIS was the only user facility that has succeeded in developing and implementing a coherent data analysis and archiving framework with modern information technology tools. The quality of the ISIS solution is revealed in the rapid adoption of MANTID at other sites. For example, Oak Ridge National Laboratory adopted the software framework for its own Spallation Neutron Source (SNS), because it was far superior to its own data-analysis tools. MANTID is continuing (2014) as a large international collaborative software development project for neutron scattering data, delivering state-of-the-art data analysis and visualisation software. The project entails collaboration between ISIS, Tessella and Oakridge National Laboratory, and is also supported by developers from ILL, PSI, ESS and the Los Alamos National Laboratory.

Spin-outs: ISIS has created successful spin-out Cella Energy

Cella Energy is an STFC spin-out, launched in 2011 by Professor Stephen Bennington from ISIS, together with Stephen Voller. Cella Energy has expertise in materials and hydrogen storage and owns unique patented technology in safe, low-cost hydrogen storage materials. The company currently (2015) employs 11 staff and has offices and a laboratory at Harwell Campus in the UK, as well as the NASA Kennedy Space Center in the US.

Hydrogen as a fuel has the potential to dramatically reduce UK dependence on oil and, importantly, is an environmentally friendly alternative to fossil fuels. However, hydrogen is a gas under normal conditions, and so the cost of storing and transporting this is technically challenging and often prohibitively costly. Cella Energy has solved this by developing a solid hydrogen storage material which could revolutionise energy generation in a number of markets. For example:

- **The hydrogen car market** is predicted to be worth £160 billion by 2050, and major car manufacturers including Toyota, Honda and General Motors have already invested over £3.7 billion in their development. Cella Energy's convenient way of storing hydrogen at normal pressures could be revolutionary for this industry.

- **Improved battery performance.** Currently, the lack of efficient and dependable batteries limits the development of many products. Cella Energy's technology performs significantly better than current lithium-ion batteries. The global lithium-ion battery market is expected to be worth $22.5 billion[32] by 2016.
- **Unmanned Aerial Vehicles (UAVs)** are currently a fast-growing market, with UAVs used in agricultural monitoring, search and rescue operations, aerial photography and even deliveries. Global UAV markets are estimated to be worth $55 billion between 2015 and 2025[33]. Together with L2 Aerospace, Cella Energy has already successfully launched a new UAV.
- **Co-combustion systems.** There are currently serious health concerns surrounding diesel emissions and government regulations have become more stringent particularly in Europe. Cella Energy has developed hydrogen systems that can feed into diesel engines, including older engines, making them more effective and reducing carbon emissions.
- **The aerospace industry** continually needs to reduce aircraft emissions and also to improve performance. As a consequence, Cella Energy's technology has attracted a great deal of attention. Safety, cost and weight are of paramount importance in aviation, and Cella Energy's technology offers an attractive means to provide power in a safe and lightweight way. In 2014, Safran and Cella Energy signed an exclusive partnership to develop hydrogen-based power systems for the aerospace industry.

Cella Energy has attracted millions of pounds worth of external investment from a number of sources since its launch. Persephone, a US private equity firm that typically invests in alternative energy, acquired Cella Energy in 2014. In this acquisition, Persephone provides financial and management support to Cella Energy, which continues to be managed by Stephen Bennington from ISIS, the original founder and the driving force behind the technology.

`Persephone's goal with the acquisition of Cella Energy is to produce a hydrogen based rechargeable clean energy source for transportation, aviation and other portable energy requirements. The future of clean and more efficient energy is closer than most would believe.' Persephone CEO Jay Lifton

4.2.7 ***ISIS plays an important role in the Harwell Campus***

Harwell Campus is a leading science, innovation, technology and business campus with research infrastructure (collectively worth around £1 billion) located on a 710-acre site near Oxford. It has been in existence in different forms for over 60 years, from the foundation of the Atomic Energy Research Establishment in 1946 to the opening of the Diamond Synchrotron in 2007 and the Research Complex in 2010. Over 5,000 people are now part of this vibrant, fast-growing community, working in some 200 organisations including key UK Research Councils, start-ups and multinational organisations that focus on a range of commercial applications including healthcare, medical devices, space, detector systems, computing, green enterprise and new materials.

ISIS has been a central part of this site for over 30 years. It sits at the heart of the Harwell science and innovation campus, contributing to an evident and strengthening community of researchers and industrialists. `Place' makes a difference in the success of science and innovation initiatives in the UK, clustering resources and industries, and enabling collaboration and advances that would not be

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32 Mountain View, Calif.-based market research firm Frost & Sullivan

33 `The Economic Impact of Unmanned Aircraft Systems Integration in the United States'. AUVSI, March 2013

possible in isolation[34]. ISIS has had an impact on the development of the Harwell Campus. ISIS's success was critical in the decision to locate Diamond at Harwell. ISIS was also a factor in the location of the UK portal for CERN: the Data Centre, Technology and Particle Physics departments were all retained at Harwell in part due to ISIS and its impact on the mobility of national and international scientists.

The Research Complex

The Research Complex at Harwell (RCaH) is a relatively recent addition to the campus, which hosts more than 100 long-term scientific visitors. It was opened in July 2010 and is a £26 million investment in offices, lab space and laser facilities available to researchers, who can also make use of any of the big facilities at Harwell (Diamond Light Source, ISIS and the Central Laser Facility). University College London (UCL), for example, is centrally involved, particularly through its UK Catalysis Hub, a very successful UK programme for Catalysis research which is hosted as part of the Research Complex. This experience has led UCL to make a formal expression of interest in building a 3,500 sq m facility next to ISIS. The University of Manchester is similarly considering creating an out-station at Harwell on the back of its success with the Manchester X-ray Imaging Facility (MXIF). These developments have helped to seed a proposal to create a university quarter at Harwell, as part of the campus masterplan, which ISIS is supporting actively.

Companies at Harwell

There are examples of local businesses that have grown substantially in large part because of ISIS or have located at the Harwell Campus in order to benefit from the scientific expertise here. For example:

- **Tessella**, which was founded more than 30 years ago as a spin-out from IBM, has built its business in providing data and software support services to major science and technology operations such as the UKAEA and ISIS.
- **AVS** has recently (2014) opened an office at Harwell; this is a result of its supply of technology for the recently upgraded Polaris instrument at ISIS. The upgraded instrument was designed in Spain by AVS and built by another Spanish engineering company, Cadinox, as part of a multi-million pound `in-kind' contribution provided to ISIS by the Spanish government. The Spanish government's promotion of these two regional technology companies has enabled both organisations to develop a stronger position within the small but demanding international market.
- **Infineum UK** is based close to Harwell and is one of the world's leading manufacturers of fuel and lubricant additives. The company has taken advantage of the ease of access to ISIS, having used the facility for a number of different research projects – looking in particular at fuel formulations with the aim of improving performance and reducing emissions. They have also applied for beam-time through the ICRD scheme at ISIS.
- **Element 6** has recently invested £20 million in their new Global Innovation Centre at Harwell. This brings all of the company's global innovation departments together in one building in order to maximise its ability to deliver the most innovative products. The new facility is home to more than 100 of the world's top scientists, engineers and technicians, and has created 60 new jobs. As described by Element 6 on their website (2014):

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[34] `Our plan for growth: science and innovation'. HM Treasury and the Department for Business, Innovation and Skills. December 2014

> *`The site at Harwell was chosen to maximise the ability of Element Six to recruit the top people from a talent pool covering a variety of scientific fields. Its proximity to Oxford and other leading UK universities also facilitates the ability of the team to enjoy productive partnerships with both academic institutions and cutting edge industries. It's the kind of R&D environment which will enable Element Six to add to a track record of innovation. This already includes detectors in the legendary Large Hadron Collider and extreme cutting tools for the aerospace industry.'*

Also mentioned previously in section 4.2.5 is a relevant case study on the supplier, Prototech Engineering, who have benefited from being located close to ISIS.

4.3 Summary

ISIS has wide-ranging and long-established industrial links, with more than 100 companies having used ISIS substantially over the past 30 years, and with Unilever, for example, writing a letter to the Government in 2006 in support for the ISIS facility. ISIS is often used by Industry as part of their research and development programmes or as part of their development process, looking at important processes such as, product design, manufacturing, process understanding, and safety testing and improvements.

As well as supporting business directly in achieving to specific research and development aims, ISIS also supports UK innovation in other important ways. ISIS research feeds into new commercialisation opportunities that can then lead to the formation of new products and technologies. This creates new UK businesses and accelerates the growth of existing businesses, directly supporting the UK economy. ISIS also supports local, national and international supply chains, often upskilling and supporting local and UK suppliers, and enabling them expand in a competitive global market place.

The number of businesses using ISIS is increasing and this can only have a positive impact on the UK economy, supporting UK research excellence and driving our knowledge economy. As detailed below, our main conclusions on the impact ISIS has had on innovation are as follows:

1. Industrial use of ISIS is significant; research with industrial links now account for 10-15% of total ISIS beam-time.
2. The types of benefits that ISIS provides to industry are wide-ranging and across multiple applications.
3. Companies who use ISIS report increased productivity, competitiveness and share value.
4. The industrial use of ISIS has and will continue to directly benefit the UK economy; we conservatively estimate £400 million up to 2025.
5. ISIS suppliers derive substantial benefits in numerous areas of their business.
6. There are many examples of the successful commercialisation of ISIS research.
7. ISIS plays an important role in the Harwell Campus.

Again, our conclusions are supported by a recent and separate International review of ISIS. For example, that review concluded:

`ISIS operations are providing an excellent capability to the user community, and are certainly world-class. ISIS has, since its creation, been able to create a culture of innovation that has had profound impact on, and will continue to change, the way neutron scattering is performed world-wide. Very few research institutions have demonstrated similar drives toward innovation and spread of the resulting technological development.'

5. ISIS Skills

5.1 Introduction

Internationally recognized facilities such as ISIS help the UK drive a knowledge-based economy, supporting world-class research, innovation and skills in a number of ways. For example, ISIS invests in the development of its staff, trains the next generation of scientists and engineers, supports industry and provides inspiration for thousands of students to study STEM subjects in higher education. In this section we explore the use of ISIS and its impact on skills in the UK. From this, our main conclusions are;

1. **ISIS staff members are nationally and internationally recognized for their work.** Our analysis of various measures of the scientific esteem and skill level indicate that ISIS staff members are essential in the national and international importance of ISIS.
2. **ISIS enables UK scientists and organisations to carry out world-leading research.** ISIS has a clear focus on user service, supporting academics to achieve exceptional results. ISIS also leads or contributes expertise to other neutron facilities and programmes world-wide.
3. **ISIS nurtures scientific talent in the UK, which we estimate is worth £30 million to the UK economy.** Over 60% of academics asked report that ISIS has played a critical contribution to UK skills in science; and over 50% report that ISIS has been critical to their own career success.
4. **ISIS trains and inspires the next generation of scientists and engineers, which we estimate is worth £3 million to the UK economy.** ISIS has a broad and highly regarded education programme, engaging with many students and young people over the last 30 years.
5. **ISIS provides valuable skills to industry.** Our analysis shows this is achieved in a number of ways and is widely acknowledged among industrial users. We highlight examples of this through case studies and the results of our industrial and supplier survey.

5.2 Discussion

5.2.1 ISIS staff members are nationally and internationally recognized for their work

ISIS staff members play an essential role in the national and international importance of ISIS as a facility. Our analysis of various measures of the scientific regard and skill level indicate that ISIS staff are held in extremely high esteem nationally and internationally and this benefits ISIS as an organisation, giving it credibility world-wide.

Staff profiling

The annual 'staff profiling' exercise undertaken by ISIS attempts to record achievements over a year to demonstrate the esteem in which ISIS staff are held, their scientific and technical expertise and any leadership roles taken internationally. The 2011-12 exercise found that staff over the course of one year:

- Gave around 170 talks at a wide variety of meetings and events, some 93 of which are listed as 'invited talks'.
- Are members of 27 external scientific and technical advisory committees for other facilities and institutes.
- Helped to organise around 30 scientific and technical meetings, not including fora such as ISIS user group meetings.
- Are involved in over 30 technical collaborative projects (e.g. EU collaborations), not including the huge number of 'normal' scientific collaborations with external colleagues.

- Are heavily involved in peer review, including journal articles, theses, experiment selection panels, grant review panels, etc. – 47 staff members list such involvement.

Awards for ISIS staff members

ISIS staff members have also received numerous awards and scientific prizes. Below we have listed just three examples of academic awards. These are in no way representative of all awards given to ISIS staff over the last 30 years but provide examples of the type of recognition given to ISIS staff. These awards are indicators of the international and national recognition these researchers have received and the impact they have had in their field.

- **Professor Jeff Penfold**, STFC Senior Fellow and ISIS Senior scientist, won a prestigious award from the Society of the Chemical Industry, The Rideal Lectureship, as well as the 2007 European Neutron Scattering Association Walter Haalg prize for his three major scientific contributions to surfactant, colloid and interface science. He also received the 1995 RSC Colloid and Interface Science Group medal, an internal promotion within STFC, and has a visiting Professorship at Oxford University since 2002.
- **Dr Alan Soper** was elected as a Fellow of the Royal Society in 2014 for leading research on the structure of water and aqueous solutions, including development of novel instruments and techniques that have revolutionised the field, and his pioneering use of computer simulation.
- **Dr Robert Dalgliesh** from the ISIS Neutron and Muon Facility was awarded the prestigious 2011 BTM Willis Prize for neutron scattering. This is in recognition of his development of novel neutron techniques that are opening up new areas of fundamental and applied research in nanoscience.

Careers for ISIS staff

Records of STFC staff show their location and that ISIS staff have progressed to new research posts in national and international locations, have moved into commercial roles, and have also supported commercial ventures (such as Cella Energy). Graduates and apprentices at ISIS have also moved through to senior posts within ISIS and at other facilities. The STFC apprentice scheme is highly competitive, and 100% of its graduates receive an offer of work as a technician at one or other of the STFC facilities.

ISIS also funds PhD-level scientists (currently over 60) who conduct their own research programmes, usually in collaboration with external researchers. We understand from the senior management team that 200-300 doctoral students have moved through ISIS, benefiting from the insight and advice over the past 30 years. The current cohort of students includes many young scientists from all over the world (e.g. the US, Canada, Australia, India, Japan, Brazil and South Korea) as well as students at UK universities.

5.2.2 ISIS enables UK scientists and organisations to carry out world-leading research

ISIS supports academics to achieve exceptional results and also leads or contributes expertise to other neutron facilities and programmes in the UK and world-wide. Research facilities such as ISIS can make a lasting contribution to the standing, capacity and capability of academic and industrial communities, through the experimental skills developed on the facility by research students and post-docs who go on to work as facilities scientists, academics and industrial engineers, amongst other things.

Our analysis of various measures, which includes the results of our academic user survey, indicate that ISIS has a significant impact on the wider research community, including the academic careers of UK and international scientists. ISIS has also had a significant influence on particular fields of research and has directly supported other scientific organisations to develop new facilities, infrastructure and enter new fields of scientific research.

Academic user survey

The 200 replies to our online survey of ISIS's academic users provided our team with an excellent profile of the importance of ISIS to its users (see Volume 2, Appendix F, Survey of Academic users for more information). The results are conclusive and emphatically positive, with users rating ISIS as critical to their own career, and over half saying ISIS has had a large and positive influence on their career progression (over 50%). A large majority (80%+) of respondents also consider that ISIS has helped them to make a significant contribution within their field, while around 60% feel that ISIS has been very important in enabling them to win research grants. A small proportion of respondents also believe ISIS has contributed to their winning a major scientific prize, which is a notable result, given the scarcity of such outcomes.

Figure 15: Impact of ISIS on academic users' research profiles and careers (n=193)

Aspect	n/a (%)	None (%)	Small (%)	Significant (%)	Critical (%)
Your impact within a field	5.4	1.1	14.1	43.5	35.9
Winning research grants	14.2	5.5	20.2	37.7	22.4
Promotion to senior post	27.4	15.6	14.5	29.1	13.4
Appointments to high-level groups	37.9	14.3	16.5	20.9	10.4
Award of major scientific prizes	47.0	17.7	13.3	16.0	6.1
Attracting industry contracts	42.5	16.0	19.9	15.5	6.1
Fellowship at learned societies	55.9	17.3	14.0	8.4	4.5

We also asked respondents who had rated their use of ISIS as 'critical/decisive' or 'significant' to explain briefly what the achievement was. Around 55% of respondents answered, citing a diverse range of achievements. For example:

'About 98% of my publications are coming from the results of my experiments in RAL.'

'I have 13 papers cited 100 times or more: nine of these arose from neutron diffraction studies, most of these at ISIS.'

'100% of my publications in the last 24 months have relied on, or been made possible by, experiments performed at ISIS.'

'My h-index is 19, in less than nine years after my first publication, all but one [of the contributing papers] featuring some ISIS input.'

We also asked senior ISIS users to think more broadly about the research field and what extent they believe ISIS has contributed positively to the skills available in the UK and internationally. This indicates that ISIS has played a critical contribution to UK skills in science. See Figure 16 below:

Figure 16: ISIS contributions to the field overall

Aspect	Not at all	A small contribution	A significant contribution	A critical contribution	No view
Developing the skills of early career researchers	0.0	5.1	32.2	61.0	1.7
Developing experimental skills	0.0	1.7	40.7	55.9	1.7
Improving the quality of doctoral training	0.0	5.2	37.9	53.4	3.4
Developing analytical skills	0.0	8.5	40.7	49.2	1.7
Developing collaborative skills	0.0	10.2	45.8	39.0	5.1
Developing project management skills	3.4	32.2	30.5	15.3	18.6

Staff profiling

ISIS staff members are playing an essential role in supporting and contributing to other neutron sources around the world (e.g. ISIS staff working for, advising or transferring to other facilities). For example, in 2014, ISIS staff:

- Have led the Muon network and Detector network. This gives ISIS credibility world-wide, as a key player in Europe for neutron scattering and muon spectroscopy.
- Have had a substantial influence on the European Spallation Source (ESS) design and strategy, with current and former ISIS staff involved in the laboratory's steering committee as well as its overarching scientific and technical committees.
- Sit on advisory boards for other facilities e.g. ESS.
- Have established long-term scientific collaborations, for example, influencing the development of the new national Chinese neutron source (which will be up and running in five years).

Awards for ISIS users

ISIS also enables researchers outside ISIS to carry out world-leading research. Below are a few examples of the academic awards and recognition that ISIS users have received linked to their work at ISIS, which is more often than not directly supported by ISIS staff. These awards are indicators of the international and national recognition working at ISIS can help achieve.

- The molecular structure of C_{60}, the novel football-shaped form of carbon also known as bucky balls, was first discovered by researchers **Robert F. Curl, Harold W. Kroto and Richard E. Smalley** who subsequently won the 1996 Nobel prize for Chemistry[35]. Subsequent studies at ISIS determined the crystal structure of C_{60}, and this combined knowledge has been essential not only in understanding the large number of C_{60} based molecules produced since but also the fundamental properties of the carbon-carbon bond.
- The 2012 Europhysics Prize for condensed matter physics has been awarded to ISIS neutron user **Professor Steve Bramwell** (London Centre for Nanotechnology and University College London), **Claudio Castelnovo** (Royal Holloway University of London and ISIS Theoretical

35 http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1996/press.html

Physics Group) and their colleagues, for the prediction and measurement of magnetic monopoles in spin ice.

- **Dr Anita Zeidler was awarded the prestigious 2014 B.T.M. Willis Prize for neutron scattering.** This was in recognition of her studies into a wide range of materials, including water, and their interactions at the atomic and molecular level. Dr Zeidler's work used ISIS and ILL (Institut Laue Langevin) facilities.

Impact of ISIS user service

ISIS also has a clear focus on user service, with a large dedicated sample environment group that offers a wide range of state-of-the-art sample environment equipment, support labs and technical expertise to support ISIS users with their science programmes. In-house expertise from ISIS staff is available to support users with their science programmes at ISIS. Team members can also arrange for more unusual apparatus and combinations of parameters to be supplied. As a result of this in-house capability on the part of ISIS staff, the time lost because of problems with sample environments for users is extremely low, at only 1.5%, which the International Review Committee called a `*truly remarkable performance'*.

5.2.3 *ISIS nurtures scientific talent in the UK, which we estimate is worth £30 million to the UK economy*

ISIS provides a significant level of 'on-the-job' training for early career researchers (post-docs) who use the facility and also has a strong training offer for staff, which is varied and unusual and compares well to industry schemes, opening the door to further national and international opportunities. ISIS also functions as a leading training provider, delivering high-quality, specialised educational experiences to hundreds of UK and international learners at all levels.

Academic user survey

Some 500-800 students gain experience each year working alongside academic users and ISIS scientific staff. This type of capacity-building is considered to be significant by the great majority of respondents to our academic survey. For example, we included several open questions in our academic user survey, inviting people to describe briefly the single most important benefit to have derived from their work at ISIS, and a significant minority elected to list training. The following bullet points encompass a cross-section of the kinds of remarks made by ISIS users:

'ISIS's main contribution to skills is in training PhDs to carry out experimental research. Using big facilities is important for learning several organisational skills (time management, preparation, collaboration, communication, etc) as well as the technical skills involved in the instrument set up and analysis. ISIS support staff are excellent: young researchers acquire a level of proficiency in experimental work they would not come close to at university.'

'I run an industrial placement scheme for undergraduate students. The majority of such students have performed work at ISIS with my team. Of these (22) students, 70% have gone on to study for physical chemistry PhDs and the majority of these have used ISIS subsequently.'

'I would like to mention that the ISIS training course was especially helpful for me, as it was the first time I came into contact with neutron scattering, which has proved very useful in my research. It also enabled me to make contacts in the community.'

ISIS training

ISIS is delivering perhaps 2,000 days of 'on-the-job' training to the students and post-docs who use the facility each year, and very many more days – indirectly – through preparatory work and post-visit analytical work at their respective universities. Some examples of the type of 'on-the-job' training for ISIS users are described briefly below (see Volume 2, Appendix K, Further information on training and education at ISIS for more information):

- ***The Neutron Training School.*** ISIS runs a Neutron Training School for PhD students and post-docs with little or no previous experience of neutron scattering. This course is run once a year, typically with 24 students, and is seven days in length. Each ISIS course is oversubscribed by a factor of five, and produces strongly positive feedback from participants.
- ***Muon Spectroscopy Training School.*** This school is one of two in the world and is funded by the European Commission. It provides practical training for PhD students and post-doc researchers on the use of muons and has been running since the mid-1990s. The school is run for a total of five days and typically accepts around 20 students annually.
- ***Lecturing.*** A review of staff activities in 2011-12 found that ISIS staff members hold around 20 external positions at universities such as visiting professorships or other appointments. A number also give individual talks at external student events or contribute to university lecture courses. This is in addition to the help they provide with the various formal training schemes mentioned above (training schools, etc.).

Economic analysis

ISIS is delivering many thousands of days of 'on-the-job' training to research students and post-docs each year: post-docs and doctoral students constitute the great majority of all ISIS scientific users. To monetise the value of their facility-enabled training delivered by ISIS scientists (in addition to the post docs' professors and academic co-workers), we assumed that an average of 1,000 post-docs / students have received the equivalent of five days experimental training each year at a unit price of £200 a day, which gives a figure of £30 million across ISIS's 30-year lifetime (up to 2014).

Type of socio-economic impact	Estimated ISIS lifetime (1985 to 2013)	Estimated future impact (2014 to 2025)*	Total estimated impact (1985-2025)[36]
Skills-related impacts	£30 million	-	£30 million

5.2.4 *ISIS trains and inspires the next generation of scientists and engineers, which we estimate is worth £3 million to the UK economy*

ISIS has a broad educational programme, which has engaged many hundreds of students and young scientists over the past 30 years, inspiring young people to pursue STEM careers. Some of these schemes are detailed below (see Volume 2, Appendix K, Further information on training and education at ISIS):

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[36] *Based on projects and research already done now. Excludes any new work ISIS will carry out in the future

- ***Particle Physics Masterclass.*** The ISIS facility takes part in the STFC's annual Particle Physics Masterclass, which typically attracts around 600 'A' and 'AS-Level' students. The aim of the event is to inspire students to pursue careers in science, technology, engineering and mathematics by providing them with 'real life' experience of a working research centre.
- ***STFC Apprentice Training Scheme.*** The STFC has been running this scheme for more than 20 years. During this time there has been an intake of 114 apprentices, split 48% mechanical, 35% electrical and 15% electronic. Apprenticeships are four years in duration and involve attendance at College. At the end of the apprenticeship scheme, *all* apprentices are offered a job as a technician, with around 50% of those new appointments being located at the ISIS facility.
- ***Graduate Training Scheme.*** ISIS participates in the highly competitive STFC Graduate Training Scheme. The appointees have permanent contracts, rather than the short-term fixed contracts that would be typical for post-docs in universities. During the first two years of the programme graduates work alongside other graduates to complete a programme of in-house training courses and workshops in a variety of personal and professional skills.
- ***STFC Sandwich Student Placement Scheme.*** STFC runs an Industrial Placement scheme which ISIS has been involved with. This offers undergraduates enrolled on a sandwich degree the opportunity to spend 12 months, working as a paid intern (c. £17,000 p.a.) at one of the STFC's several sites. ISIS has hosted a significant proportion of these interns although the number of placements available varies. In 2013-14, eight projects were advertised under this scheme.
- ***STFC Vacation Student Scheme.*** STFC Vacation Student Scheme provides undergraduate students with an opportunity to do a summer placement at one or other of its laboratories or technology centres. ISIS is a major supporter of the scheme and provides three-five students each year with the opportunity to work on projects and gain practical experience under the supervision of experienced ISIS staff. School and work experience placements are also offered to GCSE students and ISIS takes many students annually to work on small projects of typically two-three weeks' duration.

Economic analysis

We have obtained estimates of the numbers of people attending or graduating where possible, and we have gone on to reflect on a method for valuation, perhaps using market prices for courses or a cost-based approach to other educational support activities, where we have salary details and estimated mentoring inputs by ISIS staff. The results are not especially clear-cut, however; and where we have found pricing data, for summer schools, for example, we see charges that range from around £100 a day for Oxford's neutron summer school through to £300 a day for non-academics attending statistics courses. The price – and cost of delivery – will vary depending upon the educational programme in question, with post-16 apprenticeships for example costing rather less in proportionate terms as compared with PhD supervision.

As a first approximation, with ISIS staff delivering somewhere in the range 500-1,000 days of education and training support each year, we would argue that contribution might be conservatively priced at between £100,000 and £200,000. If we assume ISIS has delivered on average 500 training days each year over its lifetime, working with the lower number in our range to reflect the facility's expansion over time, at an equivalent price of £200 a day, we arrive at a total estimate of £3 million (up to 2014).

Type of socio-economic impact	Estimated ISIS lifetime (1985 to	Estimated future impact (2014 to	Total estimated impact (1985-

	2013)	2025)*	2025)[37]
Training-related impacts	£3 million	-	£3 million

5.2.5 ***ISIS provides valuable skills to industry***

ISIS supports industry in a number of ways. ISIS staff and users, who learn skills through ISIS research and training programmes, often work in or for industry during their career. It is often the case that companies will actively recruit academics who have received academic training and carried out industrially relevant research. ISIS also provides valuable skills to industry directly through collaborative research and through knowledge exchange programmes. Industry receives support directly from ISIS staff, receiving training to carry out research or support to develop particular technologies (whether ISIS suppliers or companies who are developing their own technologies). ISIS also supports universities and their own staff in developing commercial technologies and creating spin-out companies when possible.

Case studies

Below are examples of how ISIS has supported industry. These two case studies, from Siemens and Tata Steel, show how even large scale multinational companies have and are continuing to benefit from ISIS expertise:

Tata steel: ISIS staff collaborate directly with industrial partners

Tata Steel employs approximately 900 engineers and scientists world-wide in R&D. In the UK, their R&D site employs around 175 staff and focuses on steel product and applications research – for example, looking at the development of advanced welding technology and weldability of high-strength steels for demanding applications in the energy and power industry.

Research collaboration between ISIS and Tata Steel involves a number of researchers. For example, Dr Shuwen Wen is a Principal Scientist at Tata Steel in the UK. He has more than 20 years of experience in the modelling of materials and manufacturing processes and his recent research work includes weld residual stress characterization using the Diamond Light Source (I12) and ISIS (Engin-X) facilities. Prof Shu Yan Zhang is a senior scientist for the Engin-X beamline at ISIS. In 2012, she was promoted to Senior Scientist at ISIS in recognition of her valued contribution, having established close research collaborative links nationally and internationally with industries, universities and research institutes. Her closest collaborations have been with companies including Tata Steel, EDF Energy, AREVA (France), Rolls-Royce and TWI.

One example of the type of research carried out by these collaborators includes measuring the residual stresses in applications such as welded line-pipes for deep-sea oil and gas transportation[38].

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[37] *Based on projects and research already done now. Excludes any new work ISIS will do in the future

[38] `Neutron Diffraction Measurement of Weld Residual Stresses in an UOE Linepipe Subjected to Mechanical Expansion'. Shuwen Wen, Hongbiao Dong, Shu Yan Zhang, Adam Bannister and Martin Connelly

The demand for deep-sea oil and gas supply is increasing due to the higher demand on energy and security of energy supply. At ISIS, measurement of residual stress by Dr Shuwen Wen from Tata Steel, in association with Prof Zhang from ISIS and with the University of Leicester, was carried out to improve the understanding of failure mechanisms of linepipes.

Siemens ONIAC; ISIS staff provide direct support in testing the viability of new commercial technologies and infrastructure

In 2009, Siemens built the ONIAC test facility at ISIS Target Station 2 (see Volume 2; Appendix L, Siemens, ISIS and the ONIAC facility, for a full case study). Siemens used this facility to test an accelerated proton beam to produce radioactive tracers for medical diagnostics. The production of such radioactive tracers is currently performed by central facilities, which are large, heavy, complex and expensive to maintain. Siemens' aimed to use ISIS to investigate whether a simple, lightweight alternative to current technologies could be produced.

The global market for radioisotopes was valued at around £2.7bn in 2012, and is expected to grow steadily at 5-10% a year over the next five years, driven by the increasing use of PET and SPECT scanners. A very rough estimate of a unit price suggests that the global market for compact accelerators could quickly develop into a market value of hundreds of millions a year within the next 5-10 years.

There are currently two Siemens and two ISIS research engineers working on the project, part time. In addition, ISIS technicians provide vacuum, electronic and mechanical support when required. Siemens pays rental for the facility, covers the cost of staff time and covers the cost of any resources used on the experiment.

It is expected that the ISIS/Siemens collaboration on the ONIAC facility will result in a Master Research Agreement between STFC and Siemens in the near future (as of 2014) to extend partnership to other high-risk projects. In addition, the ISIS-Siemens partnership is having a direct impact on UK businesses beyond STFC. Over 8o% of the manufacturing for the ONIAC facility is contracted from UK companies; mostly locally in Oxfordshire, but the highly specific shells for the ONIAC facility were precision cut by laser in North England.

"There is always pressure to locate Siemens research in Germany. However, I believe that Siemens could not get the same level of support in German national facilities as they do at ISIS. Input to a national laboratory is also mutually beneficial. STFC is getting a first-hand view of some of the intellectual property and novel technologies developed by Siemens. Siemens can develop and test new ideas rather quickly in close relationship with STFC and utilise their existing expertise." Professor Paul Beasley, Head of Strategic Development at Siemens Corporate Technology

Academic and Supplier user survey

The value of the skills ISIS provides to industry is also described in feedback received in the academic and supplier surveys we ran (see Volume 2, Appendix F, Survey of Academic users and Appendix H, Survey of suppliers to ISIS Target Station 2 (TS2) for full information).

In response to open questions in the academic user survey, which invited academics (some of whom work for or with companies) to describe briefly the benefits derived from their work at ISIS, a significant minority elected to list industrial skills and relevant training. The following bullet points encompass a cross-section of the kinds of remarks made:

`The students that pass through ISIS learn important practical skills that are critical to industrial research, in terms of study design and the efficiency of our methodologies. In many cases, companies struggle to know how to proceed with a question may be forced to try every technique (blindly), which costs a fortune and takes forever. The ISIS scientists can work out how to get things done. There is also discipline: we have to do three months' work in two days, which really sharpens up your planning skills; we also need an ability to think on our feet, as experimental work rarely ever goes exactly to plan and the best facilities scientists will spot things going wrong early and find solutions on the fly.'

`Our group has trained many PhDs over the years, many of whom have gone on to use neutron scattering in their own research and these individuals are working in one or other of three areas: facilities scientists, academics or industrial scientists. They all get employed, not always immediately, but pretty quickly. There is generally a recruitment exercise going on somewhere. This is such a specialist technique that companies don't have the scientific know how, they will always look to recruit or collaborate, they will not develop the skills in-house themselves.'

`My research is not about inventing but about understanding and this is critical for industry, as they have to transfer from empirical to mechanistic understanding. Many of my research students now work in industry and use the knowledge we have generated. Our research also educates industrial researchers who we collaborate with.'

We also included several open questions in the supplier user survey. Here skills development was also important, for example in increased technical capability:

`We gained expertise in working with unusual materials, such as titanium zirconium.'

`The most important factor for us is the ability to develop new product and resolution for problems we may not face in normal industry.'

5.3 Summary

Internationally recognized facilities such as ISIS help the UK drive a knowledge-based economy, supporting world-class research, innovation and skills. World-class skills in UK society are one of the most important ways in which the UK can maintain its position as one of the major knowledge economies of the world. World-class research and innovation depend on the outstanding performance and contribution of UK researchers, technologists and engineers to create knowledge, exploit ideas, and build and operate large-scale facilities.

ISIS's contribution to skills is widely acknowledged in our interviews and surveys, among both academic and industrial users. It is an aspect that is praised repeatedly in the ISIS International Review, too. The skills-related benefits range from ISIS's creation of a large group of facilities scientists through to the 'on-the-job' training afforded to several hundreds of early career researchers (post-docs) and research students each year, who go on to work in academia and industry. ISIS also functions as leading training provider, delivering high-quality, specialized educational experiences to hundreds of UK and international learners at all levels, from schoolchildren to undergraduates. As detailed above our main conclusions on the impact of ISIS on skills are, as follows:

1. ISIS staff members are nationally and internationally recognized for their work.
2. ISIS enables UK scientists and organisations to carry out world leading research.
3. ISIS nurtures scientific talent in the UK, which we estimate is worth £30 million to the UK economy.

4. ISIS trains and inspires the next generation of scientists and engineers, which we estimate is worth £3 million to the UK economy.
5. ISIS provides valuable skills to industry.

Below is a quote from the International Review of ISIS:

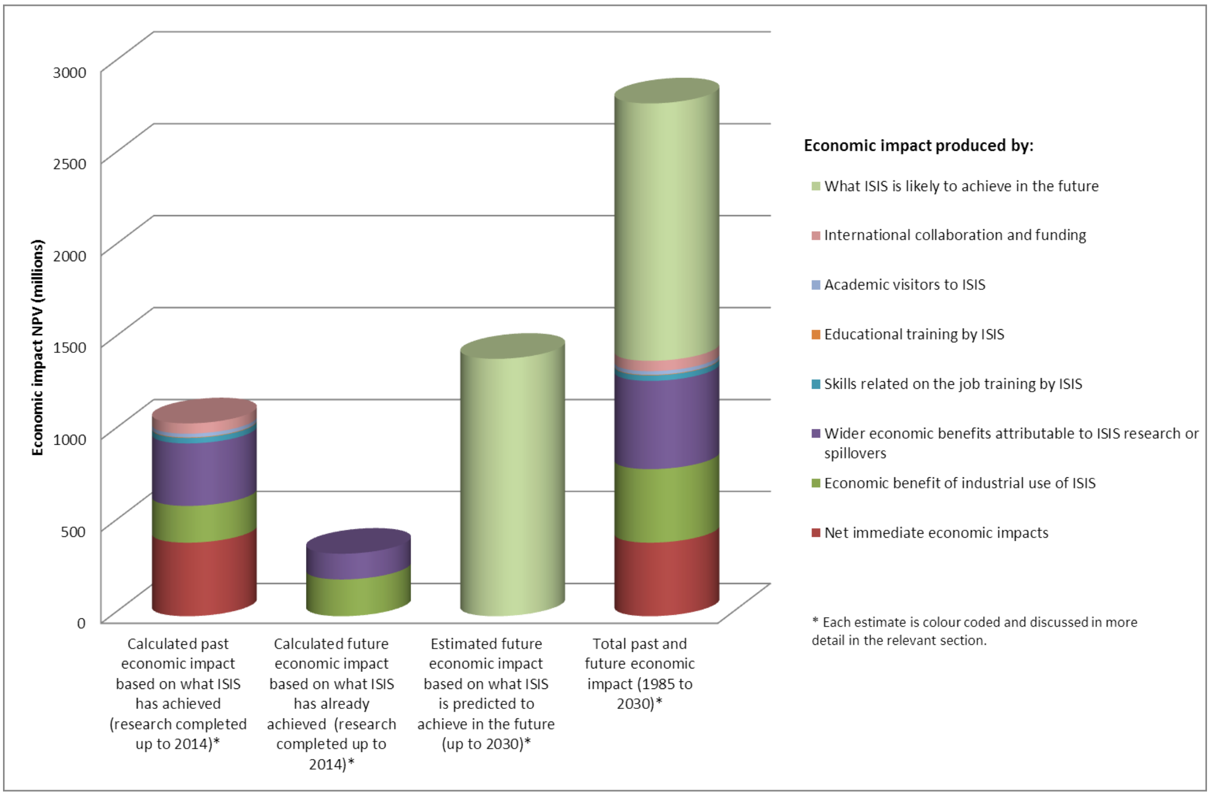
`In all research fields, top ISIS researchers and users are recognized far beyond the neutron scattering community. This is the best proof of 1) The quality of the staff, 2) The strengths and value of neutron scattering to the various scientific communities, 3) The relevance and impact of the research performed at ISIS. Finally, it is remarkable that a number of former ISIS staff, PhD and Post Docs are now on faculty positions at UK universities. This demonstrates the important impact ISIS has had on the UK science community.'

6. Economic Impacts

6.1 Introduction

In this section we explore the economic impact of ISIS. We summarise our analysis of the different types of social and economic impacts that are attributable to ISIS over its 30-year history. We add together the estimates made throughout this report in the Research, Innovation and Skills sections, and summarise this with the other direct economic impacts analysed in this section. Figure 17 represents all the estimates of the different types of social and economic impact which are attributable to ISIS.

Figure 17: Estimated past and future Economic Impact of ISIS



1. Overall, we estimate ISIS has delivered at least £1,049 million in net economic impact to the UK economy as a result of its work over its lifetime (1985-2013).

2. Based on research and innovation already completed we estimate an additional £340 million on top of this in NPV terms up to 2025.

3. With total ISIS expenditure on the order of £700 million, of which around £650 million has been provided by the UK government, and using our conservative estimate of overall economic benefit (£1,389M), we get a Return on Investment (ROI) figure of around 214%. This figure sits at the mid-point of the range of estimates of ROIs reported by Frontier

Economics in their 2014 literature review: ROIs for private rates of return (max 315%) and for social rates of return (max 155%).[39]

4. ISIS continues to operate and we would expect to see substantial further scientific and economic benefits through to 2030. The next 15 years of research could easily match the order of magnitude of benefits seen in the first 30 years, i.e. an additional **£1,000 million**.

6.2 Discussion

6.2.1 Overall economic impact of ISIS

The table below presents a list of our estimates of different types of social and economic impacts that are attributable to ISIS across its 30-year history, and outlines where we have been able to put estimates against impacts.

Where it has been possible to monetise evident impacts, they are not simply additive. For example, the net immediate economic impact is an estimate of the financial value of past activities; the estimate of impacts of the ICRD programme is anticipated future income. We have sought to overcome these difficulties by computing the net present value of estimates of future benefit flows so they can be added to past benefits. Upper and lower bounds have also been estimated for several categories of impact and, in the main, we have used the more conservative estimate in its overall summation.

[39] 'Rates of Return to Investment in Science and Innovation.' A report prepared for the Department for Business, Innovation and Skills (BIS), Frontier Economics, July 2014.

Figure 18: Overall ISIS Impacts across its lifetime

Type of socio-economic impact	Description of impact	Estimated impact of work already completed		
		Past 1985-2013	**Future 2014-2025**	**Total 1985-2025**
Direct economic impacts				
Net immediate economic impacts	ISIS expenditure generates substantial immediate economic benefits, through its direct employment and a snapshot of its purchases (TS2 build suppliers). Note: Data on all suppliers used across the life of the facility were unavailable.	£400 million	Unable to estimate	£400 million
Visitors economic impact	Several thousand academic/industrial user visitors each year, spending money on travel, food and accommodation in the local economy.	£20 million	Unable to estimate	£20 million
Wider economic impacts				
Research				
Economic benefits attributable to **completed** ISIS research (past and future)	ISIS research is underpinning innovation in the wider economy, within the UK and internationally. Our extended impact case studies suggest this wider benefit is substantial and that the net present value of future income may be as much as £140 million. Working from the £140 million above, historical data suggests that ISIS's past research outputs may be associated with wider economic benefits on the order of £340 million.	£340 million	£140 million	£480 million
Economic benefits of fundamental research	The economic benefit of long-term, global and fundamental research programmes such as bucky balls, surfactants and magnetism. Due to the nature of this impact we have not attempted to value it.	Unable to estimate	Unable to estimate	Unable to estimate
Economic benefits of technology development	Many of the techniques and technology developed on ISIS to support its research programme have been world firsts that have then been adopted by other facilities around the world. Again, due to the nature of this impact, we have not been able to value it.	Unable to estimate	Unable to estimate	Unable to estimate
Economic benefits of international influence	ISIS attracts users from across the globe and we have used international investment into the facility as a proxy of international importance, amounting to around £2 million - £3 million a year.	£56 million	Unable to estimate	£56 million
Innovation				
Future impact of industrial usage attributable to completed research (2015 - 2025)	**Future projections:** ISIS experiments are expected to support UK economic activity that will run into the billions (gross) through to 2025. We arrive at a range of estimates between £50 million and £200 million, by adjusting those gross estimates to reflect ISIS's contribution and also the net present value of that future income stream. **Past estimates**: ICRD programme is a reasonable approximation for industrial use across ISIS's life. Discounting for additionality, attribution and depreciation (and allowing	£200 million	£200 million	£400 million

Type of socio-economic impact	Description of impact	Estimated impact of work already completed		
		Past 1985-2013	**Future 2014-2025**	**Total 1985-2025**
	for commercialisation time lags), we arrive at a range of £200 million to £750 million. We have elected to use the more conservative figure.			
Wider benefits to industry from industrial supply	ISIS has had wider benefits to industry-like effects on additional sales, reputation and capabilities in addition to direct funding from equipment supply (which is accounted for under immediate economic impact).	Unable to estimate	Unable to estimate	Unable to estimate
Impacts from IP generation	Economic benefits from the licences, patents and spin-outs resulting from users of ISIS and ISIS staff.	Unable to estimate	Unable to estimate	Unable to estimate
Impacts due to Harwell Oxford Campus cluster	Impacts from ISIS being a main attractor to companies locating onto the campus or working with the campus.	Unable to estimate	Unable to estimate	Unable to estimate
Skills				
Skills-related valuation of on-the-job training	Estimated value of 500+ trained research students / post docs annually.	£30 million	Unable to estimate	£30 million
Value of training to industry	Value of direct training for industry and wider benefits from trained staff and staff transfers.	Unable to estimate	Unable to estimate	
Value of educational training	Estimated value of 100+ trainees, 1,000 training days, annually.	£3 million	Unable to estimate	£3 million
Total		**£1,049 million**	**£340 million**	**£1,389 million**

6.2.1.1 Immediate economic impact

ISIS currently employs around 370 mostly full-time people, having increased gradually from 200 in 1995. The direct impact of ISIS is measured as the Value Added of its activity, which can be approximated by the value of its gross payroll, including all elements of remuneration. Based on this approach, between 1982 and 2013, ISIS has had a gross direct impact of £355 million. To estimate the total immediate impact, we make use of multipliers to quantify the further economic activity stimulated by ISIS's direct impacts. We estimate that the accumulated gross intermediate economic impact of ISIS to the UK Economy, over the last 30 years (1982-2013), is £497.4 million. After applying a discounting factor related to the location of its suppliers (assuming 80% are UK based and 20% overseas), we estimate that the net Economic Impact of ISIS is £400 million.

Type of socio-economic impact	Description of impact	Estimated ISIS lifetime (1985 to 2013)
Net immediate economic impacts	ISIS expenditure generates substantial immediate economic benefits, through its direct employment and its purchases (suppliers)	**£400 million**

Statistics on ISIS's income and expenditure, location of suppliers and employment all fed into our analysis on ISIS's immediate economic impact. Information on each of these is given below:

- **Income and expenditure;** ISIS spent approximately £700 million between 1977, when construction began to the end of 2013[40]. Annual income/expenditure has increased steadily over the period, and showed a substantial increase after 2003, when the construction of TS2 started, but had been building quite strongly in the mid-period before the implementation of TS2. This is due is to the development of new instruments and targets for TS1 (and subsequently TS2), and the energy requirements that new state-of-the-art instruments require. The UK government has provided the large majority of ISIS's £643 million in income; however, the facility also benefits from a steady flow of international investment of £2 million-£3 million a year.

  To note: the external cost of using ISIS (e.g. the salaries of users not on the ISIS payroll) is financed by a wide range of different research funding bodies, UK and international, public and private. Researchers with EPSRC grants figure heavily in the ISIS statistics (50% of experiments), while the remainder is accounted for by other Research Councils' grant holders and a long tail of other scientists that are being funded by a diverse range of organisations: industry, universities, Innovate UK, the European Research Council, the Royal Society, the Wellcome Trust and others.

[40] Note that we use income as a proxy for expenditure for the period 1977-2003, given that it was not possible to estimate the time series for expenditure: ISIS has comprehensive records for income and for expenditure between 2004 and 2013, but annual expenditure data were not readily available for the earlier period.

- **Location of suppliers:** There is no complete historical record of all ISIS suppliers, and it was therefore decided to use the available (electronic) data about the suppliers to TS2 as the basis for our geographical analysis of the facility's expenditure over the longer term. On the assumption that ISIS's purchase of instrumentation and related systems would be the work packages most likely to produce spill-over benefits and attract national and international competition, we chose to focus our analysis on the £41.5 million related to the purchase / construction of instruments for (2013, where the overall investment, including buildings and infrastructure, amounted to more than £150 million).

  According to ISIS supplier records, 80% of the expenditure for the construction of instruments was spent with organisations with UK addresses, either within the local area (<=30 miles from ISIS) or elsewhere in the UK (23% and 57% respectively). Around a quarter of £42 million of high-value, complex purchases were won by contractors local to ISIS. This hints at the kind of local spill-over benefits that derive from large science clusters such as Harwell.

- **Employment:** ISIS currently employs around 370 people, with most staff appointed on full-time contracts and with 94% of all staff residing in Oxfordshire, or surrounding areas. Employment has increased gradually over time, from 200 in 1995 to the current levels (2014). Over the 30 years since its inauguration, ISIS's total payroll costs amount to around £355 million (in cash terms). The relative importance of the payroll (staff cost) within ISIS's total expenditure has decreased over time, from around 70% of costs to 50%, driven in part by the lab's resourcefulness in administering a larger number of instruments with a proportionately smaller team of administrators, technicians and facilities scientists. The construction of TS2 has added a series of next-generation instruments that require fewer personnel to operate, proportionally, helping to improve ISIS's basic labour productivity.

(For full information on the Economic Impact assessment methodology and analysis see Volume2, Appendix M, Economic impact assessment methodology and analysis.)

6.2.1.2 Visitors' contribution

There were almost 3,000 visits by around 1,500 scientific users in 2013/14, which is a typical number (albeit a little lower than the previous year). Scientific users tend to visit ISIS for several days at a time, on average for six days, and typically more than once in the period while their experiments are being run (ca. two visits for every visitor, historically). These scientific users tend to generate substantially more income for the local economy, as their stay invariably includes the cost of accommodation as well as expenditure on local travel and food while at ISIS. In the case of UK-resident scientific users, ISIS covers their travel and subsistence costs and this 'local economic contribution' is therefore already accounted for in the ISIS budget. International scientific visitors tend to bear their own costs, and while their major travel costs (e.g. flights) are typically spent with carriers in the country of origin, their food and accommodation is a substantial expense that benefits Oxfordshire directly.

We have assumed that day visitors spend on average £20 a day (mainly on refreshments and local transport) each, and that overseas scientific visitors spend around £780 for each visit, comprising accommodation and other subsistence and local travel, which suggests that ISIS visitors contributed around £0.75 million to the local economy in 2013/14. If we use these estimates as the basis for estimating the total economic impact of ISIS visitors over the previous 30 years, we arrive at a figure of around £22 million. Scientific and non-scientific visitor numbers have increased somewhat over the years, so given that fact and the other assumptions used in this calculation, we have included a figure of £20 million in our overall estimate of ISIS's lifetime impacts.

Type of socio-economic impact	Description of impact	**Estimated impact**
Visitors economic impact	Several thousand visitors each year, spending money on travel, food and accommodation in the local economy	**£20 million**

6.2.2 Additional economic impact

6.2.2.1 Value of assets

We estimate that a total of £245 million has been invested in capital (building, instruments, equipment), based on capital expenditure between 2004 and 2013 and extrapolating those values to the entire life span of ISIS. Note that TS1 and TS2 have entailed an investment of circa £260 million; however, those figures include non-capital expenditure such as consultancy projects with specialised engineering firms. In 1977, ISIS inherited buildings, equipment, power supplies and concrete 'shielding' blocks (together worth ~£130 million) from NIMROD. If we take into account an annual depreciation of capital of 5%, in 2013 those assets have a value of £176 million. This means that ISIS has maintained and capitalised those assets, with a combined balance sheet value of close to £200 million that the facility can continue to exploit going forwards. ISIS also estimate that to totally rebuild the ISIS facility it would cost around £0.5 billion to the UK. We have not included the value of these assets in our formal impact assessment, however, as it is important to remember that infrastructure has a retained value that enables relatively small recurrent / operational investments to deliver very much larger social and economic benefits.

6.2.2.2 Other quantitative evidence

Taken together, the 10 Extended Impact case studies used to estimate the wider economic benefits attributable to ISIS research suggest that ISIS research will underpin a substantial increase in national economic activity over the next 10 years. As described, there is no definitive means by which to relate this group of 10 cases to ISIS's total research endeavour over the past 30 years. However, we came to a view based on the size of the archive of case studies. Our group of 10 Extended Impact case studies were identified following consideration of the 50 most promising examples selected from within a larger catalogue of 150 cases, providing a means to make a wider estimate on the likely economic benefit attributable to ISIS.

It is worth noting, however, that it was outside the remit of this study to include any specific analysis on numerous case studies included in this report, which also show promise in terms of future economic benefit for the UK but which for various reasons we were not able to fully analyse. These include, for example: research case studies such as that on bucky balls; the impact of instrument development such as ChipIR; innovation case studies on the benefit of ISIS to multinational companies such as Rolls Royce; the benefit of ISIS spin-outs such as Cella Energy; and suppliers who work closely with ISIS such as Oxford Instruments; and the impact of skills development for businesses such as Siemens. The likely impact of these examples when estimating spill-overs was taken into consideration in terms of our wider economic estimates but a conservative approach was taken and these examples and others were not specifically analysed.

6.3 Summary

This study estimates that the net economic impact of ISIS is £400 million, a figure that derives from the operation of the facility and its employment of large numbers of highly qualified individuals. These direct benefits are only part of the story of course, with tens of thousands of experiments having been carried out over the past 30 years, delivering numerous further benefits in terms of new knowledge, new analytical techniques and new skills. These outcomes have in turn facilitated the realisation of wider impacts, in terms of technological innovations and new products and processes.

The numbers presented here are a conservative estimate of the impact of ISIS, due in particular to a lack of historical recording of information by ISIS as well as the impossibility of researching all impact case studies fully for a report such as this. Therefore, this kind of study can only ever provide a snap shot of the vast impact that such facilities provide academically, socially and economically and capturing the value of such impact is very challenging.

Overall, we estimate ISIS has delivered at least **£1,049 million** as a result of its work over its lifetime (1985-2013), while its current and very recently completed research will possibly amount to an additional **£340 million** in NPV terms (up to 2025). ISIS continues to operate and we would expect to see substantial further scientific and economic benefits in the longer term through to 2030 and beyond, with an expanding instrument set and planned upgrade to TS1, the next 15 years' research could easily match the order of magnitude of benefits seen in the first 30 years – some **£1,000 million**. From this perspective, the facility is delivering very significant returns on investment and might reasonably have been expected to deliver even more impressive figures had it been running at full capacity throughout its lifetime.

With total ISIS expenditure of the order of £700 million, of which around £650 million has been provided by the UK government, and using our estimate of overall economic benefit (£1,389 million), we reach a **Return on Investment (ROI) figure of around 214%**, which sits at the mid-point of the range of estimates of ROIs reported by `Frontier Economics' in their 2014 literature review: ROIs for private rates of return (max 315%) and for social rates of return (max 155%).[41] Overall, our analysis strongly indicates that publicly funded research and innovation is a key way to drive economic growth. As quoted in the report by `Frontier Economics':

`There is some evidence that, at least in terms of their impact on private sector productivity, public R&D channelled through the research councils leads to higher social returns than R&D conducted by government departments (civil and defence) or channelled through higher education. This may be because research councils conduct and fund R&D that is "closer" to industry. We also find evidence that within research council investments, the highest social returns come from science-based and applied research. Again, these may be closest to the sorts of R&D investments made by the private sector.'

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[41] 'Rates of Return to Investment in Science and Innovation'. A report prepared for the Department for Business, Innovation and Skills (BIS), `Frontier Economics', July 2014.

7. Methodology

7.1 Overall approach

This broad approach comprises in-depth research on the ISIS facility and its resultant social and economic impacts using both primary and secondary data gathered from a variety of sources including previous publications, STFC financial and administrative data, ISIS senior management team and senior scientists, academic users, industrial users, suppliers and other key stakeholders. The methodology being employed encompasses desk research, bibliometrics, questionnaire surveys, semi-structured interviews and case studies, and involves close collaborative efforts by the study team at Technopolis and STFC / ISIS throughout.

7.2 Conceptual framework

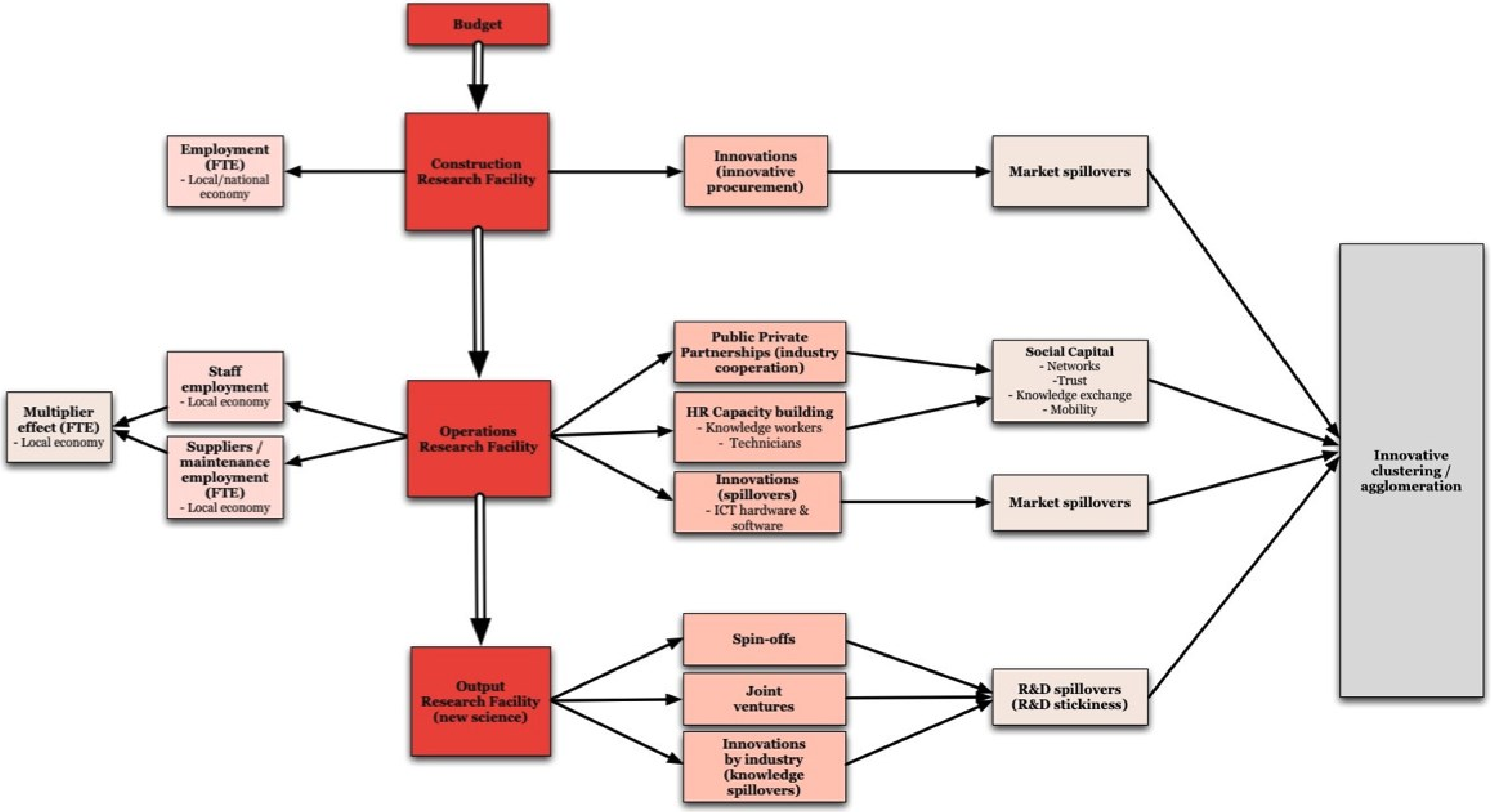
Large research facilities like ISIS make possible many different kinds of social and economic impact, both directly and indirectly.

The most extensive and important benefits comprise the advances in understanding that derive from the many thousands of scientific experiments made possible by the facility over its lifetime. There are also technical developments, in instrumentation, for example, that allow new research questions to be posed or existing research questions to be looked at in novel ways. Wider developments in a facility's technologies and systems – from its detectors to analytical software tools – also improve the power of the science as well as delivering productivity gains (for researchers). A facility like ISIS is not exclusively concerned with science, and is open to industrial users that may either compete or pay for access to the facility to run more applied research or to work alongside academics on more fundamental use-oriented studies; in both cases, big facilities can deliver useful advances in know-how and technology. There can also be technological innovations created by industrial users carrying out proprietary work at these facilities. Lastly, research facilities like ISIS can make a lasting contribution to the standing, capacity and capability of academic and industrial communities, through the experimental skills developed on the facility by research students and post-docs who go on to work as facilities scientists, academics and industrial engineers, amongst other things.

The indirect effects include the wider impacts of the knowledge and technology that derive from the experiments and measurements, which can take many forms in their own right, from profound changes in the way we understand the world to new products or services built on the technological insights. There are also financial and technological benefits that arise from esigning, building and operating these facilities, when first built but also over successive generations of upgrades and expansions, and also decommissioning. Big science facilities constitute a major market for the global scientific instrumentation sector of course, but big facilities are also important niche markets for suppliers of even quite generic products and services, demanding a level of precision and quality that is very much more exacting than the majority of segments and which can provide positive spill-overs in reputation, processes and quality overall. And lastly, large, single-site facilities like ISIS impact on local innovation ecosystems and can be rather important constituents of regional science-based clusters.

We devised a conceptual framework to guide our data-collection and analysis in order to arrive at an aggregate view of the different types of impacts that ISIS has made possible across its lifetime. It is an input-output model of sorts, making connections between financial inputs and the phases in the facility lifecycle and each of the main categories of socio-economic output. It attempts to capture the benefits that derive from the construction and operation of facilities on the one hand (e.g. user-led innovation among equipment suppliers) and, on the other, the benefits of the cutting-edge science that is made possible by the facility (e.g. knowledge spill-overs and innovations that result from research breakthroughs). The model also includes a series of wider effects, from indirect economic benefits (e.g. income multipliers) through to social capital (e.g. increased international engagement and influence) and local agglomeration (e.g. inward investors locating at the Harwell campus to benefit from improved access to ISIS and or the wider innovation ecosystem).

Figure 17: A schematic showing the social and economic impacts flowing from large research infrastructures



Source: `Big Science and Innovation' (Technopolis, 2013)

7.2.1 Approach and methodology

Our approach and methodology has comprised in-depth research on the ISIS facility and its resultant impacts using both primary and secondary data gathered from a variety of sources including previous publications, the web, STFC staff, ISIS staff and users, relevant industrial companies, campus partners and any other key stakeholders. The following bullet points outline the programme of work followed:

- Historical analysis: A programme of interviews with the current and former ISIS directors, supported by targeted desk research, to arrive at an overview of the facility, its development over time (new investments, new beamlines, new targets, new instruments, etc.) and funding levels. We have also used ISIS's substantial archive of annual reports and case studies to inform this rapid overview, as well as the report of the International Review Committee (2013).

- Desk research: to develop an analytical framework that encompasses all of the important types of research, skills and economic benefits (direct and indirect) likely to have been realized. This framework takes as its starting point the generic framework we developed as part of the Big Science project for BIS, where we checked the logic and related performance measures back with key stakeholders within the ISIS management team and the STFC headquarters.

- Desk research: to compile the relevant financials (e.g. annual income and expenditure by broad category of expenditure, including staff) over the lifetime of the facility, with a transversal analysis of major purchases (design, construction, equipment, etc.) and the related construction of a database of higher-value suppliers. Separately, to compile an historical analysis of non-academic users' involvement with the facility and related income, and the related construction of a database of users. We also developed an overview of HR-related expenditure for administrative and professional staff as well as a view of temporary visitors (using more recent data to arrive at a spatial analysis of people's residence in order to inform our estimation of induced effects through income multipliers).

- Desk research: to compile data on the anticipated financial impact of industry using ISIS instruments, through the ISIS Collaborative R&D (ICRD) programme, which was set up in 2012 to strengthen industrial engagement and broaden the facility's relevance to new sectors and to smaller technology companies.

- Academic survey: we ran an online survey of academic users to profile usage and to invite people to link the role of ISIS and neutron science in their own work (e.g. magnetic structures, phase transitions, structures and dynamics of liquids, etc.) to rate the facility's importance (criticality) to their research and to gather brief descriptions (mini-case studies, vignettes) about the academic achievements realized and any subsequent benefits in terms of subsequent major grants / awards, prizes, appointments, etc. One of the questions covered the impact of ISIS on human capital, in terms of the direct benefits to scientists and research students on their methodological skills, domain knowledge, external relationships, etc. This question module also tackled issues to do with career progression / promotions and possibly even inter-sectoral mobility and destinations. The 200 replies provided the team with an excellent profile of benefit types as well as long lists of specific research, skills and application-related outcomes.

- Industry user survey: we implemented an online survey of ISIS's industry users, administered through ISIS's academic users, as the administration does not maintain contact data for the industrial partners involved with its mainstream research programme. This indirect survey strategy proved rather ineffectual, and we obtained replies from only ten business users; that said, the replies were instructive, albeit in no way representative of the 100-plus known users.

- Supplier survey: ISIS does hold contact details of its more recent suppliers and we were able to run an online survey of the suppliers of larger, high value instrumentation work on the first phase of TS2, with around 50 responses providing feedback on the wide range of benefits derived from interaction with the facility.

- Case studies: we carried out a substantial programme of desk research to identify, compile and categorise ISIS's very substantial archive of case studies. These several hundred items were reduced to a list of around 50 good examples of both research and industry impacts and the team set about researching each of the 50 in order to update our view on outcomes and to quantify and monetise impacts where possible. In the end, some 30 case studies were prepared covering a fascinating cross-section of fields and sectors. However, in all instances, contributors highlighted the critical role played by ISIS, but went on to say that they could not attribute a monetary value to their ISIS experiments, sometimes because the development work was ongoing, but often because of the amount of subsequent investment / development work and or the commercial sensitivity of these statistics.

- Bibliometric analysis: we carried out some simple bibliometric analyses to profile journal use and citations for ISIS-related publications, from standard searches in the Scopus database.

7.3 Methodological challenges

Research impact assessment is widely understood to be a challenging field of social science research, confronting several classic measurement issues of impact pathways that are traversed across decades by multiple parties producing tacit and codified knowledge along the way. The measurement challenge is all the more difficult when the question relates to research infrastructure and the role of such a facility as the technical underpinnings of thousands of experiments conducted by tens of thousands of scientists and engineers in universities, institutes and business throughout the UK and around the world.

Conventionally, analysts have tackled the measurement challenge by focusing on the immediate impacts, counting direct employment and expenditure over time and using standard economic multipliers to arrive at an estimate of the direct and indirect effects. The better studies work with GVA to arrive at a more robust view of the value of additional economic impact and also make adjustments for leakage to other regions or countries. Occasionally, these economic impact assessments are accompanied by a more qualitative description of selected impact case studies and very rarely those case studies are monetised and included within an overall estimate of total economic impact, attributable to the facility both 'spending money' and advancing understanding (knowledge spill-overs).

We have followed the same broad approach here, on the one hand working with ISIS's financial and HR figures to arrive at an estimate of the immediate economic impact of the facility's operation over the past 30 years, and on the other, running surveys to profile and characterise impact distributions among industry users and suppliers and using case studies to trace effects and estimate the likely quantum of benefits. We have gone beyond conventional approaches in several areas, being able to take advantage of the estimates of future impacts prepared by ICRD users to provide a more comprehensive basis for estimating likely future benefits for users and secondly carrying out substantial desk research to estimate and forecasts wider economic benefits attributable to ISIS's research. We have been conservative in our estimation of likely impacts and our attribution of a share of those benefits to ISIS, in recognition of the high levels of uncertainty as regards the scale and duration of wider impacts, the scale and duration of any displacement or crowding out and the difficulty in determining a fair attribution for ISIS.

The case study methodology is a laborious and costly process, given the time over which the research is carried out and the advances in understanding percolate through to new techniques or technologies and these find their way into new products and processes. The effects spill over in many areas, and this diffusion brings its own challenges in respect to the scope of the investigation and the potential for new developments and feedback loops. Nonetheless, this kind of in-depth, longitudinal impact case study remains the best means we have for tracing and estimating the social and economic impact of research. Grossing up those individual cases remains somewhat problematic; however, we feel confident that we were able to come forward with a reasonable estimate using ISIS's case study archive to size the population and the typical shape of skewed distributions reported in the wider innovation literature.

In this particular exercise, the study team has been helped greatly by the earlier work of the ISIS and STFC evaluation units and their active preparation of research case studies for inclusion in annual reports and on the web site. The study would have taken very much longer and cost rather more money without that support.

7.4 Lessons Learned

Notwithstanding this bedrock of preparatory material, the study faced a number of methodological challenges that have been wrestled to the ground, but not always fully overcome, including:

- The central importance of the science and the global scope of its influence, which requires a broad knowledge of multiple scientific domains and an international reach. The solution here has been to work closely with ISIS staff, several of whom kindly drafted field-level reviews describing the work at ISIS over the past several decades and picking out key advances.

- The time-span over which the facility has been delivering manifold benefits, which extend over several generations of scientists as well as many organisational and information system changes. In this case, we have relied on historical records to capture the main milestones, however, for our economic impact assessments, we have used income data as a proxy for expenditure data and have made certain assumptions about the relationship between income and payroll in order to extrapolate for the earlier years

- The intangible nature of many of the benefits, and where phenomena are quantifiable they are not necessarily monetisable and therefore cannot be aggregated. This is the area where we have found no agreeable solution, and have had to revert to a pragmatic presentation of immediate economic impacts and otherwise rely on a very much more qualitative overview of the many and various benefits delivered by ISIS over the past 30 years

- Temporality. The nature of research impact pathways means there will always be a timing issue, with primary research tending to produce wide-ranging evidence of substantial anticipated future benefits, but very much less extensive / fewer data about past benefits. This reflects people's preoccupations with the here and now, to some extent, but it also reflects the way in which benefits unfold over many years and possible decades

- Our survey of industry users had to be implemented indirectly, through an open request to academic users in the hope that they would refer the study and survey to their industrial partners. This kind of approach gives very little control over response rates and ultimately produced only a small number of substantive replies. This feedback was valuable, but fell some way short of a comprehensive response and as a result did not provide the statistically robust platform for which we had hoped. This left the team with a tantalising glimpse of some really quite striking impacts, but with the small number of responses it was simply unreasonable to seek to generalise from the few to the many. It was reassuring that several of the respondents were prepared to be candid about the nature and extent of the benefits realized as a result of the research being performed at ISIS by their academic partners. That said, there is a sense that in many cases the real benefits go way beyond individual experiments and are both strategic and commercially sensitive; our follow-up interviews quickly revealed that industrial scientists and engineers were pleased to discuss their current or recent ISIS projects, much of which was work still a very long way from market, and unable or unwilling to discuss the benefits of past engagements. This is a classic 'research impact' measurement paradox, whereby respondents can speak at length about their current research – why, what and how – but its impact on products or processes or the bottom line is many years in the future and the nature and extent of such benefits is a matter of conjecture. Benefits realized are invariably based on work that stretches back very many years, and cloudy corporate memory tends to cause people to speak in only the most general terms and few people are confident enough in their view of matters to quantify or attribute some proportion of those benefits to ISIS

- Our supplier survey was rather more successful than the industry-user survey, even though we had to contend with a limited database with few named contacts. The tactical decision to focus on the larger work packages linked with TS2 was well judged, and there is clearly substantial goodwill among suppliers generally. Our supplier case studies also suggest that ISIS does provide reputational and lead-market benefits to perhaps 20% of its suppliers and as such this is an aspect of value that could be monitored or reported on going forward

7.5 Recommendations for ISIS

In terms of lessons learned for future impact assessments, several points stand out:

- ISIS should continue to improve its information systems in support of more robust monitoring and evaluation. Clearly good progress is being made, and the ability to look at near-term events is greatly improved by ISIS surveys and case studies. There may be value in doing more, however.

- Research activity. It would be helpful if ISIS could maintain a better view of the composition of the research it is supporting, in terms of broad scientific disciplines at least. It would also be useful to maintain a better view of the volumes of related research, which is in some way dependent upon access to ISIS. We understand ISIS research is typically linked with around £100 million in current EPSRC grants; and, while EPSRC may well encompass the lion's share of the disciplines using ISIS, it is also clear that there is a long tail of other users with grants from other research councils, from BBSRC to MRC and NERC. The combined value of this linked research might easily amount to several hundreds of millions, which would underline the extent of the dependency upon ISIS across the whole of the UK research base. A more accurate view of these issues ought to improve awareness of ISIS's significance across all research councils

- Industry links. It would be helpful if ISIS could find a practicable means by which to maintain better records of their manifold industrial relationships, whether that is the co-sponsors of academic users of ISIS or the suppliers of higher-value goods and services. It would be helpful if STFC's standard contracts and partnership agreements could include a clause obliging the signatories to support future evaluations and impact assessments, perhaps including a clause about confidentiality and non-disclosure to reassure people that they will have the final say in level or timing of any disclosure of benefits realized.

- Impact case studies. ISIS and STFC have responded robustly to the Government's impact agenda and have amassed a large number of excellent scientific and industrial case studies. These essays are invariably well-written and provided an excellent platform for the extended case studies presented in this report. Having a second-phase, to follow-up on those case studies perhaps two or three years later would allow the ISIS team to develop a more comprehensive account of the wider benefits, for both research and industry. This programme might also be extended to include a small number of (ad hoc) longitudinal (tracking back) impact case studies focusing on the 'jewels' in the ISIS crown. These might take the form of an edited book, whereby different authors with deep knowledge of the field are invited to write a chapter on the importance of ISIS contributions to the topic.

- It may also be helpful for ISIS to develop a programme of field-level international reviews, which would provide a more robust and fine-grained assessment of contributions and breakthroughs, set in the context of a more thorough review of wider international efforts. The EPSRC and ESRC have both been advocates of such international reviews, and have well-documented procedures. These exercises can be costly in staff time and cash, but the process can be made more affordable by running one or two reviews each year so that a programme cycle may take around five years. This would be an excellent platform for future impact assessments, say in 2020, as well as supporting STFC's annual reports to BEIS.

- Career tracking survey. ISIS alumni / community may provide a platform for this kind of exercise, going forward, or possibly using social media such as linked-In to run data-mining exercises to track the progression of its academic users and their post-docs. An alumni programme or some other community-based network may be a way forward, providing value to the community on an ongoing basis while providing a platform for ISIS to research issues (in the manner of a local authority 'citizens panel', widely used for omnibus surveys).

- ISIS has run various user surveys down the years, and there may very well be value in running an annual user survey to invite people to share information on new developments (from awards to prizes to spin-outs and commercial sales).

This is all likely to require more administrative resources and possibly additional budget, too, which we understand will be a challenge in the current financial environment. On the upside, expanding and strengthening the ISIS evidence base may help to secure additional funding to allow the facility to return to its full utilisation levels and continue its upgrading programme and planned activities through to 2025. We believe that would constitute excellent value for money for both STFC and the UK taxpayer.

For the full Appendix, please refer to the ISIS Lifetime Impact Report, Volume 2

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November 2016

ISIS Lifetime Impact Study

Volume 2 - Appendices

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ISIS Lifetime Impact Study – Volume 2

technopolis |group|, May 2015

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1. Introduction

This document contains the supporting technical appendices for Volume 1 of the ISIS Lifetime Impact Study. Specifically, the following annexes are presented:

- **Appendix A** describes the ISIS neutron and muon source in detail, including its history and a background on its users and usage, including an introduction to its industrial use
- **Appendix B** describes the conceptual framework in detail that is used to guide the study and its data collection
- **Appendix C** includes the full description of a range of case studies describing examples of the academic and industrial impact of ISIS
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Appendix A The ISIS neutron and muon source

A.1 Introduction to ISIS

ISIS cost around £110M to develop originally, benefiting from a substantial legacy of equipment and infrastructure from the NIMROD proton accelerator, and has since been extended with a second target station, at a cost of around £150M. ISIS's annual operating budget is around £40M a year currently (2014), having increased steadily in cash terms from around £10M a year in the mid-1980s. It has a staff of around 370 people and hosts around 1,500 scientific visitors each year, carrying out more than 700 experiments entailing more than 3,000 user days annually. It is the UK's only short-pulsed neutron spallation source, and while it is a national facility it has a very substantial international presence, with around a third of its visitors coming from outside the UK and with 15-20% of its annual income also being secured through international grants, contracts and contributions-in-kind. It also has a significant and growing industrial programme, with active links to more than 100 companies.

A.2 History of ISIS

The ISIS facility was developed at the Rutherford Appleton Laboratory (RAL) over thirty years ago, with the project being approved in 1977 and officially inaugurated in 1985. It was developed on the site of an earlier accelerator (NIMROD) that was used for particle physics (research that subsequently moved to CERN). The NIMROD site had buildings, equipment, power supplies and concrete 'shielding' blocks (together worth ~£130m) that were inherited by the ISIS facility, as well as RAL staff with specialist expertise in physics and engineering that was relevant to the development of a spallation source.

Around £110M was invested by the UK funding councils in additional equipment and effort to develop the site. The resulting facility consisted of a spallation neutron source, with a single target station and over 20 specialised beam lines channelling neutrons of different energy and wavelengths into specialised experimental areas. When it opened, it was the most advanced spallation neutron source in the world, and played a critical role in demonstrating to the global scientific community the feasibility and benefits of using a spallation source for neutrons, as opposed to the more conventional approach of using a reactor source.

The ISIS neutron source was originally expected to have an operational life of some 20 years (1985 to 2005), but its evident success led to a process of ongoing refurbishment and further investment. As of 2014, £150m has been invested in the addition of a second target station (TS2), and a further seven beam lines (TS2 Phase 1). This, with the further expansion of TS2 in Phase 2, is intended to extend the life of ISIS for a further 20 years, through to 2025.

Figure 1 – Selected Event Timeline

Year	Event
1957	Rutherford Appleton Laboratory opens
1963	NIMROD proton synchrotron opens
1978	NIMROD closes. Construction of ISIS starts
1984	First neutrons produced at ISIS
1985	ISIS is officially inaugurated with 3 neutron instruments (HRPD, IRIS and TXFA [TOSCA]) First international agreement signed, with Italy
1986	First agreement signed with KEK Japan (for contribution to MARI) Muon facility under construction Nine instruments commissioned (HRPD, LAD, LOQ, HET, TFXA, IRIS, SXD, POLARIS, EVS)
1987	First reflectometer (CRISP) begins operation First muons on the EC muon facility
1988	PRISMA instrument commissioned
1990	First agreement signed with RIKEN Japan to set up the RIKEN-RAL muon facility Two new instruments commissioned (MARI, SANDALS)
1992	Signing of agreement with Australian Nuclear Science and Technology Organisation (ANSTO) to enable access for scientists to ISIS
1994	Two new muon instruments (EMU and DEVA) come into operation
1996	Tantalum target in routine use (rather than uranium)
1997	First dedicated engineering instrument (ENGIN) starts operation
1998	The first time-of-flight single crystal spectrometer with a large area detector (MAPS), starts operation
1999	The first time-of-flight powder diffractometer with large area detectors (GEM) comes online
2000	Volume of data gathered in year exceeds 100gb (1+ orders of magnitude more than a decade before)
2003	Construction of Target Station 2 begins. Engin-X instrument commissioned – the first instrument to have all its data acquisition and device control performed by PCs
2008	First neutrons on TS2
2009	Seven Phase 1 neutron instruments on TS2 available for users
2011	TS2 Phase 2 (Chipir, Larmor, Zoom and Imat instruments) construction begins ICRD scheme launched
2015	Four TS-2 instruments operational

A.3 The facility

At the heart of ISIS is an 800 megaelectronic volt (MeV) proton accelerator system (an injector and a synchrotron), producing intense pulses of protons, 50 times a second. The protons are accelerated in the linac and synchrotron to high energies (84% of the speed of light) and then ‘fired’ at targets, such as tungsten. The two target stations (TS1 and TS2) at ISIS use the high-energy protons to generate neutrons by the spallation process, and the neutrons are then moderated to make them usable for neutron scattering experiments. The resulting neutrons are channelled towards various experimental areas and instruments in order to conduct studies of materials and / or processes.

The neutron is a powerful tool for the study of condensed matter (solids and liquids) in the world around us, having significant advantages over other forms of radiation in the study of microscopic structure and dynamics. Compared to the original target station, TS2 is optimised for low energy neutrons, providing not only greater capacity at ISIS, but also opening up new areas of research.

In addition to producing neutrons, ISIS is also the world's most intense source of pulsed muons for studies in materials science. Muons are created in a similar way, by impacting protons into a thin carbon target (upstream of the neutron target) to produce pions, which then decay into muons. Muon spectroscopy provides an alternative – and often complementary – technique to neutron scattering. Spin polarised muons can be implanted into virtually any material, and monitored, giving information about local atomic structure and dynamics.

The first neutrons from ISIS were delivered in 1984, and after a few years for ramping up performance ISIS has routinely produced annual integrated currents greater than 600 mA-hours during 120 – 180 user days per year scheduled into 4 or 5 user cycles. Machine run-up usually begins about 10 days before the start of each cycle, and after the end of each cycle about 3 days are usually scheduled for accelerator physics studies. The ISIS facility is crewed by five shift-teams on a 24 hours a day, 365 days a year basis and during user cycles some 60 – 100 additional people are on call around the clock to support operations if necessary.

Over the past 10 years (up to 2014) significant investment and effort has been put into the upgrade of the ISIS accelerator to facilitate implementation of TS2 and into the replacement of key accelerator equipment to underpin sustainable operations at a 90% availability level. The number of instruments available to users has increased steadily over time, from five instruments in 1986, to 22 in 2007 and jumping to 27 in 2009, following the opening of TS2. In addition to these 27 instruments, there are four instruments funded and operated by Japan's largest research institute, RIKEN (Japan), two of which (ARGUS and CHRONUS) are available for use by general users for around 25% of their time. Another instrument (INES), operated by Italy is not included in the ISIS proposal system.

Figure 2 lists the main instruments in use at ISIS, as of May 2014, and the research themes for which they are relevant.

Figure 2 – ISIS instruments

Instrument	Target Station	Description	Bioscience/Soft matter/Polymer	Engineering and Imaging	Magnetism/superconductivity/Condensed Matter Physics	Materials Chemistry and Interfaces	Materials and Energy	Structural Biology
CRISP	TS1	Polarised Beam Reflectometer.	Principal	Minor	Secondary	Secondary	Principal	
ENGIN-X	TS1	Engineering Science Diffractometer.		Principal			Secondary	
GEM	TS1	High intensity diffractometer.		Secondary	Principal	Secondary	Principal	
EMU	TS1	Muon spectrometer for general materials studies	Minor		Principal	Minor	Secondary	
HIFI	TS1	High field muon spectrometer for condensed matter and chemical	Secondary		Principal	Principal	Minor	
HRPD	TS1	High resolution powder diffractometer		Minor	Secondary	Principal	Secondary	
IRIS	TS1	A high-resolution quasielastic spectrometer.	Principal		Secondary	Principal	Principal	
LOQ	TS1	A small angle neutron scattering instrument.	Principal	Minor	Minor	Principal	Secondary	Principal
MAPS	TS1	A high-resolution direct-geometry spectrometer.			Principal	Principal	Secondary	
MARI	TS1	Mari is a chopper spectrometer.	Secondary		Principal	Secondary	Secondary	
MERLIN	TS1	MERLIN is a high intensity chopper spectrometer.			Principal	Secondary		
MUSR	TS1	Muon spectrometer.			Principal		Minor	
OSIRIS	TS1	A high-flux and high-resolution Terahertz neutron spectrometer.	Secondary		Principal	Principal	Principal	
PEARL	TS1	Powder diffractometer specifically designed for *in situ* studies		Minor	Secondary	Principal	Minor	
POLARIS	TS1	High intensity powder diffractometer for small sample volumes.		Minor	Secondary	Principal	Principal	
SANDALS	TS1	Light element diffractometer optimised for studies of liquids and glass	Secondary		Minor	Principal	Secondary	
SURF	TS1	A high flux reflectometer optimised to study liquid surfaces	Principal			Principal	Secondary	Secondary
SXD	TS1	Single crystal diffraction using the time-resolved Laue method .			Secondary	Principal	Minor	Minor
TOSCA	TS1	A high-resolution, broadband spectrometer	Secondary		Minor	Principal	Principal	
VESUVIO	TS1	A high-energy Compton spectrometer	Secondary		Minor	Principal	Principal	
INTER	TS2	High-intensity chemical interfaces reflectometer	Principal		Minor	Principal	Principal	
LET	TS2	A high-resolution cold chopper spectrometer	Secondary		Principal			
NIMROD	TS2	Wide Q-range diffractometer	Secondary		Minor	Principal	Secondary	
OFFSPEC	TS2	Offspec is an advanced reflectometer	Principal	Minor	Secondary	Principal	Principal	
POLREF	TS2	Polref is a polarised neutron reflectometer	Minor		Principal		Minor	
SANS2D	TS2	Flagship small angle scattering instrument	Principal	Minor	Secondary	Principal	Secondary	Principal
WISH	TS2	Long-wavelength diffractometer			Principal	Secondary	Minor	
IMAT	TS2 In construction	Unique instrument delivering imaging and diffraction for engineering and	Minor	Principal	Principal	Principal	Principal	
LARMOR	TS2 In construction	Advanced neutron polarisation instrument to access new time and length	Principal	Minor	Secondary	Principal	Principal	Principal
Zoom	TS2 In construction	Focussing small angle instrument for hierarchical structures	Principal	Secondary	Secondary	Principal	Secondary	Principal
ChipIR	TS2 In construction	Studies of neutron induced single event effects in electronics		Principal	Secondary			

Principal Research Areas
Secondary Research Areas
Minor Research Areas

A.4 ISIS users and usage

A.4.1 Introduction

Some 300 research groups involving 1,500 scientists will typically use the ISIS facility during the course of a year, with experiments being undertaken in a wide range of fields. In addition, ISIS staff and research groups also undertake experiments, either in collaboration with external researchers or on their own (applying for beamtime through the same routes as external users). A small number of research projects undertaken through use of the facility might be termed basic science and are concerned with the fundamental properties of matter, but the majority are strategic longer term studies aimed at understanding properties of materials such as superconductivity and magnetism.

Users gain access to the facility through one of three routes:

- Open calls for proposals (user programme). This is the principal access route, accounting from more than 85% of beam time in a typical year. External researchers, from the UK and abroad, access ISIS via one of the Facilities Access Panels, which assess proposals on their scientific merits. 10-15% of the research supported through the mainstream 'User Programme,' involves some degree of collaboration with industry, whether that is industrial partners co-funding research students or helping frame research questions or providing samples

- The ISIS Collaborative R&D (ICRD) programme. This new access route was introduced in 2011, in an effort to broaden the use of ISIS by industry, and this has quickly developed into the main route through which industry gains direct access to the facility

- Paid proprietary access. In addition to the User Programme and ICRD, ISIS provides third parties with the option to pay a commercial rate to gain access to beam time and to use particular instruments. A small amount of proprietary work is undertaken, with individual clients paying for each 24-hour access period

The amount of usage by researchers is dependent upon the beam time available. Notionally, about 180 days a year are available for research purposes, however, pressure on ISIS budgets has led to the decision to restrict beamtime in order to make savings (e.g. in energy costs) and the facility has been running with 120 days beam time each year for the past 24 months. With the expansion in the number of instruments available, through the addition of TS2, ISIS has been able to maintain and even increase marginally the number of instrument-days available, even with the capped beam days.

A.4.2 User programme

<u>Proposals</u>

ISIS runs two proposal rounds in most years, each of which attracts 400-500 proposals. The proposals are peer reviewed by one of seven Facility Access Panels (FAPs), which rank proposals on a scale from 10 (world class) to 1 (unsatisfactory).

The figure below summarises the proposals received and accepted by ISIS during the two rounds in 2012, as well as the days requested and scheduled respectively in these proposals. The average number of days allocated per experiment is around 4 days.

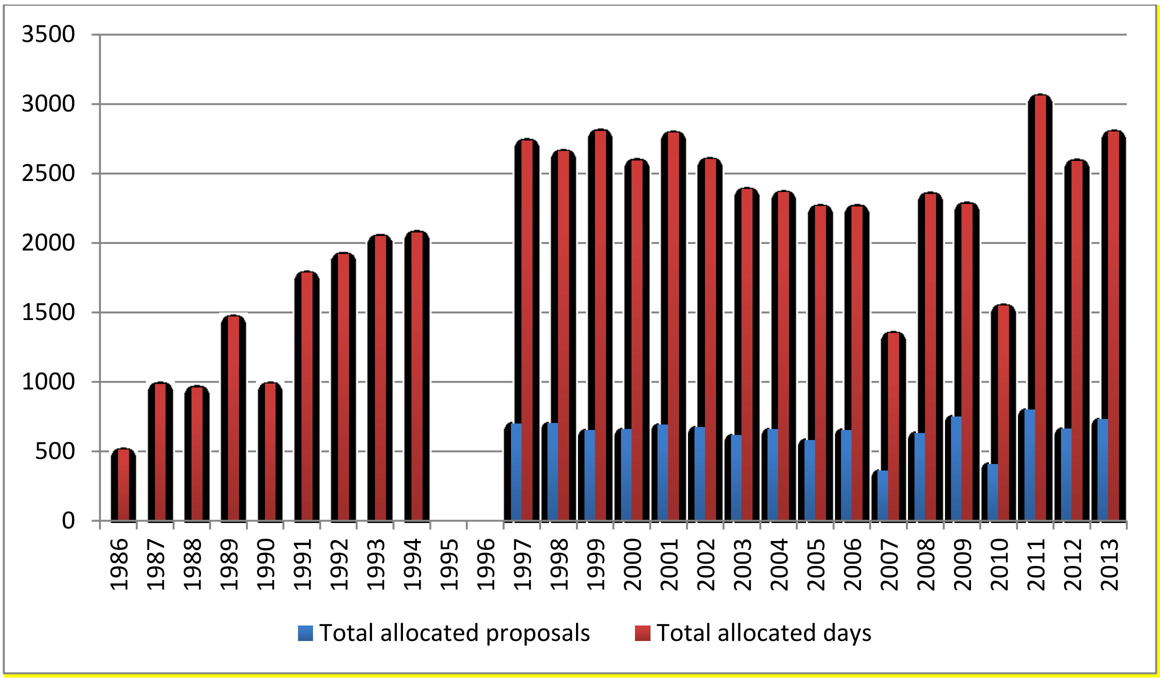
Figure 3 – Proposals from recent rounds of the user programme

	Proposals received	Proposals accepted	Days requested	Days scheduled
Round 2012/1	435	333	1,915	1,346
Round 2012/2	498	345	2,172	1,325

<u>Experiments</u>

Figure 4 shows the number of experiments performed (proposals allocated) and the number of days delivered (days allocated) through the User Programme across ISIS's history, for those years where data is available.

Figure 4 – Experiments performed and days delivered per year



Source: Based on data extracted from ISIS beamtime database

The number of experiments has been broadly stable for the 20 years from the late 1990s, at around 650 experiments a year, but has increased to around 700 following the opening of TS2: improvements in instrument performance have tended to lead to more complex experiments, involving more measurements, rather than simply to more experiments. In 2013, ISIS ran 730 experiments, with an average 120 days delivered to users on each of the fully scheduled instruments. The number of days delivered overall increased gradually for the first 10 years of operation, from 500 in 1986 to 2,000 in 1994. It has then remained at around 2,500 days per annum over the last two decades.

Almost 75% of all ISIS usage (i.e. of all allocated beamtime) is accounted for by UK-resident applicants. The figure below lists the top 20 UK universities that ISIS users in the 2010-13 period were affiliated to. Of the remaining ISIS usage (international applicants), approximately half is through specific collaborations with other countries (including EU funded access), and half is through general access for high quality science. In 2012, proposals were received from 29 different countries (plus the UK), with applicants from Italy, Japan and the USA accounting for the largest number of proposals from international scientists.

Figure 5 – Top 20 UK universities, by number of ISIS experiments (2010-13)

Rank	Institution	Total (days)	%	Cum %
1	University of Oxford	703	10%	10%
2	University College London	412	6%	16%
3	University of Edinburgh	406	6%	21%
4	University of Warwick	304	4%	26%
5	Queen Mary University of London	291	4%	30%
6	University of Bristol	242	3%	33%
7	University of Bath	241	3%	37%
8	University of Durham	217	3%	40%
9	University of Manchester	176	2%	42%
10	University of Cambridge	175	2%	45%
11	University of Glasgow	160	2%	47%
12	University of Nottingham	152	2%	49%
13	University of Sheffield	147	2%	51%
14	King's College London	143	2%	53%
15	Imperial College London	113	2%	55%
16	University of Liverpool	110	2%	56%
17	University of Birmingham	96	1%	58%
18	Queen's University of Belfast	87	1%	59%
19	The Open University	80	1%	60%
20	Royal Holloway University of London	78	1%	61%

ISIS also employs over 60 PhD level scientists who conduct their own research programmes, usually in collaboration with external researchers. Around 15% of ISIS time goes to proposals with an ISIS principal investigator. These users apply through the same process as external applicants.

Users / visitors

Figure 6 shows the number of visits by researchers to ISIS to perform experiments over recent years, together with the number of unique visitors. The number of user visitors and visits is somewhat variable, but has generally been increasing over time, and in particular, in the period since the implementation of TS2. The number of applicants is also shown, based on a 3-year rolling count. The numbers here are rather more stable. Figure then provides a breakdown of the user visits and visitors in just 2012/13 by origin and experience level, which reveals the broadly equal split between UK resident scientists and international scientists among professors and a ratio of around 2:1 UK: international visitors for PhD students.

Figure 6 – User visits and unique visitors for experiments at ISIS

Year	Rounds	Visits	Unique visitors	No. Applicants	No. successful applicants
2006	2	1,405	873		
2007	1	937	611		
2008	2	2,185	1,112	2,455	1,934
2009	2	2,002	1,000	2,490	2,051
2010	1	1,519	801	2,523	2,093
2011	2	2,087	1,205	2,709	2,243
2012	2	3,152	1,412	2,469	2,069

Figure 7 – User visits and visitors 2012/13, by origin and academic status

Visits	Professor	Postdoc	Student	Total
UK	192	1,010	1,038	2,240
International Partner	85	272	114	471
International Other	40	243	158	441
Total	317	1,525	1,310	3,152

Visitors	Professor	Postdoc	Student	Total
UK	69	336	446	851
International Partner	49	153	86	288
International Other	26	138	109	273
Total	144	627	641	1,412

In addition to visitors' use of the facilities, the Xpress service (a system of 'mail-in' measurements) has become increasingly popular, and is now available on all instruments. Since such measurements began, in 2005 (on the GEM diffractometer), 1,076 Xpress measurements have been carried out.

A.5 ISIS and industry

A.5.1 Industry in the ISIS User Programme

The majority of ISIS users are academics that have secured beam time on ISIS instruments through the periodic calls for proposals peer reviewed by one or other of the seven FAPs. The ISIS user office estimates that 10-20% of these mainstream experiments include some industrial component, whether that is direct involvement in the experimental work or more often indirect support through the specification of particular research questions or the provision of materials / samples.

The indirect and varied nature of industrial engagement means that ISIS is not able to provide a definitive overview of industrial collaboration, however, ISIS and STFC staff generously researched recent proposals and annual reports in order to provide a good sense of the nature and extent of industrial participation through the mainstream ISIS user programme.

For the three years, 2011 – 2013, ISIS identified around 750 instrument days that were allocated to proposals that made an explicit reference to industry involvement (137 days in 2011, 294 in 2012 and 326 in 2013).[1] If this situation were representative of the whole period of ISIS's history (i.e. an average of ~250 allocated days for proposals with industrial links per year), then we could estimate 7,500 days were allocated to proposals with industrial links during the last three decades. However, both the number of proposals in general and the number of proposals with industry links has been increasing over time, and so 2,000 days is perhaps a better estimate.

Further details were extracted from these recent proposals in order to profile the exact nature of the involvement of industrial partners. This link is most commonly the funding, or part-funding, of students involved in the proposal (in the experiment or wider project), for example through EPSRC CASE studentships. In other instances, the industrial partner is a sponsor of the associated research project (e.g. an EPSRC collaborative research grant). In addition, the industrial partner may be providing materials, samples, data or specimens for the experiments at ISIS, or providing additional expertise or computing facilities for the subsequent analysis. In a small number of cases a representative of the company is listed as the principal investigator (PI) or co-investigator on the ISIS proposal, or they coordinate the wider project that the experiment relates to. Finally there are examples of companies included in proposals as being explicitly interested in the results of the experiment, or are foreseen as a likely route to market for subsequent outcomes.

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[1] ISIS did attempt to trace industrial use across its history, however, explicitly detailing industry involvement within proposals has only been made mandatory in the last couple of years, so it was not possible to obtain a good overview across time. The annual reports also give some hints of the history of use by industry. For example, the annual report for 1987 states that agreements were signed with BP and ICI and that work started on the application of resonance radiography in collaboration with Rolls Royce and Bristol University.

The specific cases of day allocations with industrial links identified for the past 3 years cover 72 individual companies (18, 43 and 52 respectively). More than three quarters (79%) of these companies are linked to proposals that have been allocated less than 10 days in total. The other 15 companies are mentioned in proposals that were allocated between 10 and 138 days. This 'top 15' is shown in Figure 8, sorted in descending order based on the number of days allocated to proposals with an explicit link to the industry user in question in the 2011-13 period. The great majority of the top 15 industry users are large multinational companies (MNCs), many of which are PLCs headquartered in other countries elsewhere in Europe or the US, underlining the importance of ISIS on the one hand and the quality of UK science on the other.

Figure 8 – Top 15 industry users (2011-13 user programme)

	Company	Company	Type	Allocated days
1	Unilever	Consumer goods	MNC	138
2	Toyota	Automotive	MNC	57
3	BP	Oil & Gas	MNC	47
4	Johnson Matthey	Industrial technologies	MNC	42
5	Rolls Royce	Aerospace	MNC	40
6	Merck	Pharmaceuticals	MNC	38
7	General Motors	Automotive	MNC	35
8	Sasol Technology	Oil & Gas	MNC	31
9	MI Swaco	Oil & Gas	MNC	19
10	EDF	Power and energy	MNC	18
11	Syngenta	Agrochemicals	MNC	18
12	Aqura GMBH (Evonik Industries)	Specialty chemicals	MNC	12
13	Borealis	Chemicals	MNC	12
14	European Thermodynamics Ltd	Electronics	SME	11
15	Cella Energy	Energy / advanced materials	SME	10

Before 2011 there are ad-hoc mentions of industrial links, both within proposals and within the annual reports – but only a handful each year. In total there are 111 companies where a link to proposals has been identified over the full 1986 – 2014 period from the different sources, with the majority appearing in just one or two years. There are just five companies where links have been identified in five or more years during the last decade (Unilever, ICI, Rolls Royce, BP and Kodak).

Industry partners benefit from their ability to shape sometimes quite fundamental research questions and their proximity to the research results, the main findings however are expected to be published in the open literature, as is the case with all experimental work supported through the mainstream ISIS user programme.

A.5.2 The ISIS collaborative R&D (ICRD) programme

A wide range of industries has made use of ISIS instruments over the years, either indirectly through collaboration with academic partners, via the mainstream ISIS user programme, or directly through commercial access. The former is somewhat arms length and the latter is rather costly and technically demanding, and as a result, ISIS has conceived a new access route for the private sector that blends the positive attributes of the two existing channels, which is low cost (academic collaboration) and faster / controlled access (commercial access): the ISIS Collaborative R&D (ICRD) programme.

The ICRD was set up in 2012 to provide any business (or non-academic organisation) with a UK manufacturing or research base with an opportunity to join the programme and thereby secure a fast-track means by which to access ISIS beam lines and instruments.

When a company joins the ICRD programme, they form a partnership with ISIS, during which they undertake a specific programme of industrially related research and ISIS beam time will be provided as an in-kind contribution to the partnership agreement. The programme accepts applications all year round and due to the nature of some industrial problems requiring very fast responses the ISIS Collaborative R&D programme will give access to neutron and muon beams within two weeks of submitting an application.

ICRD applications include details of the goals of the proposed project, as well as an estimate of the potential economic benefits to the company and the UK. They are assessed by a small panel with the appropriate expertise, under strict confidentiality rules, outside of the normal ISIS peer-review process. If applications are technically sound, the company has a UK manufacturing or research base and the partnership has the potential to deliver benefit to the UK economy, they will be successful. Upon completion of the application, participants sign a Collaborative Research Agreement (CRA) with STFC.

ICRD users are not charged for access on the understanding that ISIS has the right to publish the results of the industrialist's 'proprietary' experimental work, which is expected to produce knowledge spillovers of benefit to the wider academic and industrial communities, sufficient to offset the cost to the tax payer of free access. The ICRD scheme allows users to 'buy' exclusive rights to the results where they deem them to be of sufficient commercial interest to warrant paying the ISIS commercial rate. We have been told about one case where an industrial user has elected to pay to retain the findings of its investigative work. In other interviews, industrial scientists have underlined the potential importance of this new access model as a means by which to increase industrial use of ISIS, both in terms of the number of users and the number of experiments. Put simply, ISIS's commercial access model is sufficiently costly to cause the senior management team at most smaller technology companies to refuse to support their R&D department's proposals to apply to ISIS for beam time. The ICRD scheme amounts to a de-risking strategy that ought to mean more businesses will be able to win approval for carrying out more fundamental (speculative) experimental work (at ISIS), with the potential for greatly enhanced insights and possibly profoundly important innovations. The new programme has already enabled ISIS to extend its industrial user community beyond the historical core of 10-20 very large international companies. Feedback from interviewees and surveys suggests the scheme is widely regarded as an important and industrially relevant innovation in the supply of facility-based services.

A.5.3 Route 3 - commercial route

If industry wishes to use ISIS for proprietary research, beam time can be purchased at a commercial rate. The number of companies accessing the facility in this way is very small and in 2012/2013 there was just a single example of ISIS being used in this way. This has been the case historically too: annual reports reveal that in 1990, 1% of ISIS funding was accounted for by industrial contributions, and that in 1993 a total of 30 days of beamtime were purchased by industry.

Appendix B Conceptual framework

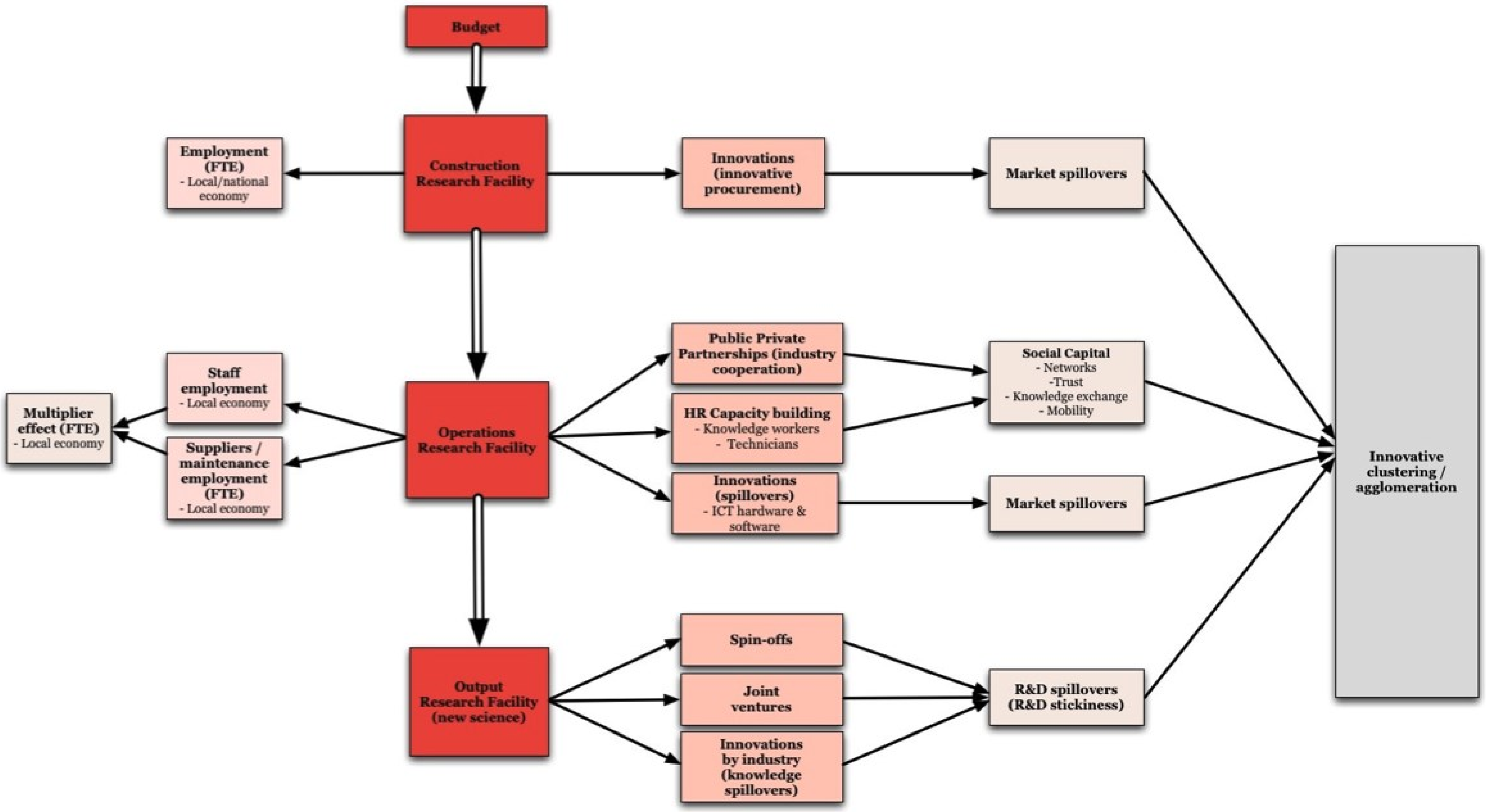
B.1 A singular model

We devised a conceptual framework to guide our data collection and analysis in order to arrive at an aggregate view of the different types of impacts that ISIS has made possible across its lifetime.

Figure 9 attempts to capture in a single diagram the spectrum of benefit types discussed in the evaluation literature; it is an adaptation of a scheme developed for a review of the role of large-scale research facilities, which Technopolis carried out for the Dutch government in 2011 and was presented in the methodological review, Big Science and Innovation (Technopolis, 2013).

It is an input-output model of sorts, making connections between financial inputs and the phases in the facility lifecycle and each of the main categories of socio-economic output. It attempts to capture the benefits that derive from the construction and operation of facilities on the one hand (e.g. user-led innovation among equipment suppliers) and, on the other, the benefits of the cutting edge science that is made possible by the facility (e.g. knowledge spillovers and innovations that result from research breakthroughs). The model also includes a series of wider effects, from indirect economic benefits (e.g. income multipliers) through to social capital (e.g. increased international engagement and influence) and local agglomeration (e.g. inward investors locating at the Harwell campus to benefit from improved access to ISIS and or the wider innovation ecosystem).

Figure 9 – A schematic showing the social and economic impacts flowing from large research infrastructures



Source: Big Science and Innovation (Technopolis, 2013)

B.2 Operationalising the model

As with any visual scheme, this input-output model is rather synthetic, and so we have disassembled the elements and presented them in a simple table, built around the two key parameters – stage in the facility lifecycle and benefit type – and itemised the specific benefits we would anticipate within that phase and for that broad class of benefit. For example, in the top row, we present the types of research benefits that the literature tells us we should expect to find. In the design phase, scientists are using current and recent research to push the envelope of facility design and construction (e.g. more powerful proton-driven spallation sources, improved boosters for greater neutron density) with an evident evolution in the power of facilities globally as one moves from one generation to the next. The raison d'être of big facilities is frontier research, allowing scientists to study and hopefully answer questions that previously could not be addressed experimentally, and thereby supporting new discoveries and analytical techniques.

Figure 10 tabulates the main sorts of benefits we would expect to find when studying ISIS. Figure takes this same table of benefits and itemises the measurement implications in each cell: whether our research will produce qualitative or quantitative measures.

Figure 10 – Overview of benefits by broad type of benefit and stage in the facility lifecycle

	Design and construction phase	Operational phase
Research	Development of the scientific case for new large-scale facilities underpins the evolution of facility science / instrument design globally and can influence institutional or national research agendas (with the changed possibilities)	New discoveries, new knowledge New methodologies and analytical techniques
Skills	Planning and design studies are technically and intellectually demanding and produce new insights and sustain / create capabilities than can be reused in other similar facilities nationally or internationally	Large-scale research facilities will typically operate with a dedicated in-house team of highly specialised (unique) facilities scientists and technicians Training in experimental techniques for research students and post-docs Develop, demonstrate, share new analytical techniques with public and private sectors Develop experimental skills of non-academic users
Innovation	New large-scale facilities constitute important lead markets for suppliers, encouraging firms to develop next generation engineering solutions, machines and instrumentation. These innovative developments can provide suppliers with a platform for future sales or wholly new product lines	New knowledge / new discoveries underpin innovation (spillovers) Big science facilities attract / create knowledge-intensive businesses that provide specialist technical services to the facility on a commercial basis (and other laboratories too)
Economic	Direct economic benefits of purchases of the works, capital equipment, goods and services required to build Indirect benefits of these investments, realised through economic multipliers	Direct economic impact of the facility's annual spend on staff, equipment and consumables, etc. Indirect economic benefits produced by the lab's annual running costs (multipliers, resulting from the lab's purchases of goods and services and staff spending their wages on goods and services) Direct economic benefits derived by industrial users (paid) proprietary research Indirect economic benefits of the innovations enabled by the new knowledge / discoveries realised through research at the lab

		Clustering / agglomeration effects around major research facilities

Figure 11 – Implications for measurement

	Construct	Operate
Research	Qualitative Oral testimony / desk research (ISIS place in history of development of neutron source for materials science)	Quantitative and qualitative Bibliometric analysis to count / judge ISIS-related publication output over time (inc. % of all publications in high impact peer reviewed journals) and some form of citation analysis to gauge the international standing (field average?) of the work Case studies of notable research breakthroughs made possible by access to ISIS
Skills	Qualitative Oral testimony Case studies (e.g. ISIS support to the design of the ESS through its staff participation in the 11 ESS instrument scientific and technical advisory panels; ISIS support to the design of the US Spallation Neutron Source at Oakridge)	Quantitative and qualitative Overview of staffing levels (numbers, occupations, skill levels) Overview of visitors (numbers, experience level, discipline, sector, nationality, etc.) Overview of education and training initiatives, from short courses to apprenticeships (itemise, describe initiative's objectives, audience, scale and scope; count beneficiaries) Case studies of one or two initiatives, capturing the benefits / impacts on participant's skills / productivity / employment Overview / meta-analysis of international MoUs
Innovation	Quantitative and qualitative TS2 supplier survey to profile distribution of types of spillover benefits among suppliers of larger / high tech work packages Case studies of particularly notable lead-market effects (e.g. Oxford Instruments superconducting magnet systems for target station 2 [CS on ISIS web site])	Quantitative and qualitative Survey of ISIS industry users to profile the types of innovation benefits realised through working with ISIS Case studies of notable innovations made possible by ISIS, which have led to substantial economic benefit Case studies of ISIS spinoff businesses Case study of the clustering / agglomeration effects around ISIS at Harwell
Economic	Quantitative TS2 supplier survey to estimate income / jobs attributable to user-led innovations / spillovers made possible by ISIS contracts	Quantitative Time-series analysis of annual expenditure Analysis of staff payroll and staff residency Analysis of visitors' stays (duration / expenditure) Application of multipliers to expenditure Survey of ISIS industry users to estimate income / jobs attributable to innovations made possible

		by ISIS

Appendix C Examples of academic and industrial impact

C.1 Introduction

The study team compiled several hundred examples of research or innovation outcomes from ISIS annual reports and case studies, and whittled this very long list into a somewhat shorter list of 50 candidates for further investigation. The team went on to contact people or organisations responsible for each of these possible case studies where possible. Ultimately, we have been able to prepare updated information on progress and outcomes in around 30 cases. These are shown below in an abridged form, grouped into research impacts and industrial impacts, whereas in practice the great majority illustrate both useful advances in knowledge and potential future industrial applications.

C.2 Research impacts

C.2.1 Nanoparticles from consumer products

Engineered oxide nanoparticles are widely used in cosmetics and pharmaceutical products, and are routinely released into wastewaters through drains. The effects of these relatively novel particles on the ecology and health of rivers are unclear, but there is currently no efficient way to remove them from wastewater during sewage treatment.

Researchers used ISIS to study the behaviour of nanoparticles in river and wastewater, and demonstrated that discrete nanoparticles and small aggregates were likely to be more toxic to aquatic organisms than larger aggregates. They also found that coating silica nanoparticles with detergent-like material caused the particles to stick to other components and sink, while uncoated nanoparticles stayed dispersed and were more likely to continue through the effluent stream. This showed that coating nanoparticles provides an efficient method of removing nanoparticles during the sewage treatment process and allows for their removal from the water system. This could provide the necessary evidence for developing new environmental legislation to safeguard aquatic ecosystems and water supplies.

C.2.2 Landfill and water pollution

There are several thousand landfill sites in the UK alone, handling millions of tonnes of waste annually. The potential contamination of groundwater and watercourses by toxic chemicals leaching from these sites poses a significant threat to public health, and it is therefore of paramount importance that the safe containment of waste leachate takes place. Landfill sites contain liners to help minimise the possibility of waste escaping into groundwater, and provide a way to drain leachate for treatment. Commonly these liners contain compacted clay layers several feet thick. The effectiveness of this compacted clay is an important question – particularly under conditions of dehydration, which can cause the clay to dry and crack.

A team of researchers used ISIS to better understand the structure and dynamics of interlayer fluid in expanded clays, using phenol – a highly toxic chemical found in many everyday products. The work demonstrated that phenol remains relatively mobile, even in clays with nanometre-sized pores, and that even though trapping phenol requires just a single molecular layer, drying and shrinking clay cracks, letting the phenol escape. This new knowledge – combined with research showing that organic cation coatings encourage phenol to stick to clay should soon enable the development of organoclays that effectively immobilise waste.

C.2.3 Atmospheric pollutants

Water vapour forms droplets on particles of material in the atmosphere, some of which are covered in surfactant films that act as an oily lipid layer on the droplets. These films are partly responsible for the size of the droplets in the cloud, whether the cloud rains, its reflectivity and lifespan. The whole dynamic of the cloud could be changed by what is in the cloud and it's droplets. The representation of cloud processes in climate models has been a source of uncertainty in understanding changes within the climate system, and the IPCC has suggested that a complete understanding of past and future climate change requires a thorough assessment of aerosol-cloud-radiation interactions.

A team of scientists used the ISIS facility to look at the rates of different chemical reactions that remove surfactant films, in order to understand the chemistry that is important in the atmosphere. The results, alongside concurrent experiments oxidising water droplets at the Central Laser Facility, have shown that some lipid films are relatively unreactive and show resistance to oxidation, meaning that they should have a longer lifetime in the atmosphere. This represents an important discovery in the understanding of cloud chemistry.

C.2.4 Green solvents

Carbon dioxide in its liquid form can act as an efficient, cheap, non-toxic and non-flammable medium for processing foods, drugs and chemicals, and is also increasingly used to replace common petrochemical solvents. However, CO_2 in liquid form acts as an uncooperative solvent, and dissolves only small amounts of water. Thus, scientists have been looking at ways to modify the properties of CO_2 by adding suitable surfactants that encourage water to disperse within it – and to do so with a surfactant molecule that does not contain environmentally-damaging fluorine (as many existing additives do).

Experiments at ISIS have now contributed towards the development of a new fluorine-free surfactant (TC14) that enables small pockets ('reverse micelles') to form in liquid CO_2, causing it to thicken into a viable solvent for commercial-scale enhanced oil recovery. The pressure can also be altered so that dissolved material can be separated and removed again, leaving the CO_2 ready for re-use without the need for more extensive cleaning (as is the case if water is used as the solvent). The structure of these pockets and how they function under high pressure were studied at a molecular level as part of the development work at ISIS.

C.2.5 Drug delivery

An important research area for the global drug delivery industry (worth around £80 billion in 2014) is the development of methods that are both safe and effective. One option is the use of nanostructured materials (which have one structural element smaller than 110nm), but scientists first need to learn how to control the size, shape and orientation of these materials before they can be deployed safely and effectively.

Scientists have been making use of ISIS over many years to explore a range of nanostructured materials, including:

- Studying the growth of silica-surfactant architectures during the formation of mesoporous silicates. Experiments at ISIS have led to an understanding of the mechanism of formation of these architectures that is sufficient to make similarly structured films from polymer-surfactant complexes, which could eventually be used in drug delivery.
- Studying the internal structure of PLGA nanoparticles used for in-vivo drug release. Measurements at ISIS helped to characterise the materials, which are now the subject of a patent application.
- Studying the shape and size of self-assembled polymer-protein conjugates, which form giant amphiphiles, and are aimed at drug delivery for treatment of heart disease.
- Studying partially oxidised cellulose nanofibrils, used for thickening aqueous formulations. This started with research at ISIS into more environmentally friendly personal care products, and resulted in two patents being filed by Unilever. The research was then taken to the next level, with nanofibrils used for drug delivery through skin similar to sports gels. The nanofibrils have been used to stabilise Pickering emulsions that could be used in drug for release applications, as well as for generating high surface area materials as catalyst supports and for absorption applications.

C.2.6 Printable solar cells

The solar installation market (worth $102 bn worldwide in 2014) is currently dominated by crystalline silicon, while alternative 'thin film technologies' account for just 10%. These technologies are not as efficient as current crystalline silicon cells, and have a shorter lifespan, but they are much cheaper to manufacture, and have the potential to be produced in large quantities.

Several different strands of research relating to the development of thin film solar cells have been undertaken over the last ten years at ISIS (up to 2014). The most recent, involving researchers from the University of Sheffield and UK start-up Ossila, explored polymer (thin film) solar cells, made by depositing thin layers of photovoltaic material on a substrate. The experiments looked at a particular blend of copolymer to determine how different molecular weight polymers affect the efficiency of the cell. The results showed that as the length of the polymer increases, the performance improves due to an interesting stratification effect, but only up to the point where the polymer chains are so big they start to fall out of solution. This improved understanding of the polymers used in thin cell solar cells and their effects on overall cell efficiency means that devices can be optimised by Ossila to improve efficiency, making the components more efficient and thus more competitive.

The research has also led to follow up work, in the first instance using the ISIS facility for the same set of experiments, but using different polymers to see if the results are common. Ossila has also secured funding to speed up discovery of polymer technology for eventual use in devices such as thin film solar cells, light-emitting diodes and low cost printed electronics.

C.2.7 Lung health

Lungs are coated with a thin layer of liquid containing a mixture of lipids and proteins. This lung surfactant is essential for the exchange of oxygen and CO_2, and many respiratory diseases are caused by inadequate lung surfactant. Damage to lung surfactant is also thought to be the cause of an ozone poisoning condition, which has been directly linked to significantly increased death rates from respiratory failure. Another substance secreted by the lung tissue, mucus, functions as a protective barrier that traps dust and other particles. It can also present a barrier to the uptake of inhaled drugs, particularly in patients with increased mucus.

Scientists are using ISIS to tackle these issues, investigating the interface between gases and liquids to study surfactants and polymers, in which weak electrostatic interactions play a significant role in creating complex structures and behaviours. For example:

- Researchers at ISIS tested cheaper and more accessible synthetic treatments for infant respiratory distress syndrome that could help to develop synthetic lung surfactants that are safer and can be more precisely targeted at clinical needs. The researchers were able to mimic change in lung capacity to discover how proteins and phospholipids act together to enable lung function.

- A research team used ISIS to investigate how fast ozone reacts with the lipid layer of lung surfactant, and whether it led to any structural changes to the crucial interfacial material. The results showed that the surfactant reacts rapidly with the ozone, leading to a change in the surface tension, a slight reduction in the amount of material at the interface, and a significant thinning of the surfactant layer.

- A research team carried out studies at ISIS to investigate the ability of various polymers to diffuse through a layer of mucus at the atomic scale, in order to determine a more effective method of drug delivery, piggy-backing on the polymer.

C.2.8 Bio-active glass bone replacement

Bioactive glasses are a group of surface reactive glass-ceramic biomaterials showing biocompatibility that has led them to be investigated extensively for the use of implant materials in the human body, allowing repair and replacement of diseased or damaged bones.

A team of researchers used ISIS to develop and investigate the properties and reactions of Bioglass, which provided understanding into how and at what rate the calcium of the Bioglass was released into the bone. This has helped in the development of mechanically stronger joint replacements, and clinical trials are expected shortly.

C.2.9 Nuclear waste

Hydroxyapatite (HA) is a biomineral similar to bones and teeth, and it is particularly suited for nuclear waste remediation and storage because it is stable over long geological periods, resistant to self-radiation and can incorporate radioactive metals into its structure. HA can be produced by a species of Serratia bacteria, and this "bio-HA" is able to bind ten times more radionuclides than synthetically-produced HA.

Researchers used ISIS to follow, in-situ, the nucleation and growth of the biomineral on the bacterial surface over 48 hours. The aim was to understand the steps to biomineral formation, so synthesis conditions for improved radionuclide uptake can be optimised. The research group are now working with the Japanese Atomic Energy Agency (JAEA) to investigate if these biominerals can be used to decontaminate soils.

C.2.10 Tackling antimicrobial resistance

Pathogens such as bacteria and fungi constantly evolve to keep the upper hand in the face of the antibiotics used against them. Changes in their genetic make-up enable germs to modify the targets of drug action, or the site of drug entry, rendering the antibiotic ineffective. Research at ISIS is accelerating progress in the race to better understand the origin, spread, evolution and development of resistance. Insights into how antibiotics interact with the surface of microbial cells to gain access, the molecular mechanism of antibiotic action, and development of membranes that mimic those of bacteria will facilitate the rational understanding and design of new antibiotics. For example:

- Only in the last couple of years have scientists uncovered the molecular mechanism by which penicillin remains inactive while transported through the body, and springs into action once it has reached its bacterial target. Researchers have used ISIS to determine the location of hydrogen in penicillin, which plays a crucial part in changing the shape of the molecule during its transition from inactive to active state.

- The outer membrane surrounding the bacterial cell constitutes the microbe's first line of defence against attack by antibiotics. A model outer membrane was built using proteins and lipids, and the ISIS facilities were then used to confirm that the internal structure of this artificial membrane mimicked that of its bacterial counterpart. After adding a bacterial protein, scientists were able to follow how the antibiotic colicin interacts with the membrane, proving that this model can be used as a system to investigate how antibiotics scale this defensive barrier, aiding in the development of effective novel drugs.

C.3 Industry user innovation

C.3.1 Protein surfaces and biosensors

Orla Protein Technologies has been developing protein surfaces suitable for use in biosensor devices since 2002. These devices contain a chip covered by antibodies that recognise and bind molecules and can quickly and accurately identify the presence of pathogens, allowing the correct course of treatment to be initiated. ISIS was critical for the company in addressing two essential steps in technology development – the optimisation of the orientation of antibody molecules on the biosensor, and validation of the reproducibility of the manufacturing process. Using neutron scattering, Orla were able to view their antibody layers in action as they were binding to specific target molecules and rejecting others. Tweaking this technology to optimise the process, they established a suitable manufacturing method.

In 2008 Orla established a spin-out company with a multinational electronic communications supplier, and created a miniature wireless sensor that can rapidly detect infectious diseases and send information using a smart phone. The company announced in 2014 that it had developed a biosensor for the simultaneous detection of three respiratory virus pathogens. This low-cost device could be used for consumer diagnostic applications in remote or rural areas, and the technology is now ready for pilot production. The parent company Orla, has also now secured £500k in funding from business angels to expand its activities in advanced protein technology and mobile medial diagnostic applications.

C.3.2 Surface active molecules

Surface active agents – or surfactants – are compounds that, when dissolved in water, concentrate at interfaces with the air, oil or other substances. They are often found blended with a range of ingredients in home and personal care products, as well as adhesives, coatings, drug delivery systems and pesticides. The interfacial activity of surfactants can be explained in terms of their molecular structure, and give rise to a wide range of surface chemistry functions such as emulsifying, foaming, glossing, lubricity and surface conditioning.

ISIS scientists, in partnership with Oxford university have pioneered applications in the area of surfactants over the past two decades, through the use of neutron reflectivity (NR) and small angle neutron scattering (SANS) – experimental techniques that enable measurements on surfaces and near surface areas up to 100 nanometers. This partnership has led to the development of important experimental techniques, new understanding and a redefinition of major theoretical models of surfactants, as well as the production of over 400 publications. Their work in this area has also been critical in the continuous development and improvement NR and SANS instruments available at the ISIS facility.

C.3.3 Catalyst for PVC production

INEOS ChlorVinyls is Europe’s largest manufacturer of PVC and chloromethanes; which are important components of many everyday products, from window frames to pharmaceuticals. Production of chloromethanes creates dimethyl ether as a by-product, representing a waste of materials and energy, and causing undesirable effects in later stages if not removed.

To overcome these problems, INEOS wanted to minimise the by-product by modifying the catalyst. It was necessary for the intermediates on the catalyst surface of the reaction process to be identified, and researchers used two ISIS instruments to examine the interaction at a molecular scale. The results enabled the surface of the catalyst to be modified, leading to improvements in manufacturing and a significant reduction in the unwanted side product. The new catalyst has been used successfully at INEOS’ Runcorn site now for 10 years.

The methodology has since been further developed and applied to other catalytic systems and applications, including the reforming of methane to produce 'synthesis gas' that can be used as fuel, for example in the Fischer–Tropsch process. Sasol Ltd - an international energy and chemical company that uses Fischer-Tropsch - has now been working with ISIS to look at the iron-based catalysts it uses. So far, this has resulted in the development of a model for the composition of the catalyst as it progresses from the precursor to steady state in operation, and new insights that will contribute to future modifications of the catalysts used by Sasol.

C.3.4 Glass corrosion

Glass corrosion from moisture occurs in numerous applications over many years and, while often not visible to the eye, can lead to poor adhesion and performance of coatings. Research was undertaken at ISIS into the interactions between liquid water or humid atmospheres and glass surfaces, which found water penetrating deep into glass, even in specially coated windows (such as in aircraft). There was industry interest in these (surprising) results, and they offer valuable input for future improvements in glass and glass coatings.

Appendix D Economic impact of ISIS research

D.1 Introduction

This appendix presents a selection of Extended Economic Impact Case Studies, where the study team has sourced various market forecasts and other economic projections and made assumptions about the relative importance of ISIS research within that context and what amounts to a credible attribution rate for ISIS. The financial estimates have been arrived at almost exclusively by the review team, following extensive desk research.

The extended case studies were picked from a longer list of around 50 ISIS case studies, focusing on those where there was the best chance of quantifying possible future economic benefits. The extended case studies build on the original case studies shown in the appendices of the draft final report, which focus on the research itself and the contribution of ISIS instruments to that undertaking, and which talk about application areas in a rather more conditional manner. In the treatment that follows, we begin with a paragraph about the ISIS research and then move into a more exploratory discussion of potential future applications and market value. Each case is then summarised in a simple table showing an overview of our estimate of likely future economic impacts that might reasonably be 'claimed' as being attributable to ISIS.

D.2 Case studies

D.2.1 Bioactive coatings and improved hip replacement implants

The global orthopaedic devices industry (est. £17 billion in 2012) suffers from relatively high failure rates in its implants, which require expensive (and often painful) replacement. Modern implants are covered with layers of hydroxyapatite (HA), a calcium carbonate, that bonds well with bone, and is used to integrate the implant into the body, but 18% still fail, often due to residual stresses that are 'locked-in' after fabrication. Researchers used ENGIN-X at ISIS to explore how the bonds between metal, HA and bone are created, and to study the effects of different treatment techniques on the stress profile in implants. This allowed the creation of a *validated* residual stress model that can be used by the orthopaedic implant industry more generally to assess the quality of HA coatings, which has the potential to improve the reliability of implants globally.

If this model is widely adopted it could deliver substantial savings to national health services in the UK and internationally; we estimate it could save the UK NHS more than £20M a year based on current knee and hip replacement numbers and revision rates by 2020 (up £200M in total between 2015 and 2025). There would be substantial quality of life improvements too, for the thousands of people with implants. The improved coating methodology / model is relevant to many areas of musculoskeletal surgery and orthopaedic devices, and as such the benefits of its wide-scale use could be far higher for the NHS (and private hospitals). Given the substantial uncertainty around the rate and extent of adoption of the model and associated improved coating techniques, we have chosen to use the narrower estimate of benefits to the UK NHS around hip replacement.

Even this conservative annual figure ought to produce cumulative savings in excess of £200M. We elected to 'claim' 5% of those savings for ISIS, or £5M, due to the critical contribution of high-resolution neutron scattering (Engin-X) to the development of the experimental data used to validate their computer models.

The impact on the UK medical devices industry is harder to determine, as the market is dominated by US multinationals and UK market share of NHS implants is perhaps 10% of a £500M a year market, with a smaller share of the coated metal implants for hips and knees. However, the number of procedures is increasing year on year as medical devices and implant procedures improve and the treatment is judged suitable for younger and more active people. Demographics – the ageing population – will also drive increasing use of these procedures.

The UK market could easily increase to £750M by 2020, and the UK industry's ability to retain or increase its 10% market share will hinge on technological innovations of this kind. In light of this, we feel it is reasonable to attribute £3M-£5M of the increase of its sales in 2020 (£75M) to technological innovation in coatings, and perhaps as much as £20M in additional sales between 2015 and 2025. Exports ought to be improved too, so this figure is likely to be conservative. We elected to 'claim' 5% of this projected additional economic activity for ISIS.

ISIS has also contributed to the creation of new, more durable, bioactive implant coatings, as well as an associated patent application for a novel bioactive coating that has strengthened the technology portfolio of a UK-based spin-off company Taragenyx, which is aiming to create and develop the next generation of bio-regenerative implant solutions. The company is just three years old and is still building its team scientific and commercial staff (c. 10 people in 2014) and technology portfolio, and is rather more broadly based than bioactive coatings for hip replacement joints. According to Companies House, the company had an asset value of around £0.5M at the end of 2013/14. Given the somewhat indirect link between ISIS and Taragenyx and the uncertainty around the likelihood that it can capture a large share of the market for implants,[2] we have elected not to claim any value for ISIS at this time. That situation may change radically of course within the next five years, with rapid growth in implants and the potential for major disruption by patented new technologies.

Type	Total	Attribution to ISIS	ISIS benefits
Savings for NHS	£100M up to 2025	5%	£5M
Additional economic activity in UK	£20M up to 2025	5%	£1M

References and notes

The National Joint Replacement (NJR) Centre's 11th Annual Report (2014)[3] provides useful data to help size the market in the UK: there were more than 450,000 hip and

[2] The NJR Centre Annual Report 2014 shows that two companies – Stryker Corporation [US HQ, $9 billion, 2013] and DePuy [US, owned by Johnson and Johnson} – account for around 80% of the implant devices used in the UK.

[3] www.njrcentre.org.uk/

knee replacements carried out in 2012/13, and that the 10-year revision rate (replacement for whatever reason) is around 4% overall (based on patient level records going back to 2000). Revision figures differ widely by type of joint and age of recipient, with for example, replacement rates for partial knee joints in younger patients reaching 20% in some cases. Failures are most often the result of dislocation or infection triggered by wearing / debris, however, implant materials are often the starting point. An improvement in the bond between the HA coating and the bone ought to improve 10-year revision rates: a 25% improvement in the average revision rate for hip joints (from 4% to 3%) would reduce the number of revisions within the current 200,000 or so hip replacements from 8,000 to 6,000. The NHS estimates the cost of a hip or knee replacement, on average, at around £5.5K, which amounts to a cost of around £2.5 billion a year for 450,000 procedures. The cost of the medical devices constitute around 10-20% of this figure, so up to £0.5 billion a year.

The bioactive coatings patent application: AHMED REHAN; MARKX GERARDUS HENDRICUS [GB] as the inventors and TARAGENYX LTD [GB] as the applicant (owner)

Dr Ahmed's journal article is … Neutron Diffraction Residual Strain Measurements in Plasma Sprayed Nanostructured Hydroxyapatite Coatings for Orthopaedic Implants. R. Ahmed, Nadimul Haque Faisal, Stefan M. Knupfer, Anna Maria Paradowska, Michael E. Fitzpatrick, Khiam Aik Khor, Jan Cizek. Materials Science Forum (Volume 652)

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D.2.2 Novel antiferromagnetic (AF) materials for data storage

The ISIS WISH instrument is being used to characterise and design novel antiferromagnetic (AF) materials for application in computer storage, which could revolutionise the speed and environmental performance of electronic devices globally. A research team from Nottingham University working in collaboration with the Institute of Physics and Charles University in Prague, the University of California Berkeley, University Compluense de Madrid, Oak Ridge National Laboratory, STFC and Hitachi Cambridge has been investigating new materials which could increase computing speed, efficiency and memory capacity.

The international consortium was funded by the EPSRC and the European Research Council (ERC) and elected to use ISIS to investigate / characterise a series of new Antiferromagnets (AF). AF materials possess few of the usual features associated with ferromagnets: for example, they do not posses macroscopic magnetic fields and therefore are not sensitive to external magnetic fields. Antiferromagnets exhibit (1) high reorientation speeds which translate potentially into faster computing, (2) no stray fields which translate into more memory per area and (3) non-volatility which translates into no power being consumed while idle and (4) low energy consumption when switching, which means lower running costs.

The WISH instrument is a long-wavelength diffractometer that is able to provide high-resolution data for magnetic systems (amongst other things) and which provides the sensitivity needed to measure thin AF layers, one atomic layer at a time (roughly 1000 times thinner than a human hair). A very challenging and unique measurement technique, which according to researcher Dr Peter Wadley, "could not have been conducted anywhere else." Dr Wadley added

> *"The ISIS research has been a stepping stone towards functional AF spintronics and the research is proceeding towards even better material systems, which will hopefully be useful for functioning spintronic devices. The replacement of volatile RAM with high-speed non-volatile MRAM should produce massive gains in access speed and reduce carbon emissions associated with computing, which are huge. The associated societal benefits would also be huge. The team will be returning to ISIS with new and modified materials until they have precisely the right material for applications"*

Dr Wadley argued it was too early to estimate the value of potential applications of novel AF materials, but suggested that it could be very large indeed.

> *"The field of AF spintronics is very active at present and the development of room temperature working AF devices, could bring about not only an increase in speed and efficiency of computing systems but also a change in the fundamental architecture of computing leading to further gains. The potential commercial impact of spintronic devices cannot be overstated, and the role for AF materials within this new field could be very significant"*

The review team elected to look a little further into the question of future markets, in order to arrive at a first approximation of likely benefits.

Existing market research reports suggest the value of such a new material could run into hundreds or even billions of dollars annually, if the evidence of growth in the value of spintronics devices is any indication. Spintronics (or spin transport electronics) is a relatively new field of applied research, which emerged from discoveries in the 1980s, including giant magnetoresistance (GMR), by Albert Fert et al in France and Peter Grünberg et al. in Germany (1988), and jointly awarded the Nobel Prize for Physics in 2007). It is a large and growing area of physics research that has already application in fields including mobile phones, healthcare, automation, IT and automotive industries. The most common example is in data storage where the hard disk read heads use this technology, and also in new magnetic memories (magnetoresistive RAM or MRAM or spin-RAM). These application areas are large global markets and as such the commercial benefits of next-generation technologies will be very large indeed. As an indication of scale, the market for MRAM currently accounts for $5.28 billion of a $8.5 billion dollar next generation memory industry and is predicted by 2017 to account for $9.37 of $16.08 billion dollars (Markets and Markets analysis).[4]

There is a real likelihood of a UK breakthrough in the area of AF materials, albeit this is a widely research topic with strong interest globally. There is clearly substantial potential for new IP and new companies in this area, albeit the routes to market are likely to be through internationally HQed multinationals, whether that is through licence agreements or a trade sale of any associated startups.

US, Japanese and Taiwanese electronics companies dominate data storage markets presently (e.g. IBM, Motorola / Everspin, TDK, etc), however, new entrants like Crocus Technology (founded at the Spintec R&D centre in Grenoble in 2006 with 154 patents) have launched breakthrough MRAM technologies. Crocus Technologies attracted $300M in investment funds from Russia within the first two years of its launch and it has gone on to commercialised several MRAM applications and has licenced that technology to IBM, amongst others, and led several established players to elect to buy in the technology rather than attempt to develop it. This story gives confidence that there may still be opportunities in mass storage for new entrants.

Assuming there is new IP and startups linked with UK research, future sales (turnover, royalties, shares) are likely to run into the tens of millions, given the critical role these technologies could play in what is an enormous and rapidly growing market globally. ISIS's contribution is hard to determine, as there is a very substantial research effort underway internationally and many other neutron sources and other large research facilities (e.g. Diamond) are actively involved. However, if we assume the UK may see up to £100M in income of one kind or another related to AF spintronics over the next 10 years, it is arguably reasonable to claim perhaps £5M of that new economic activity as being attributable to ISIS, which has had a long-term influence on this developing field. The global industry will derive substantially larger benefits from ISIS's work.

[4] These statistics are taken from the public summary of a market research report published in 2012, which is a priced publication with a cost of almost $5,000 for a single user licence and almost $8,000 for a corporate licence. Next Generation Memory Market (2012-2017), By Technology (DRAM, SRAM, Flash Memory, Memristor, Magneto Resistive RAM (MRAM), Phase Change RAM (PCRAM), Ferroelectric RAM), Application & Geography, produced by Markets and Markets, 2012.

With no meaningful data storage industry, the UK's primary impact pathway is likely to be the social and environmental benefits derived from more powerful electronics (e.g. in computing, automotive, etc) and greener electronics. These are open and competitive markets, so the improvements may not impact heavily on prices – or not for long – and will be realised mostly in the form of producer and consumer spillovers.

Summary

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity in UK	£100M up to 2025	5%	£5M

References and notes

http://www.nmi.org.uk/industry-support/sector-info/

D.2.3 Spider Silk and medical devices

Spiders spin their web from a feedstock – a mixture of water and silk proteins. It is stored inside their bodies in large sacs and when it is pulled through their spinning ducts it transforms into a very resilient solid. The silk is light, thin, flexible and strong. In fact, despite being a protein, it is five times stronger than steel by weight and three times tougher than Kevlar. Its thermal conductivity is also very good, and similar to that of copper.

The production of spider silk in commercial quantities could therefore have a wide range of potential uses in military, industrial and consumer applications. Because spider silk is in some ways superior to the materials currently available in the market, it could also lead to an expansion of demand and market opportunities (e.g. in wound patches / artificial tendons / implant coatings, or capsules for drug delivery).

The traditional silk market is estimated at approximately £3 billion a year globally, at the raw fibre level. Given its superior physical properties, spider silk is well positioned to penetrate that market. Spider silk could also make significant in-roads into the significant and growing technical textiles market for high-strength/performance fibres. For example, the market for aramid fibres – a class of heat-resistant and strong synthetic fibres, dominated by DuPont's Kevlar® made in the US, Japan and Northern Ireland - is currently estimated to be worth around £2bn (equivalent to 75,000 metric tonnes of fibre), with predictions that this will rise by 50% by 2020.

Unfortunately spiders are unsocial carnivores and farming them to produce silk in large quantities is not feasible or economical – leaving the option of trying to replicate the process and material artificially. After years of trying to develop commercial spider silk, big companies including DuPont and BASF have dropped out. However, a handful of much smaller entities are now claiming progress.

A team of researchers from the Oxford Silk Group (University of Oxford) have been using ISIS over the past decade to try to uncover the secrets behind the fundamental processes of silk spinning, exploring the transformation of silk feedstocks from stored gel to solid fibre at the atomic level. Using instruments designed with the ability to probe biological materials, the team have been able to see the change in position and shape of native silk proteins during the conversion process. This has increased understanding of the complicated silk spinning process, which is fundamental for artificial development and future applications.

The Oxford Silk Group recently created a company, Oxford Biomaterials Ltd (OBM), to develop silk technologies for commercial application. It is focused on the development of novel silk-based biomedical products such as vascular grafts based on its Spidrex® technology – for which it hopes to establish a worldwide market. Spidrex® fibres and scaffolds exhibit excellent mechanical properties, and preliminary trials have demonstrated Spidrex® to be entirely biocompatible and an excellent substrate for colonisation by mammalian cells. This has resulted in the development of an entirely novel range of absorbable medical devices based on the proprietary Spidrex technology platform.

According to Companies House, OBM has an asset value of nearly £0.5M. It has also spun out a further 2 companies to develop and commercialise Spidrex as well as other silk-based products in medical devices. These are:

- Neurotex Ltd – which was established to develop silk-based products using Spidrex® for a new generation of nerve repair materials. The Spidrex nerve repair technology is currently being trialled in peripheral nerve repair, but there are plans to roll out the work to spinal nerve repair. The company aims to take a part of the 'efficacious neural regeneration conduit' market, which is estimated to be worth £64 million annually. A 10% market share would therefore equate to some £6M a year and as much as £600M through to 2025

- Orthox Ltd – which has taken forward OBM's cartilage repair technologies using Spidrex®. The company casts silk into shapes suitable for use in replacement joints. Because the silk implants do not irritate or harm the body's cells, they not only provide tough replacement surfaces but also encourage regrowth of new tissue. Spidrex® MRS™ is currently in pre-clinical evaluation, and Orthox has been awarded £563,000 to develop long-term safety data and fund clinical studies on FibroFix™ Meniscus. The NHS estimates the cost of hip and knee replacements alone cost it around £2.5 billion each year, of which medical devices constitute around 20% of this total. We have therefore assumed that there is a potential market for Spidrex joints of at least £500M per annum in the UK alone – if we estimated a 10% market share, this would equate to around £50M (albeit the joint coating is only one part [cost element] of the overall device)

Both Orthox and Neurotex technologies are reported as having shown great promise in early trials, and should soon enter full clinical trials in late 2014 or early 2015.

In Germany, the firm AMSilk has begun selling spider silk protein to producers of shampoos and cosmetics. The company reports that it is hoping to roll out products generating annual sales in the next couple of years of more than £6 million, and is targeting sales of more than £60 million once large-scale production of synthetic fibres is under way.

These predictions underpin the £50M-£60M annual economic output we estimate for Spidrex® products under development at Orthox Ltd and Neurotex Ltd by 2020, perhaps a £300M in total through to 2025. The additional sales will displace some economic activity elsewhere in the UK economy, so the net benefits may be smaller, perhaps £150M. We have elected to attribute 2% of this figure for ISIS (£3M) because of the long-term use of the facility by the Silk Group that has helped establish these companies and products and multiple additional investments by other organisations in the development of these novel materials.

While it is likely that the research into processes of silk spinning that has been undertaken at ISIS will have contributed to global understanding, and may be benefiting the development of a wider range of silk-based products entering the £3bn technical silk textiles market, we found no information on these developments or their links to ISIS, and so we have elected not to suggest any value for ISIS beyond the immediate spin-outs at this time.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£150M to 2025	2%	£3M

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D.2.4 Pollutant gas filtering

The efficient removal of CO_2 and SO_2 represents a major challenge in the development of the 'low carbon economy'. Currently, amine solutions are used to capture the CO_2 from power plants, but the regeneration of these amines comes with a considerable cost and their highly corrosive nature means that their long-term application is significantly limited. Thus, the development of alternative materials to remove CO_2 more efficiently, with higher rates of regeneration and at lower cost, is important to the development of the 'low carbon economy.'

The IPCC has recommended a 50-85% reduction of global greenhouse gas (GHG) emissions from 2000 to 2050 and a peak in emissions no later than 2015. Currently, the major source of emissions in the UK is power stations, which generate over a quarter of its CO2 emissions (145 Mt of 464 Mt in 2013). If the UK is to meet its legally binding targets to reduce GHG emissions, it will therefore need to achieve near-zero emissions from its power stations by 2030.

Carbon capture and storage (CCS) is seen as one of a number of solutions that will be needed to achieve ambitious emission-reduction targets. CCS will allow continued use of fossil fuels within the future energy mix, providing capacity to respond to growing demand in a way that other low carbon technologies are not able to. However, several challenges must be overcome before CCS can be deployed on a large scale. These are related to the three main areas in the CCS value chain: capture, transport and storage. Extensive research, testing and development is ongoing within all these areas, and improvements are continuously reported.

The most mature capture processes use **amine solvents** to 'scrub' CO2 out of the flue-gas mixture. However, using these solvents is energy-intensive and requires up to 30% of the output of a power plant to operate. They also create toxic by-products that represent health and environmental risks. Substantial research is therefore being carried out globally to find alternative solvents or other mechanisms, which can dramatically lower the costs of CO2 capture while also offering improved environmental performance.

One alternative is to use solid materials known as "metal-organic frameworks" (MOFs) – fine powders whose particles' surfaces are covered with nano-size pores that collect CO2 molecules. MOFs have the potential to function as more environmentally friendly and efficient alternatives to amines for selectively removing CO2 from large, stationary sources including power stations. Scientists from the University of Nottingham have been using ISIS to research porous MOF complexes that show promise for gas separation and storage due to their high surface area and tuneable functional pore environment. The University's Chemistry Department has developed and patented a non-amine-containing porous solid that adsorbs large amounts of CO2 and other acidic gases (SO2, NO2) called NOTT-300, which is inexpensive to manufacture, chemically and thermally stable, synthesised in water (environmentally friendly) and maintains its porosity upon recycling. The structure of NOTT-300 was designed using a combination of neutron diffraction (using WISH) and neutron spectroscopy (using TOSCA) to determine its crystal structure and locate CO2 and SO2 molecules within the pores. This combination of methodologies and instruments at ISIS allowed the elucidation of the material properties of NOTT-300, providing invaluable information on how these porous materials trap gaseous species.

The team claim that NOTT-300 is cheaper and more efficient than existing materials at capturing polluting gases from flue gas. The material – covered in patent application UK 1205365.8 and published in Nature Chemistry, 2012, 4, 887–894 – is available to license from the university. It has the potential to reduce fossil fuel emissions through the cheaper and more efficient capture of polluting gases, and could lead to innovative technologies to tackle global warming.

Carbon capture and storage is seen as a cost effective and affordable way to help countries to secure, low carbon energy supplies. Fossil fuels currently provide robust, flexible and diverse sources of electricity. Without CCS, their limited future role in the energy system will impact negatively on the security and diversity of electricity supply, as well as significantly increase costs on the public / Government. For key industries, CCS is also the only technology that would enable significant emissions reductions. If CCS is not available, then ultimately many of those industries may have to close or relocate, with major loss of employment and revenue. The cost of reducing carbon dioxide (CO_2) emissions will also be dramatically higher without CCS (up to 70% higher internationally according to the IEA). Failure to deliver CCS as a key mechanism for cutting carbon emissions will therefore have profound implications for the UK economy. Estimates show that the costs of a low-carbon energy mix in 2050 could be around £30 billion (1% of GDP) per year higher without CCS and possibly £10bn by 2025.

CCS also represents a major green growth opportunity. Worldwide up to £25 billion has already been committed by Governments to support CCS projects. It has been estimated that by 2050, 964 GW of total installed CCS power generation capacity will be needed globally to reach required emissions reductions. This would create a market worth over £100bn per year from 2020, in particular in the US, China, India and other coal and gas dependent nations. This offers substantial export opportunities for UK businesses, albeit many of the major technologies / work packages are controlled by large US or Japanese conglomerates (e.g. GE, Mitsubishi Heavy Industries). There remain important opportunities for UK manufacturers, such as Doosan Babcock, who are pushing alternative power technologies like Integrated Gasification Combined Cycle (IGCC), which converts coal to gas and allows CO2 to be removed without the use of Amines.

Full-scale CCS is only now beginning to be implemented internationally (pilot-scale integrated plants are in use in Germany, Norway and elsewhere) and it is likely to be at least another 10 years before it is in widespread use, because of the economics (capital and recurrent costs amount to a substantial share of total costs for a large coal-fired power station). Notwithstanding the cost and environmental challenges, Amine-based technology is expected to dominate over the next 10-20 years.

It has been estimated, that if CCS opportunities develop as anticipated internationally, UK-based engineering and manufacturing firms could benefit from additional income of more than £3 billion a year by 2030 (mostly in export sales for engineering design services and specialist plant and equipment).

Work on MOFs at Nottingham and elsewhere may help this huge global market become a reality earlier, and generate additional income for the UK specialty chemicals sector. The global market for amines – all applications, from pesticides to cleaning products – was estimated at around 5.8MT in 2012 or $30 billion (at around $5,000 / tonne), with estimated growth rates of 3.8% pa through to 2022, driven by China and other developing economies especially in Asia.[5] The use of Amines in CCS applications is small and not separated out in the market research reports, which is understandable given the limited and small-scale use of the technology in 2012. One might imagine that the roll out of CCS could drive growth in the market for amines, perhaps reaching $1 billion a year by 2025, in the absence of any technological breakthrough. That in turn would suggest that materials like NOTT-300 might ultimately be addressing a global market valued in the hundreds of millions sterling annually; perhaps £2 billion in total through to 2025. If UK specialty chemicals companies can maintain a 10% share of that global market, which is currently dominated by German (BASF) and US companies (Huntsman and Taminco), that could yield perhaps £200M in additional economic activity for the UK through to 2025 and some valuable royalty income for the University of Nottingham. Given the critical role played by ISIS in tuning the design of NOTT-300, we believe it is reasonable to claim a proportion of this projected future income (for UK chemicals sales globally) for ISIS. However, NOTT-300 has yet to be licenced and numerous other companies and universities are working on competing solutions, so given this and uncertainty over future market development, we elected to work with a conservative multiplier of 1% applied to the anticipated £200M in net additional income to the UK economy through to 2025. Given the very many uncertainties involved at every point in this forecasting work, we have been content to claim a benefit for increased material sales and not claimed any benefit for ISIS of the possible acceleration in the roll out of CCS in the UK itself, helping extend the life of coal-fired power stations, and the likely cost-savings of a non-amine technology in capital and operational terms. NOTT-300 could deliver environmental and reputational benefits too, resulting from that earlier roll out of CCS nationally. We note that NOTT-300 has very many more potential industrial applications than carbon capture.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£200M to 2025	1%	£1M

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D.2.5 Damage accumulation in train wheels

Railway wheels operate in a demanding environment with high normal contact forces and significant tangential forces. The resulting stresses often exceed the yield stress of the as-manufactured wheel material, leading to wear and fatigue damage.

Wheelset maintenance and renewal comprises a significant portion of the whole-life cost of railway rolling stock. The UK passenger rail industry currently replaces approximately 20,000 wheelsets every year, at a typical cost of £6,000 each (including purchase, fitting, etc.). Wheel tread damage is often the dominant factor controlling wheel life, so even a modest 10% life extension to wheelsets could bring savings to the UK rail industry worth £12M annually. Wheelset manufacture, transportation, maintenance and disposal are also energy-intensive processes. Improvements in wheelset life should therefore also offer environmental benefits. A recent US rail research presentation[6] estimated the annual costs globally at around $700M, noted the proportionate increase in the frequency of residual stress as a factor in early / unexpected failures of wheelsets (as wheel design, manufacture and operations have improved). The presentation also acknowledged that research had yet to explain the phenomenon fully.

At the University of Huddersfield, the Institute of Railway Research (IRR) has a longstanding interest in wheel-rail interaction, including wheel and rail damage. Working with the Rail Safety and Standards Board (RSSB), the IRR has been investigating railway wheel damage mechanisms. This work identified the need to understand the physics of the different damage mechanisms, supporting the development of wheel damage and cost models. Research on monitoring and simulation of wheel damage is being carried out in collaboration between IRR, Siemens (train manufacturer) and Lucchini UK (wheel manufacturer). The way in which wheel damage rates change through the life of a wheel is of particular interest, and residual stresses are thought to be an important contributory factor.

While in previous research in Italy and the US (at TTCI), Lucchini succeeded in measuring some stresses in the wheels, collaborative work with IRR at ISIS provided an opportunity to push this research further and investigate how the residual stresses change through the life of the wheels (new wheels, used, damaged). The experiments were performed using the Neutron Diffraction technique at the ISIS Rutherford Appleton Laboratory on the ENGIN-X instrument, which is one of the few facilities worldwide capable of measuring stresses in such large and heavy samples. Results of the ISIS experiment indicated significant axial tensile stress in the wheels near the end of their life, which may be linked to a different wheel failure mode known as a 'vertical split rim defect.' The findings of this experiment have been of particular interest in the USA,[7] where vertical split rim defects are more common, and have lead to IRR becoming a key participant in the International Collaborative Research Initiative (ICRI). The ICRI brings together researchers in the wheel/rail

[6] Scott Cummings from the TTCI research centre in the US estimated that wheel damage globally was costing around $675M for wheelset replacement and a further $35M a year relating to derailments and slowdowns. These figures were set out in a presentation given to the 18th AAR Annual Review Conference, hosted by the Transportation Technology Center, Inc. (TTCI is the research and testing centre of the Association of American Railroads).

[7] http://www.railjournal.com/index.php/north-america/north-american-railways-combat-split-wheel-rims.html

damage field from across the world, sharing data and methods to develop a better understanding of damage mechanisms and contributory factors.

A better understanding of the triggers of residual stress should lead to further optimisation of wheel maintenance (such as inspection and balancing intervals), and might justify the use of different (more costly) materials or a smaller minimum wheel diameter. It could also identify opportunities for changes to wheelset manufacturing processes or materials to further improve through-life performance. Lucchni, Siemens and the Association of Train Operating Companies (ATOC) are continuing this research at ISIS, through the ICRD programme.

Findings of several experiments, including those conducted at ISIS, have also lead to the publication of a best practice guide for identification of wheel damage, which includes advice on damage prevention, maintenance practices and rectification.

Related to these research activities, the IRR is currently developing the 'Centre for Innovation in Rail' at Huddersfield; this is a £20m project supported by a substantial Regional Growth Fund (RGF) grant and project partners RSSB, Unipart Rail, Omnicom and the National Skills Academy for Railway Engineering. Central to this development is the IRR's expertise in wheel/rail contact and damage, linked to the associated risk and safety issues. New laboratory equipment will include a test rig focused on wheel/rail adhesion in traction and braking, and the damage that can be caused to wheels and rails under these conditions. This will be a full-size rig using real wheelsets, traction motors and brake equipment. Its aim is to develop hardware and software to optimise traction and braking performance to improve operating safety and efficiency, and to reduce the incidence of wheel damage.

We would expect this ongoing research to lead to practical changes in design and operating principles, which should begin to be implemented in the next several years, and shared with / discussed the European and international rail industry, and could give an average 20% extension to the average life of a wheelset. Based on the safer 10% estimated improvements, and £12M a year saving in costs for train operators, which will build up gradually as rolling stock is refurbished or renewed, we estimate there could be as much as £50M in savings to the UK economy by 2025. The scale of these benefits is small in comparison with total operating costs, but should however, help to contain prices for rail travel and cargo. It may also reduce imports in some measures, with a reduction in the numbers of wheelsets being purchased from predominantly overseas manufacturers. Lucchini has a finishing plant in the North West, but the wheels and wheel sets are developed and manufactured in Italy.

There is very substantial international research feeding into design and operating principles, so while the neutron diffraction experiments have provided unique insight into the failure modes, the practical response to that research is more broadly based. For this reason, we elected to allocate 1% of those benefits to ISIS.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£50M to 2025	1%	£0.5M

D.2.6 Cleft palate hydrogel

Cleft palates are the most common birth defect in Britain, with one in every 700 babies affected. Babies born with this condition usually have problems feeding, and may have speech difficulties, as well as issues with their hearing, dentition or facial growth. In severe cases, radical surgery is required, taking up to 10 expensive operations to correct the problem, and future complications can occur as the child grows.

A team of materials scientists and medical professionals from the University of Oxford and the John Radcliffe Hospital in Oxfordshire, working in collaboration with colleagues from the Georgia Institute of Technology (GIT) in the US took up the challenge to find an improved surgical treatment.

With the help of ISIS, the researchers developed an intelligent hydrogel that expands in a highly controlled manner when surgically implanted (historically, tissue expanders expand equally in all directions, which is not always appropriate). As this material is placed into the palatal cleft, it swells to accurately fill in the gap, which in turn encourages skin growth over and around the plate. Once sufficient tissue has been generated, the plate can be removed. The researchers used ISIS to investigate the novel hydrogel at the molecular level, "ISIS provided us with the high level of structural detail we needed to assess the material. It gives unique and accurate results that we can't get with any other technique," said Professor David Bucknall from GIT.

In early 2011, Oxtex Limited was created as a spin-out from the University of Oxford to further develop the technology. Within a short period of time, the company attracted over £500,000 of seed funding from investors and won several awards. In 2012, Oxtex secured another £65,000 in funding from the Technology Strategy Board (which became Innovate UK, in 2014) to scale up its manufacturing process.

The Oxtex website states that "progress towards initial clinical trials in both animals and humans is underway. The first trial in small animals will begin in September 2014, through collaboration with a number of specialist veterinary centres. This will be followed, by the end of 2014, by the launch of the first human trial, which will be conducted across several UK hospitals. An improved treatment for more severe cases of crossbite (poor alignment between the upper and lower dental arches) is also being pioneered through collaboration with the University of Malaya, where initial in-man trials commenced in early 2013. A range of dental applications is being developed through collaboration with the Harvard Dental School where the first canine trials were launched in 2013. It is anticipated that the first product launch will be for veterinary application devices and will take place in January 2013. This will generate early revenues ahead of the human use devices attaining CE marking later in 2013, following which these devices can be distributed throughout Europe."

Its use is expected to improve patient outcomes, lowering the risk of soft tissue damage and associated complications (e.g. pain and tissue necrosis), by enhancing the predictability of the surgery due to the gel's controlled expansion properties.

The gel can be specified with different expansion profiles, allowing reconstructive surgeons greater flexibility in its use.

Future applications go well beyond cleft palate repair: the hydrogel provides a reliable method for expansion of soft tissue in procedures such as dental implant surgery where bone augmentation is required. In the UK alone, 80,000 dental implants are fitted every year, which can cost between £1.5K-£4K for each procedure, where the implant itself might constitute around 10% of the total cost.[8]) The report also shows an estimated 70% of cases require bone augmentation, which assuming these are the more costly procedures, would suggest the relevant UK dental implant devices market was around £20M in 2013 (10% of the cost of 50,000+ procedures costing up to £4K each in total). Other applications of the material include soft tissue expansion following removal of carcinomas, treatment of congenital birth defects, scar tissue and wound repair.[9]

Soft tissue repair is a significant and growing market globally, with specialist market research company Orthoworld,[10] valuing orthopaedic (including orthodontic) applications at around ¢4.5 billion in 2013, with annual growth rates of 6-7% over the past five years. Analysts forecast the Global Orthopaedic Soft Tissue Repair Devices market to grow even more strongly over the 5-year period, 2013-2018, at around 9% CAGR.[11] [12]

Taken together, these different market research data suggest the global market for an intelligent hydrogel for reconstructive surgery could run into the many tens of millions, replacing the use of current devices in more severe cases, but also accelerating growth in the market overall as a result of its greater applicability and improved health outcomes. The future potential for such hydrogels must run into the many hundreds of millions globally, within 10-20 years, as they displace older technologies. In the UK, the cumulative value of the market might easily reach £100M between 2015 and 2025, of which perhaps 50% might be additional and not substituting for existing devices.

Oxtex itself is still in its infancy, and is a small medtech company, firmly in the clinical trials phase at the point this report was prepared, and still spending rather than making money. However, its core staff of four directors has established a well-regarded business with a balance sheet value of around £200K and a list of impressive research and trials partners. The value of this technology on the open market is unknown, however, there is a substantial appetite for such investment opportunities among both venture capitalists and other equity investors and it seems highly likely the business could attract a trade sale with a price running into the millions, and perhaps as much as £5M.

Given the critical importance of a definitive understanding of the material's properties to the success of the hydrogel, we elected to 'claim' for ISIS, 5% of our

[8] http://www.dentalimplantscosthq.co.uk/dental-implants-cost-uk/

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estimated £5M company valuation and 2% of the our estimate of £50M in additional economic activity (up to 2025).

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£50M by 2025	2%	£1M
New business	£5M in 2015	5%	£0.25M

D.2.7 Nanotube ink

Transparent Conductive Films (TCFs) are used in more than 90% of high tech displays and touch screens in the electronics industry, with the global TCF market estimated to be worth more than $2 billion (2012). TCFs are optically transparent materials, which are electrically conductive in thin layers. The industry standard TCF is Indium Tin Oxide (ITO) (with a 93% market share and around $1.5 billion in 2012), however, this is brittle and not an ideal material for touch screen devices. It is also expensive to produce with the price of indium, a rare earth metal, fluctuating according to market demand (current market prices are around $600/kg which peaked at more than $1000/kg in 2005).

Single-Walled Carbon Nanotubes (SWNTs) have been proposed as an ideal alternative. SWNTs have excellent thermal conductivity, mechanical and electrical properties making them particularly useful in nanotechnology, electronics, optics and other fields of materials science and technology. 'Once processed, carbon nanotubes offer significant advantages over established technologies for applications such as smartphone and tablet touchscreens, as they can be bent and folded without loosing conductivity. Carbon nanotubes now put innovations such as an ultra-compact tablet with a screen that folds in half within our reach.'[13] However, their use has been limited by the sonication (application of sound energy to agitate particles in a sample) process, which is not readily scalable, and the ultra-centrifugation methods used to solubilise (increase the solubility) the SWNTs, which disrupts their structure.

A new innovative, scalable reductive dissolution technology using liquid ammonia produces solubilised carbon nanotubes in the form of inks, which can then be deposited as films, has been developed. This method was originally developed by the London Centre for Nanotechnology (LCN), a multidisciplinary research and technology centre jointly owned by UCL and Imperial, whose experiments at ISIS were critical in providing evidence of the SWNTs both in solution and at a sufficiently concentrated level. Using *in situ* small angle neutron scattering on the ISIS instrument LOQ, the team at LCN discovered that using sodium metal dissolved into liquid ammonia reduced the SWNTs. The solution was then evaporated to leave an expanded nanotubide salt. The charged SWNTs can then be dissolved in an organic solvent to produce inks of individual SWNTs whilst maintaining SWNT length. These findings were very important in the subsequent decision by The Linde Group[14] to commercialise the technology, which they gained an exclusive licence for in 2011. The licence agreement negotiated by UCLB grants Linde exclusive rights to a portfolio of IP developed in the LCN relating to the carbon nanotube separation and purification process. The licence is the culmination of a programme of collaborative work between the LCN and Linde over several years and is a good example of successful technology transfer, taking a process developed in the university lab to full industrial scale-up. The nature of the terms and financial outcome of this agreement are commercially sensitive and were not available to the study team.

[13] http://annual-report.linde.com/annual-2013/innovative-drive/report-carbon-nanotubes.html

[14] The Linde Group is a Munich headquartered multinational specialised in industrial gases and engineering with more than 60,000 staff in 100 countries. The Linde Group UK is a significant operation and includes much of the former operations of the BOC Group, which Linde acquired in 2006,

The Linde Group's first SWNT product, SEER^{e-} Ink, was launched in 2013 at the Fourteenth International Conference in the Science and Application of Nanotubes (NT13). The product was aimed at the R&D market originally, however, the focus is being expanded to the TCF market, where it can be used in place of the traditional ITO. The continued scale up of the technology, which is already competitively priced, will help lower the price of SWNTs further and provide an even more competitive technology relative to current alternatives. The marketing of this technology is being led by the Linde Group's electronics division in the US, having been commercialised by its nanotechnologies team in California. The product is in the market and generating income, however, information about sales of the product is not reported publicly by Linde in its annual reports or other corporate documents.

According to a report by Allied Market Research, entitled 'Transparent Conductive Film (TCF) Market (Technologies, Applications and Geography) – Global Opportunity Analysis and Forecast – 2013-2020,' the global TCF market is forecast to reach $5.86 billion by 2020, growing at a CAGR of 17.2% during the forecast period (2014-2020). A specialist market research company, Touch Display Research, has come forward with a much more ambitious forecast however suggesting that the non-ITO TCF market alone could reach $8.1 billion by 2021 (four times the value of the current market for all TCF variants). This report profiles over 220 companies and research institutes working on advanced transparent conductive (TC) materials and provides a detailed analysis of metal mesh, silver nanowire, carbon nano tube (CNT), conductive polymer, graphene, and other technologies.[15] [16] It assumes strong growth in new technologies (displacing ITOs) and dramatic growth in the Asia Pacific region with less strong performance in Europe. There is also a potential for SWNTs to be used beyond TCF in applications such as composites, sensors and biology.

The UK has a relatively small industrial base addressing the TCF market, and as such there are valuable but limited opportunities for the UK to capture much of the growth in these emerging markets. The Touch Display Research report suggests the market for new technologies (within the TCF area) is likely to grow so vigorously and be so large that there will be good opportunities for businesses in the UK. Equally, there are numerous other global businesses researching and launching their own nano ink products that will compete with SEER^{e-} Ink. Notwithstanding these qualifications, based on the forecasts, capturing even 1% of the global market for novel TCFs could add £50M a year to the UK economy by 2020, and perhaps as much as £0.25 billion between 2015 and 2025. Taking 1% of that figure to reflect the contributions of ISIS to the development of this novel technology, through its support for the team at the London Nanotechnology Centre, seems reasonable, which would give an estimated financial value of £2.5M

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£0.25 billion by 2025	1%	£2.5M

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http://www.ucl.ac.uk/enterprise/enterprise-news/uclb-licensee-linde-launch-seere-carbon-nanotube-ink

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D.2.8 Organic semiconductors

Semiconductors are the basis of modern electronics, used in transistors, microchips, LEDs and solar panels, with a global market value in excess of £230 billion (2013). Organic semiconductors are an important new class of semiconductors, combining the virtues of plastics (easily shaped) with the electrical properties of semiconductors, creating the potential for novel low-cost applications (e.g. in solar panels or display screens). The global organic electronics market is around £13 billion (2013). Sales have been growing strongly over the past five years and are forecast to strengthen further, increasing to £60 billion by 2020 (CAGR of 29%), more than doubling the share of organics within the global market for all semiconductors.

OLED (organic light-emitting diodes) displays are the largest segment in the organic electronics market, accounting for almost 75% of the overall market in 2012. It is also the fastest growing area of the market, presently. The market for next-generation plastic and flexible OLED displays was around £500M in 2014 and is expected to rise to $16 billion by 2020 according to IDTechEx market research. Growth forecasts take it as a given that industry and the research base will continue to characterise and develop these materials, allowing their wider application, opening up new markets and substituting for conventional technologies in other cases.

To realise the full potential of organic semiconductors, the fundamental physics of these materials needs to be better understood. ISIS facilities have been used to contribute to world-class research in this field. For example:

- HiFI spectrometer at ISIS was used to investigate mechanisms of electron spin relaxation in organic semiconductors by a research group from Queen Mary's University led by Dr Alan Drew. They concluded that there is a strong dependence of avoided level crossing resonance amplitude on temperature and atomic mass, implying that a spin-orbit based spin relaxation mechanism is thermally activated. The results are important for applications in spintronics

  Electronics companies are very interested in developing spintronic devices because they offer the scope of enhanced functionality, higher speed and reduced power consumption. New organic materials provide an opportunity to produce such devices at much lower price. Current understanding of organic spintronics underlines the potential of replacing traditional spintronic materials in niche applications such as memory devices and sensors. For an indication of the scale of the opportunities, the global market for MRAM was approximately £3.4 billion in 2013 and growing rapidly

  Organic materials could easily accelerate growth rates and capture a meaningful fraction of that market place within the next 10 years. The development of organic spintronic devices is still at the research phase, with no devices on the market currently, however commentators expect a breakthrough before long. It is therefore somewhat premature to attempt to forecast the potential value of the likely future market for organic memory devices, but nonetheless, it seems highly like that it will be commercialised widely within the next 10 years and have a global market value running into the many billions

The UK is most likely to capture the benefits of this new class of devices through consumer spillovers (we all benefit from the improvement in the functionality of devices without having to pay in full for that improved performance) primarily and possibly to a much smaller degree, through specialist tech firms and startups selling into global semiconductor value chains. This increased economic activity is likely to comprise design-based work – so-called “fabless manufacturing” – or niche manufacturing, rather than large-scale manufacturing, which has been substantially outsourced over the past decade: the UK has a small share of the global electronics market (c. £2.3 billion in 2013; <1% of the global market and shrinking at around 5% a year[17])

ISIS is one of the very few places in the world where such experiments can be carried out, and as such, ISIS has been contributing to important advances in our fundamental understanding of these materials, which is essential for successful future applications. Location matters and these advances in understanding may give UK-based multinationals and small tech firms something of an advantage over their competitors in the biggest electronics manufacturing countries like Taiwan and could go someway to helping the UK to retain more of its electronics industry in the medium to long term

- Muon scattering at ISIS was used to study mobile spin dynamics and charge carrier motion in an aluminium-related material, with the aim of providing an upper limit for the mobility achievable in high quality bulk organic semiconductors. These experiments were conducted by the research team of Dr Alan Drew in cooperation with scientists in the UK and Switzerland from the University of Fribourg, the University of Sheffield, the University of London, the Paul Scherrer Institute and ISIS. The results have benefited semiconductor research generally, especially relating to molecules in OLEDs, as similar materials are used in electroluminescent displays and other large-area electronic devices: OLED displays are used in laptops, tablets, TV sets and lighting (and smaller displays in mobiles and wearable electronics).

The UK is among the world’s leading players in plastic electronics research, with large, world-leading groups at Cambridge University and Imperial College, and significant activity elsewhere, including ISIS. However, translating this academic capacity into new industries and jobs is proving challenging, in large part because of the smallness of the UK industrial base in the area and the dominance of global players in the Far East. The largest (~65%) producer of organic displays is in Asia Pacific, home to 75% of all electronics manufacturing capacity globally. Some of the big names in the industry are Samsung Electronics, TDK, RiT Display, Pioneer, Visionox, LG Display, Sony Corporation and AU Optronics Corp. Even though the UK has a small semiconductor industry, which was worth £3.8 billion in 2009 (reducing to £2.3 billion in 2013), they use a traditional approach and switching to new organic semiconductors has been slow. There are exceptions, with examples of new

[17] These data are taken from the public-access overview report of the charged publication, Electronic Component Manufacturing in the UK - Industry Market Research Report, published by companies and markets.com

companies such as Cambridge Display Technology (Sumitomo Chemical Group), Plastic Logic (Rusnano) and Avecia (Nitto Denko Avecia).

To summarise, there is potential for the UK to contribute to the development of the global organic electronics market through research (including the experiments done at ISIS) and there is a great potential for new IP as well as new company creation in the sector, but the most likely route to the market is through established international (Asian) electronics companies due to the very competitive market situation globally. From what we see in the market today, new OLED knowledge created in the UK is most likely to generate revenue through licence agreements or the trade sales of any associated startups.

Considering the rapid growth of the global OLED market as well as the strong academic activities in the area in the UK, the overall future revenue (licences, funding brought in through new startups as well as trade sale, etc) for the UK (domestics and international) is likely to run into the many tens of millions of pounds, and may be as much as £500M over the next 10 years through to 2025. The contribution of ISIS is difficult to judge, as a lot of research in the area is going on worldwide in academic institutions as well as within the large electronics companies. Notwithstanding these caveats, we believe ISIS's contributions to our understanding of these materials has and will continue to be critical and as such believe it is credible to assign to ISIS 1% of our estimated total future economic output for organic semiconductors in the UK. These knowledge spillovers will also benefit other countries and UK consumers, through improved products. There is as yet no monetisable benefits from this work, that we have been able to identify, however, we estimate the value of the contribution of ISIS over the next 10 years may be as much £5M.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity in UK	£500M up to 2025	1%	£5M

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D.2.9 Forensic science

Fingerprints are unique friction ridge skin impressions that, when left on an object or at a crime scene, can link a suspect to the object (e.g. a weapon or tool) or the location. The chance of two people – even identical twins - having the same fingerprints is extremely low (1 in 64 billion). Combined with the fact that the pattern does not vary with time (or even for a substantial period after death), it provides a unique identifier of an individual. This may be exploited for intelligence purposes (via databases) during an investigation or for evidential purposes when a suspect is brought to court.

In practice, so-called latent (non-visible) fingermarks are the greatest source of evidence, since they are not visible to the naked eye and therefore commonly left unnoticed by a criminal. The challenge is to make the latent fingermark visible. Although research over many decades has resulted in a diverse range of reagents – from coloured powders, to "superglue" and chemically specific reagents – only approximately 10% of latent fingerprints detected are developed to a level that is considered adequate proof of identity in court. This motivates innovation of more effective and sensitive physical and chemical technologies to visualise latent fingermarks.

Scientists at the University of Leicester, led by Professor Robert Hillman, have come up with a new technique to address this important challenge. They are using fingerprints on metal surfaces as a template to deposit coloured electrochromic polymer between fingerprint ridge deposits. The insulating nature of the deposits directs the polymer to the bare metal to generate a negative image of the fingerprint, while the visual contrast can be adjusted by application of a small voltage. This electrochromic technique was developed further using the ISIS facility. The second-generation concept involved functionalising the polymer film by binding flurophore molecules to its interior. Upon exposure to light, these flurophores re-emit light of different colours, allowing a three-dimensional visualisation of a high quality fingerprint image. The approach relies on optimising the functionalisation chemistry, and ISIS instruments were used to measure the generation, stability and flurophore occupation dynamically during the reactions. The experiments proved the validity of the functionalisation concept, which will now contribute to the enhancement of forensic science methods.

The new method has the potential to partially replace conventional fingerprint detection powders, which had an estimated annual global market value of around $90M in 2013 or around 10% of all forensic powders and chemicals. However, it is most likely to be used as a complementary technique for analysis in more difficult cases, so expanding rather than reducing the market value.

The research team is taking part in a wider research programme generating technologies that have appeared in the UK Home Office Fingermark Visualisation Manual, a document provided to all UK police forces and widely used by law enforcement agencies worldwide. It is their hope that future development of the fluorescence technology will feed through to this in due course.

This forensic technique is not a "product" that can be sold in the market in a traditional sense, albeit the materials and associated toolkit may be developed as such and could be something that is picked up by a UK-based specialty chemicals manufacturer or value-added suppliers. There is however strong overseas competition in this specialist field. The major benefit for the UK would be improved forensics and more effective criminal prosecutions; crime is a huge social and economic cost. According to the "The Economic Cost of Violence Containment," a report written by Institute for Economics and Peace in 2013, crime costs the UK economy more than £124 billion a year, or 7.7% of GDP. This calculation included the cost of police investigations, courts and prison expenditure as well as a vast amount in lost productivity. For example in 2012 murder cost the economy £1.3b, other violent crimes £45b, theft £4b and burglary £5.3b. Moreover, the cost of directly responding to crime (e.g. the cost of criminal justice system) is approximately £220M a year.

Additionally, better investigation methods lower crime rates. This trend has been already noticed with the expansion of the use of DNA testing. If the UK overall could lower its crime rate to match the average level for the South East of England, for homicide and violent crime, the Institute for Economics and Peace estimates there would be an expansion in economic activity for the UK of £23.4 billion up to 2025.

We were not able to find good data on the link between improved fingerprinting and reduced crime rates, however if the new fingerprinting method is successfully implemented, it seems likely to produce some efficiency gains in the criminal justice system. A 1% improvement in the cost effectiveness of the national criminal justice system would amount to £20M plus in direct savings over 10 years. If we further assumed a 0.1% reduction in national crime rates attributable to the new methodology, which would yield a further £23.4M in savings. The contribution of ISIS to the evolution of the new technique has been rather important, and might credibly 'claim' 5% of the anticipated future UK social and economic benefits.

Type	Total	Attribution to ISIS	ISIS benefits
Savings for public sector	£22M up to 2025	5%	£1.1M
Reduced crime	£23.4M up to 2025	5%	£1.2M

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D.2.10 Keeping nuclear power plants safe

Every day of operation, the steel and concrete that make up a nuclear power reactor's containment structures are bombarded with radiation and stressed by both high temperature and high pressure. Over time, these forces can potentially weaken even the toughest materials.

Given the harsh conditions, coupled with an absolute requirement for safe containment of radioactive material, procedures for assessing the structural integrity of plant components are strictly regulated and nationally codified. These integrity assessments have a major impact on the lifespan of the power plant.

A nuclear power station has many thousands of welds, e.g. 2,000 welds in the large bore steam pipework.[18] Welded joints are particularly vulnerable to plant degradation and material ageing, and account for most structural failures.[19] A number of weld repair techniques are available, and new welding procedures for joining materials are being developed; however, before deploying them, the very high levels of qualification and validation required by the nuclear industry and regulators must be met.

While welding joins components during fabrication, or remedies in-service degradation such as cracks, it may leave weak areas in the material. The heat from welding may cause localised expansion; when the finished weldment cools, some areas contract more than others, leaving residual stresses that can decrease the material's strength. This was the case in 1997, when steam leaked from the Hunterston nuclear power station in Scotland, caused by a creep crack that was initiated and grew through the pipe wall adjacent to a repair in a stainless steel pipe weld.[20] A 2001 survey of weld repair technologies used by utilities in the US found that 40% of all repairs to steam chests, piping and headers resulted in subsequent cracking.[21]

A review of published literature at the time of the Hunterston leak revealed a paucity of knowledge about weld residual stresses associated with repairs. This led to the initiation of a programme of investigation involving researchers at the Open University and British Energy (now part of EDF Energy), funded by the EU's Training Industry in Neutron Stress Measurement (TRAINSS) network.[22]

The researchers used neutron diffraction at ISIS's ENGIN-X instrument to directly measure residual stress in weld repairs. These were the first measurements of their kind and revealed the surprisingly severe nature of residual stress fields associated with repairs. Most importantly, the research demonstrated that the simplified predictions of stresses at weld repairs routinely used to support safety cases were

[18] http://www.sns.gov/workshops/nst2/presentations/05-fitzpatrick.pdf

[19] Edwards L et al (2008). Adv. Mat. Res 40-41: 391-400

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[21] Gandy D. W., Findlan S. J. and Viswanathan R., 2001, "Weld repair of steam turbine casings and piping – an industry survey", ASME J. Pres. Ves. Techn. Vol. 123, pp 157-160

[22] http://ec.europa.eu/research/brite-eu/thematic/html/2-3-03.html

not conservative. As a result, British Energy launched a multi-million pound programme of weld modelling development and validation, carried out across the period 2001 – 2010, to underwrite safety cases for repaired Advanced Gas-cooled Reactors (AGR). Work by the Open University for British Energy was used to develop improvements in weld residual stress simulations to validate predicted creep relaxation and to characterise the nature of residual stress concentrations at weld repair.

Research at ISIS has helped to confirm an hypothesis that the high failure rates of weld repairs is due in large part to residual stress, which is vey much more problematic than had been previously understood. The improved awareness of the risk of weld-induced residual stresses has resulted in the development of new repair procedures that have a very much lower failure rate (validated through experiments at ISIS) and as a result the UK regulator is allowing plant owners to extend the lives of these hugely costly pieces of infrastructure through major refurbishment programmes.

The new understanding of weld repairs and refined life-analysis methods underpinned by these measurements has allowed the lives of the Hartlepool and Heysham 1 AGR power stations to be extended to 300,000 hours, rather than the previous restriction of 175,000 hours caused by uncertainty about creep damage to weld repairs in the main boiler support structures. With each of these reactors generating around £700,000 of electricity per day, these life extensions represent a major contribution to the UK economy, on jobs and on security of electricity supply. It also deferred the need for decommissioning and replacement of the two nuclear power stations at a cost of several billion pounds each.

In 2013, EDF announced that Hartlepool had been given a 5-year life extension, from 2019 to 2024. According to EDF estimates these extensions will secure the jobs of 1,500 employees and contractors. EDF has calculated a wide range of benefits for (5-year) plant life extensions to the 15 reactors in the UK's nuclear fleet, including 30M tonnes of CO2 emissions (on the assumption that the reduction in generating capacity would be made up by fossil fuels, mostly gas), £650M a year in contracts for mostly UK-based businesses to carry out the repair and upgrading work associated with the extensions and the safeguarding of 2,000 jobs in the power industry (gas power stations employ far fewer people). The University of Manchester used EDF statistics to estimate that a 4-year extension to the Oldbury Power Station (2008-2012) had produced an additional 7 terawatts of electricity, worth £300 million to the taxpayer and saving around six million tonnes of carbon dioxide in comparison with the alternative (gas fired power stations).

The 2008 Nuclear White Paper "Meeting the Energy Challenge" highlighted the key importance of nuclear power to fulfil the UK's commitment to cut carbon emissions by 80% by 2050 and to secure its energy supply. As most existing nuclear power stations are scheduled to close by 2023, the government has identified eight sites as potentially suitable for the deployment of new nuclear power stations in England and

Wales before the end of 2025.[23] Insights from research conducted at ISIS will help optimise the lifespan and safety of new nuclear built.

While there are numerous references to the cost savings associated with the deferral of the decommissioning and replacement of the UK's nuclear fleet, EDF's impact assessments have tended to focus on the additional economic activity associated with the refurbishment of power stations and the safeguarding of employment. They are working on the assumption that nuclear would largely be replaced by gas, with its dramatically lower capital investment / employment requirements and higher fuel costs (imported).

The role of ISIS and engine-X was clearly critical in confirming the nuclear industry's hypotheses about residual stress and validating the robustness of alternative weld-repair procedures, and in that sense ISIS has been an important source of evidence that has persuaded the UK regulator that it is safe to allow refurbishment of the nuclear fleet. However, the power industry has been researching this issue for more than a decade along with multiple research groups, and the development of improved simulation tools and welding procedures has also been carried out by others. Those organisations (Manchester, OU) have also claimed these benefits for themselves through their recent REF Impact Case studies. As such, we argue ISIS should claim a small share (1% attribution) of the very large amount of additional economic activity that will result from this major refurbishment work over the next decade.

Type	Total	Attribution to ISIS	ISIS benefits
Additional economic activity	£6.5 billion or £650M a year up to 2025	1%	£65M
Savings in terms of tonnes of carbon dioxide	300M (30M tonnes of carbon dioxide emissions saved each year up to 2025	1%	3M tonnes of carbon dioxide up to 2025
Jobs safeguarded	2,000 power jobs safeguarded, up to 2025 4,000 jobs supported in the contracting industries	1%	60 jobs safeguarded

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Appendix E Bibliometric analysis of ISIS papers

E.1 Introduction

Research undertaken at ISIS has resulted in the publication of some 400-500 articles annually, for most of its history. This provides a good platform for some simple bibliometric analyses and consideration of both the quality and impact of that body of material, as well as trends in publishing behaviour.[24]

Bibliometric analysis is increasingly used to provide a view of research performance of individual institutions or national public research systems, making extensive use of publication records available in large international bibliographic databases managed by organisations such as Scopus (Elsevier) or the Web of Science (Thomson Reuters).

The aim of this bibliometric analysis is to assess the quality and impact of research output originating (at least in part) from use of the ISIS facility over its lifetime. For practical reasons, explained below, the analysis focuses on those ISIS-related journal articles published during the 23-year period, 1991 – 2013.

E.2 Methodology

The publication records used for the bibliometric analysis were extracted from the ePubs open access archive of STFC,[25] which records and holds publications produced by researchers using STFC facilities (including ISIS), and makes them available online.

ISIS' current data management policy requires that references for publications related to experiments carried out at ISIS must be deposited in the STFC e-Pubs system within six months of the publication date. However, historically this has not been the case, and instead STFC has trawled for publications to populate the database.

We did run a series of tests to compare ePubs with other publications databases (e.g. SCOPUS) and concluded that the STFC repository was the best starting point from which to assemble a reasonably comprehensive bibliographic record of ISIS related research publications. It had good coverage of ISIS outputs (at least after 1991), including articles in journals not currently indexed in international bibliographic databases, or those that were produced by researchers not affiliated with ISIS.

To interrogate the ePubs database, the 'orgunitid:67' search expression (provided by ISIS) was used, which is thought to cover most outputs from the ISIS user facility. We then applied a filter for each year between 1984 and 2013 and exported the corresponding records individually in RIS format. Figure shows the resulting number of ISIS-related publications recorded in ePubs, for each of the past 30 years.

[24] Bibliometric analysis concerns the systematic study of relevant indicators, including subject areas, type and quality of publications, citation counts to primary research papers across time and countries, etc. to measure the impact of a researcher, research group or a research organisation. Highly cited works published in high-impact peer reviewed journals are usually correlated with other more qualitative peer evaluation of research performance.

[25] https://epubs.stfc.ac.uk/about

For comparison, the next column shows the annual counts of ISIS-related publications listed within ISIS Annual Reports. In addition, we separately tested two methods to independently query the Scopus database for ISIS research outputs (the results are presented in the final two columns). The keyword AFFIL(ISIS) returned more publications than that contained in the ePubs repository (see Scopus, key-1) and after further investigation, this was deemed to be because it contained records that did not relate to the ISIS facility. We also used a unique affiliation ID in Scopus that specifically identifies the ISIS facility (ID=60001724), but we obtained substantially fewer records (see Scopus, key-2) than via ePubs. Furthermore, neither of these direct search strategies was able to identify those research outputs where none of the authors are affiliated with ISIS facility itself.

Figure 12 – ISIS publications identified via different query approaches since 1984

Pub. Year	ePubs total	ISIS annual reports	Scopus key-1	Scopus key-2
2013	511	n/a	518	206
2012	442	419	497	214
2011	392	402	521	206
2010	401	402	532	217
2009	255*	345	502	208
2008	268*	403	463	191
2007	304*	394	540	232
2006	432	363	588	229
2005	419	336	471	197
2004	467	?	452	172
2003	409	?	396	139
2002	469	?	364	154
2001	443	331	326	111
2000	580	448	422	187
1999	487	533	377	128
1998	470	467	283	107
1997	522	408	369	166
1996	439	?	252	110
1995	495	467	151	50
1994	490	376	142	20
1993	359	429	64	10
1992	480	253	90	19
1991	347	?	60	6
1990	382	223	31	2
1989	296	?	13	
1988	264	?	8	
1987	122		10	
1986	95	106		
1985	71	100 (since 1983)		
1984	38			
Total	**9,881**		**8,380**	**3,279**

* During these years (2007-9) publications were not entered into the e-Pubs repository in a systematic way – hence the low counts relative to the wider period. The ISIS annual report figures are likely to be a more accurate view of total ISIS publications during these years.

While ePubs provides the most comprehensive record of ISIS publications, this information needed to be combined with data from Scopus in order to provide further profiling and citation analyses. This required digital object identifiers (DOIs).

For the records downloaded from ePubs, we extracted all DOI character strings that are used to uniquely identify an electronic publication. There are certain publication types or past publications that do not have DOIs and consequently our analysis excluded those research outputs. Notable examples include the Rutherford Appleton Laboratory (RAL) Technical Reports and PhD theses. In some other cases, although

DOIs existed, the exported RIS file did not include the corresponding DOI, possibly due it being entered under URI, which is not exported.

The figure below again shows the total number of ISIS publications in the ePubs repository, along with the number of these publications with DOIs, and the consequent % 'loss' in recorded publications between the ePubs total and the ePubs DOI count. This shows that 75% of all ePubs recorded publications have DOIs, and that this figure has increased steadily over time, to the point where less than 10% of the total recorded output in 2013 is 'lost' to the analysis because of the missing document reference. Given that a majority of publications up to 1990 had no DOIs, we decided to consider 1991 as the starting point for subsequent analysis.

We then used the list of DOIs to formulate a query in the Scopus database. From this we found that Scopus could not always identify a valid entry in the database based on these queries. So, although the ePubs repository returns a count of 400-500 ISIS-related research outputs for most years since 1991, our interrogation of Scopus using the DOIs found only 50-100 publications between 1991 and 1998, increasing to 200-350 between 1999 and 2012, reaching 440 in 2013. In some cases this represents the current limitations of the Scopus data holdings in so far as it does not index all journals where ISIS researchers have elected to publish. In others, Scopus records simply have a missing data point in the DOI field. We again recorded the number of publications found in each year and the % loss with respect to the number of entries in SFTC's ePubs repository (see last two columns below).

Figure 13 – ISIS publications identified via different query approaches since 1984

Pub. Year	ePubs total	ePubs DOI	% loss		Scopus DOI	% loss
2013	511	466	9%		444	13%
2012	442	397	10%		378	14%
2011	392	340	13%		331	16%
2010	401	334	17%		323	19%
2009	255	192	25%		182	29%
2008	268	211	21%		196	27%
2007	304	240	21%		234	23%
2006	432	317	27%		304	30%
2005	419	333	21%		325	22%
2004	467	376	19%		335	28%
2003	409	346	15%		274	33%
2002	469	393	16%		329	30%
2001	443	342	23%		274	38%
2000	580	429	26%		296	49%
1999	487	373	23%		191	61%
1998	470	337	28%		62	87%
1997	522	390	25%		65	88%
1996	439	295	33%		108	75%
1995	495	322	35%		123	75%
1994	490	256	48%		87	82%
1993	359	194	46%		60	83%
1992	480	319	34%		54	89%
1991	347	204	41%		74	79%
1990	382	181	53%			
1989	296	151	49%			
1988	264	119	55%			
1987	122	59	52%			
1986	95	44	54%			
1985	71	22	69%			
1984	38	10	74%			
Total	**9,881**	**7,406**	**25%**		**5,049**	**26%***

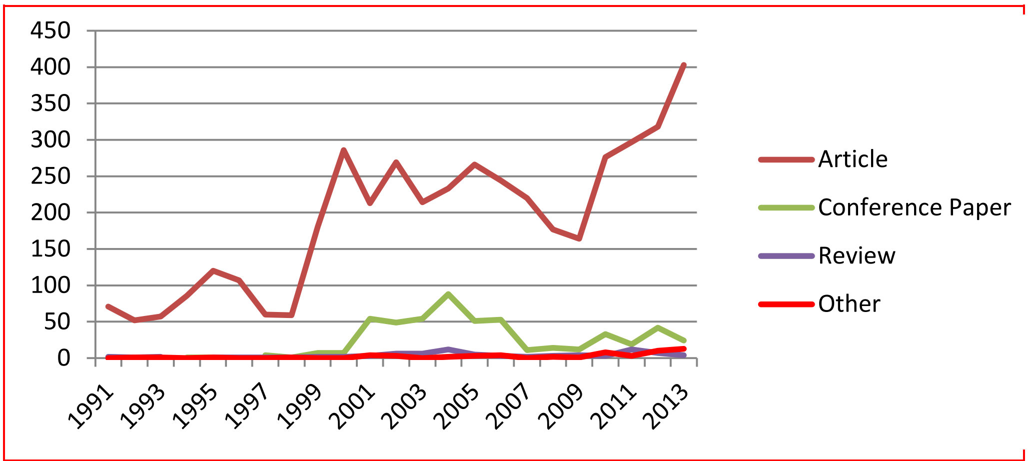
* % of 6820 ePubs records with DOI in period 1991-2013

A significantly more labour intensive alternative is to attempt to match each ePubs publication based on journal title, volume and page numbers and then validate those using words in the publication title and author names. However, while this technique ought to be somewhat more robust, it is beyond the scope of this study. In the following paragraphs, therefore, we take the 5,049 publications (1991-2013) from ePubs that are identifiable within Scopus as our starting point for analysis, and assume that the other ~2,000 publications during this period that were not identifiable in Scopus would not materially change the result of the analysis.

E.3 Publication types

The majority (86%) of ISIS research outputs are peer-reviewed research articles, with most of the remainder being conference proceedings. The absolute number of articles, and their proportion of all ISIS publications have both increased since 1991. It is plausible that this profile is largely a reflection of Scopus' improving journal coverage over time, however, there may also be an element of changing publication practice among ISIS researchers and increased publication in mainstream, well-established journals as opposed to book chapters and technical reports. Indeed, ePubs lists 20-30 published reports annually in the 1990s dropping to around 5 after 2001.

Figure 14 – Number of publications in different document types



Note that the publication year used in our analysis is that of ePubs, while the actual Scopus database year may slightly differ.

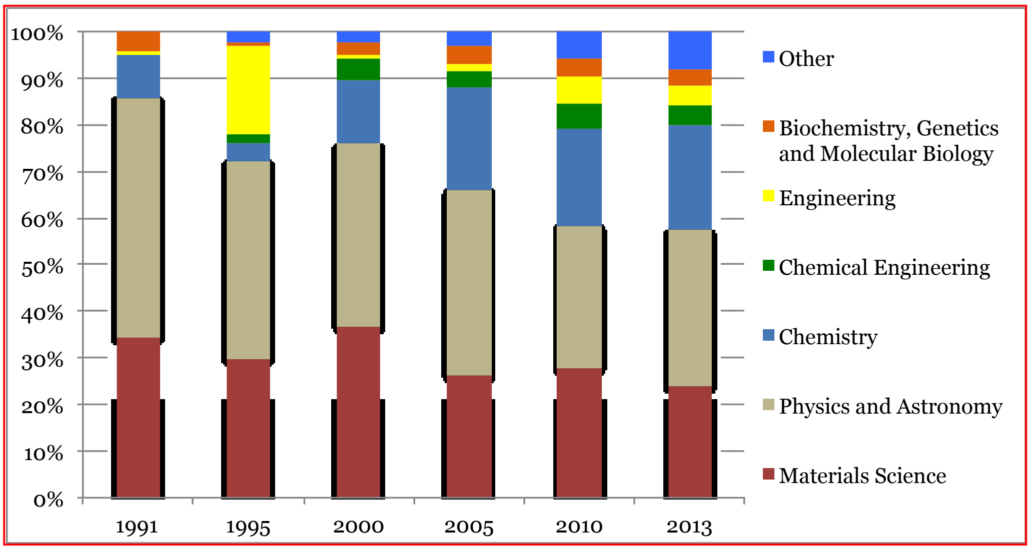
E.4 Subject areas

ePubs divides ISIS publications according to four major subject areas: physics, chemistry, engineering and biology. However in Scopus, journals are classified under four different subject clusters (life sciences, physical sciences, health sciences and social sciences & humanities), which are further divided into 27 subject areas. Note though that journals may belong to more than one of these subject areas. Individual publications have also been assigned to these subject areas, according to where they were published. Again, publications may be assigned to more than one subject area.

The following figure takes selected years (for presentational simplicity) and plots the distribution of ISIS publications between different subject areas. As publications can be attributed to more than one subject area, the percentages do not strictly show the proportion of publications in each area. Rather, they show the proportion of all 'subject area allocations' accounted for by each area. For example, 74 publications from 1991 are identifiable within Scopus, and these are allocated to 120 subject areas in total (1 or 2 subject areas each on average). Of these publications, 41 were allocated to materials science, and so this subject area accounts for 34% (= 41/120) of all allocations.

The figure suggests that ISIS publications in the 'Physics and Astronomy' and 'Materials Science' subject areas have dominated throughout the period. However, this dominance has reduced over time, as an increasing proportion of publications are allocated in other areas. In particular 'Chemistry' has seen a rapid rise over the period shown, and now accounts for over 20% of 'allocations'. The proportion of allocations to 'other' areas (not listed in the figure) have also increased year-on-year. This includes, in particular, 'Energy', 'Medicine' and 'Mathematics'.

Figure 15 – Number of publications, and proportion in different Scopus subject areas

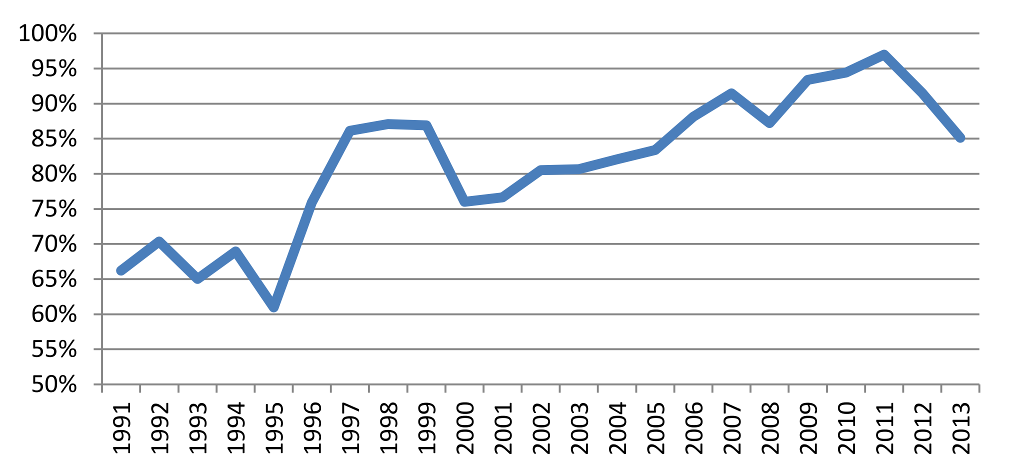


E.5 Publication country of affiliation

Next we looked to understand the country of affiliation of publication authors, drawing on the convention reported by Scopus whereby a given publication can have multiple affiliations. Based on the information provided by Scopus we only know if at least one author on a publication is affiliated to a given country, and not how many authors are affiliated to that country. This means that a publication with a UK affiliation may have 1 UK-based author, or 100.

The first figure below plots the proportion of publications each year that have at least one UK author. Across the whole period, 84% of publications had a UK author. However, the figure suggest that this proportion has generally increased during the period, from ~65% in the early years to ~90% more recently.

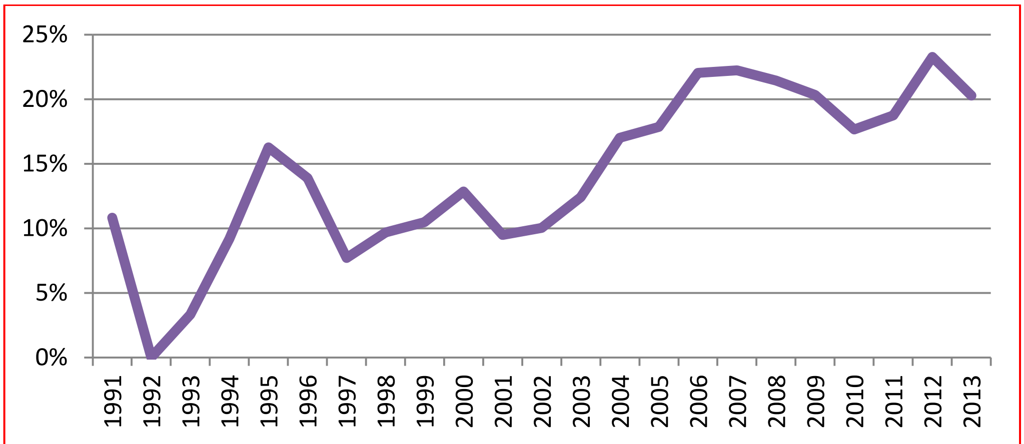
Figure 16 – Proportion of publications with UK author(s)



This may seem counter-intuitive. However, it is important to note again that the data is not showing UK-resident authors as a proportion of all authors, which we might expect to see decline over the period, in line with trends in international research cooperation more generally. It shows the proportion of publications that have at least one UK-resident author. Given ISIS' publication policy (to credit ISIS scientists in most instances) it is not surprising that there is a UK author affiliated with the majority of publications throughout the period. And the increasing proportion could reflect better enforcement of / adherence to this policy.

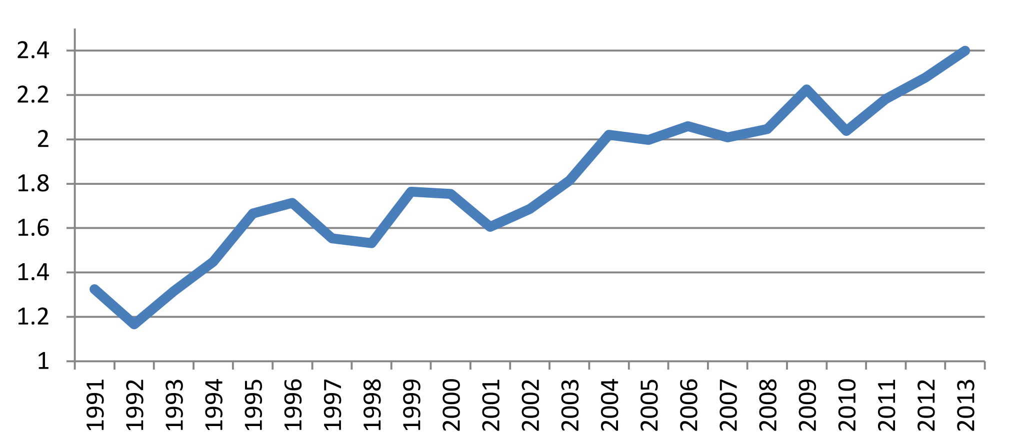
Indeed, if we look at the trends in the appearance of authors from certain other countries, there also tends to be an increase during the period in the proportion of publications with at least one author from that country. As an example, the trend for the United States is shown below.

Figure 17 – Proportion of publications with US author(s)



This reflects the fact that more broadly the number of countries involved in any given ISIS publication each year (on average) has increased over the period (see figure below). While in the early 1990's ISIS publications tended to involve just 1 or 2 countries, for the past decade they have tended to involve 2 or more.

Figure 18 – Average number of countries affiliated to each publication in a year

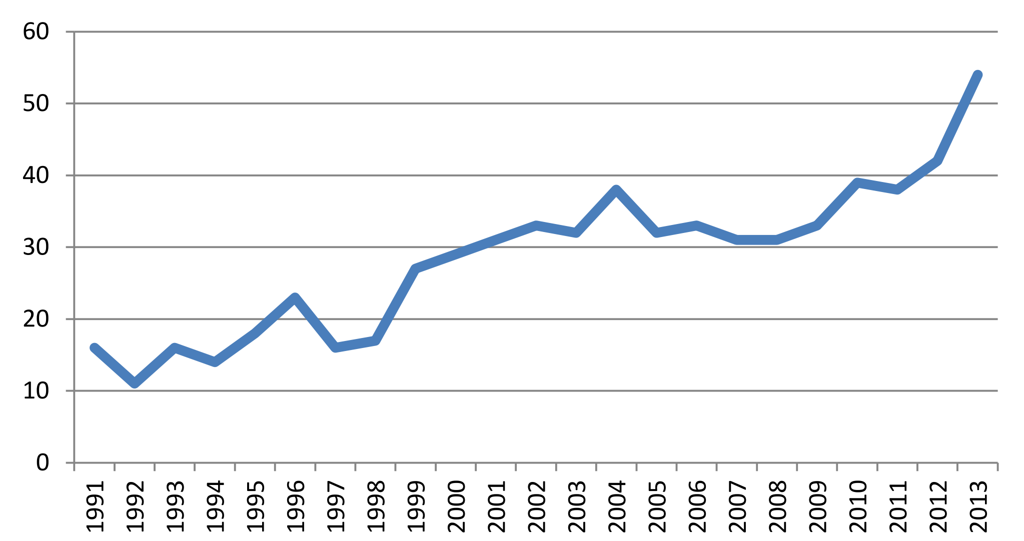


Across the full 1991 – 2013 period, the authors of ISIS publications represent 66 different countries in total. The most common are listed below, with the proportion of all publications that have at least one author from this country. Each of these countries has been affiliated to at least 250 ISIS publications during the period.

- France (17%)
- United States (16%)
- Germany (13%)
- Italy (10%)
- Japan (8%)
- Australia (5%)
- Switzerland (5%)

There has also been a significant increase in the number of countries affiliated to publications each year across the period, from just 10-20 countries in each of the first five years shown (see figure below), to over 50 in 2013.

Figure 19 – Total number of different countries affiliated to publications each year



E.6 Top cited articles

Figure 37 lists the top 10 ISIS-related journal articles, in terms of citation counts, for five selected 'publication years,'[26]. All things being equal, a good paper published 10 years ago will have amassed more citations than a similar paper published three years ago. Therefore only those citations made within a 3-year window following publication have been used, in order to make a fairer comparison between groups of publications of different vintages. The citation counts exclude self-citations.

We have provided the top citation count for 2012, noting that in this case, the 3-year citation period is yet to conclude, and the results need to be understood as such.

The table lists the year of publication, the journal title and volume, along with the title of the publication in question and its 3-year citation count. We have also included an 'influence' indicator called SNIP (Source Normalized Impact per Paper) for the corresponding journal and the given publication year, which has only been available since 1999 and so is not included in the 1998 publication listing.

The analysis shows that for most publication years the top-rated publication has amassed 200+ citations in the 3-year window considered. In three of the years considered, the top 8 papers have all amassed more than 100 3-year citations. The papers published in 2006 perform less well on this analysis.

[26] Note that citation counts at Scopus only go back to 1996.

Figure 20 – Top 10 publications (for selected years) by citation count within 3 years of the publication year

Year	Journal	Volume	Title	SNIP	Cited by
2012	Nature	482	G-protein-coupled receptor inactivation by an allosteric inverse-agonist antibody	8.580	58
2012	Physical Review Letters	108	Spin waves and revised crystal structure of honeycomb iridate Na 2IrO 3	2.417	49
2012	Physical Review Letters	108	Giant improper ferroelectricity in the ferroaxial magnet CaMn 7O 12	2.417	35
2012	Nature Physics	8	Nature of magnetic excitations in superconducting BaFe 1.9 Ni 0.1 As 2	5.979	28
2012	Physical Review B - Condensed Matter and Materials Physics	85	Phase diagram of Ba 1-xK xFe 2As 2	1.250	27
2013	Nature Materials	12	Enhancement of the superconducting transition temperature of FeSe by intercalation of a molecular spacer layer	8.673	24
2012	Nature Chemistry	4	Selectivity and direct visualization of carbon dioxide and sulfur dioxide in a decorated porous host	3.519	23
2012	Journal of Catalysis	293	Unusual reactivity of visible-light-responsive AgBr-BiOBr heterojunction photocatalysts	2.222	23
2012	Angewandte Chemie - International Edition	51	Magnetic control over liquid surface properties with responsive surfactants	2.295	20
2012	Proceedings of the National Academy of Sciences of the United States of America	109	Role of semiconductivity and ion transport in the electrical conduction of melanin	2.641	19
2010	Reviews of Modern Physics	82	Magnetic pyrochlore oxides	19.900	235
2010	Journal of the American Chemical Society	132	Metal-organic polyhedral frameworks: High H2 adsorption capacities and neutron powder diffraction studies	2.115	128
2010	Nature Physics	6	Evolution of spin excitations into the superconducting state in FeTe 1-x Sex	4.807	89
2010	Advanced Materials	22	Depletion of PCBM at the cathode interface in P3HT/ PCBM thin films as quantified via neutron reflectivity measurements	2.842	87
2010	Journal of Chemical Physics	133	Small angle neutron scattering from 1-alkyl-3-methylimidazolium hexafluorophosphate ionic liquids ([Cn mim] [PF6], n=4, 6, and 8)	1.028	66
2010	Proceedings of the National Academy of Sciences of the United States of America	107	Small-angle scattering and the structure of ambient liquid water	2.499	58
2010	Physical Review B - Condensed Matter and Materials Physics	81	Dispersive spin fluctuations in the nearly optimally doped superconductor Ba (Fe1-x Cox)2 As2(x=0.065)	1.419	55
2010	Physical Review B - Condensed Matter and Materials Physics	82	Long-range magnetic order in CeRu2Al10 studied via muon spin relaxation and neutron diffraction	1.419	50
2010	Structure	18	Metal Ion Roles and the Movement of Hydrogen during Reaction Catalyzed by D-Xylose Isomerase: A Joint X-Ray and Neutron Diffraction Study	1.441	49
2010	Journal of the American Chemical Society	132	Potassium(I) amidotrihydroborate: Structure and hydrogen release	2.115	48
2006	Journal of the American Chemical Society	128	Ordered mesoporous Fe2O3 with crystalline walls	2.223	243
2006	Journal of Applied Crystallography	39	DASH: A program for crystal structure determination from powder diffraction data	7.407	185
2006	Nature Physics	2	Magnetism at the interface between ferromagnetic and superconducting oxides	-	170
2006	Reports on Progress in Physics	69	Neutron and x-ray diffraction studies of liquids and glasses	5.086	133
2006	Physical Review Letters	96	Ferroelectricity induced by acentric spin-density waves in YMn2O5	2.803	119
2006	Journal of Physical Chemistry B	110	Liquid structure of the ionic liquid 1,3-dimethylimidazolium bis{(trifluoromethyl)sulfonyl}amide	-	111
2006	Biophysical Chemistry	124	Ion solvation and water structure in potassium halide aqueous solutions	0.807	109
2006	Journal of Applied Crystallography	39	ENGIN-X: A third-generation neutron strain scanner	7.407	101

Year	Journal	Volume	Title	SNIP	Cited by
2006	Journal of the American Chemical Society	128	Synthesis and crystal structure of Li4BH4(NH 2)3	1.166	92
2006	Journal of Applied Crystallography	39	The preparation and structures of hydrogen ordered phases of ice	6.004	90
2002	Nature	416	Molecular segregation observed in a concentrated alcohol-water solution	6.874	418
2002	Nature	416	Formation of isomorphic Ir3+ and Ir4+ octamers and spin dimerization in the spinel CuIr2S4	6.874	174
2002	Journal of the American Chemical Society	124	Amplified optical nonlinearity in a self-assembled double-strand conjugated porphyrin polymer ladder	2.333	172
2002	Chemical Society Reviews	31	Towards a fundamental understanding of natural gas hydrates	3.794	158
2002	Applied Physics A: Materials Science and Processing	74	Crystal structure and spiral magnetic ordering of BiFeO3 doped with manganese	1.146	147
2002	Nature	416	Observation and interpretation of a time-delayed mechanism in the hydrogen exchange reaction	6.874	126
2002	Acta Materialia	50	Elastoplastic deformation of ferritic steel and cementite studied by neutron diffraction and self-consistent modelling	3.126	111
2002	Applied Physics A: Materials Science and Processing	74	TOSCA neutron spectrometer: The final configuration	1.146	105
2002	Annual Review of Physical Chemistry	53	Scattering resonances in the simplest chemical reaction	3.096	102
2002	Journal of Physics Condensed Matter	14	Ferromagnetic fullerene	1.105	98
1998	Nature	395	Localized vibrational modes in metallic solids		301
1998	Nature	395	Spin fluctuations in YBa2Cu3O6.6		277
1998	Nature	391	The structure of a new phase of ice		183
1998	Carbohydrate Research	308	Gelatinisation of starch: A combined SAXS/WAXS/DSC and SANS study		160
1998	Journal of Physics Condensed Matter	10	Frustration in Ising-type spin models on the pyrochlore lattice		129
1998	Journal of Chemical Physics	109	Water confined in Vycor glass. I. a neutron diffraction study		113
1998	Journal of Solid State Chemistry	139	High-Temperature Powder Neutron Diffraction Study of the Oxide Ion Conductor La0.9Sr0.1Ga0.8Mg0.2O2.85		104
1998	Journal of Colloid and Interface Science	203	The adsorption of lysozyme at the silica-water interface: A neutron reflection study		103
1998	Journal of Chemical Physics	109	Water confined in Vycor glass. II. Excluded volume effects on the radial distribution functions		96
1998	Journal of Chemical Physics	109	Neutron diffraction study of high density supercritical water		60

E.7 Top journals by frequency of ISIS publications

Figure 38 presents a series of lists of the top ten *journals,* based on the number or frequency of ISIS research publication, for four publication years: 2002, 2006, 2010 and 2012. The great majority of journals fall in the SNIP band, 1.0 – 2.0, with a small number of exceptions, notably the journal of Physics Conference Series (lower influence at 0.274) and Acta Materialia (higher influence at 2.858).

The previous analysis of top 10 *papers* revealed a rather different list of journals, dominated by higher-impact journals like Nature, Science or the Journal of Applied Crystallography.

Figure 21 – Top 10 journals (for selected years), by frequency of ISIS publications

Year	Frequency	Journal title	SNIP
2012	48	Physical Review B Condensed Matter and Materials Physics	1.250
2012	22	Physical Review Letters	2.417
2012	21	Langmuir	1.377
2012	18	Journal of Physics Conference Series	0.274
2012	18	Journal of Physics Condensed Matter	1.008
2012	11	Soft Matter	1.189
2012	9	Journal of Physical Chemistry B	1.250
2012	8	Journal of Instrumentation	0.861
2012	8	Inorganic Chemistry	1.336
2012	8	Chemistry of Materials	2.240
2012	8	Acta Materialia	2.858
2010	50	Physical Review B Condensed Matter and Materials Physics	1.419
2010	21	Langmuir	1.381
2010	12	Physical Review Letters	2.628
2010	12	Journal of Physics Condensed Matter	1.039
2010	9	Materials Science Forum	0.393
2010	9	Chemistry of Materials	1.838
2010	8	Review of Scientific Instruments	1.378
2010	8	Physical Chemistry Chemical Physics	1.190
2010	8	Journal of Physical Chemistry B	1.198
2010	7	Soft Matter	1.376
2010	7	Journal of the American Chemical Society	2.115
2006	75	Physica B Condensed Matter	0.504
2006	29	Physical Review B Condensed Matter and Materials Physics	1.558
2006	13	Acta Crystallographica Section B Structural Science	1.573
2006	11	Physical Review Letters	2.803
2006	11	Journal of Physics Condensed Matter	1.216
2006	11	Journal of Chemical Physics	1.264
2006	9	Journal of Physical Chemistry B	1.416
2006	8	Langmuir	1.426
2006	8	Journal of Solid State Chemistry	1.295
2006	7	Journal of the American Chemical Society	2.223
2006	7	Chemistry of Materials	1.946
2002	57	Applied Physics A Materials Science and Processing	1.146
2002	21	Journal of Physics Condensed Matter	1.105
2002	19	Langmuir	1.475
2002	17	Journal of Solid State Chemistry	1.196
2002	13	Chemistry of Materials	1.841
2002	12	Physica B Condensed Matter	0.609
2002	11	Journal of Chemical Physics	1.317
2002	10	Journal of Materials Chemistry	1.456
2002	8	Physical Chemistry Chemical Physics	0.965
2002	7	Solid State Ionics	1.350
2002	7	Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers Detectors and Associated Equipment	1.010
2002	7	Journal of Physical Chemistry B	1.471

E.8 Citations of ISIS publications

We also looked at the aggregate citation counts for all ISIS publications that we were able to match between ePubs and Scopus, for each of the four publication years: 1998, 2002, 2006, and 2010.

Figure presents a count of ISIS publications and 3-year citations (self-citations excluded) for the four years in question, alongside an average citation count indicator (citations per publication – CPP). It shows a relatively stable average citation count across the four years, ranging from a high of 7.7 in 2010 to a low of 4.0 in 2002.

Figure 22 – Aggregate annual publication numbers and citations of ISIS papers

Publication year	Publications	Citation count	Average CPP
2010	323	2493	7.7
2006	304	1593	5.2
2002	329	1314	4.0
1998	62	422	6.8

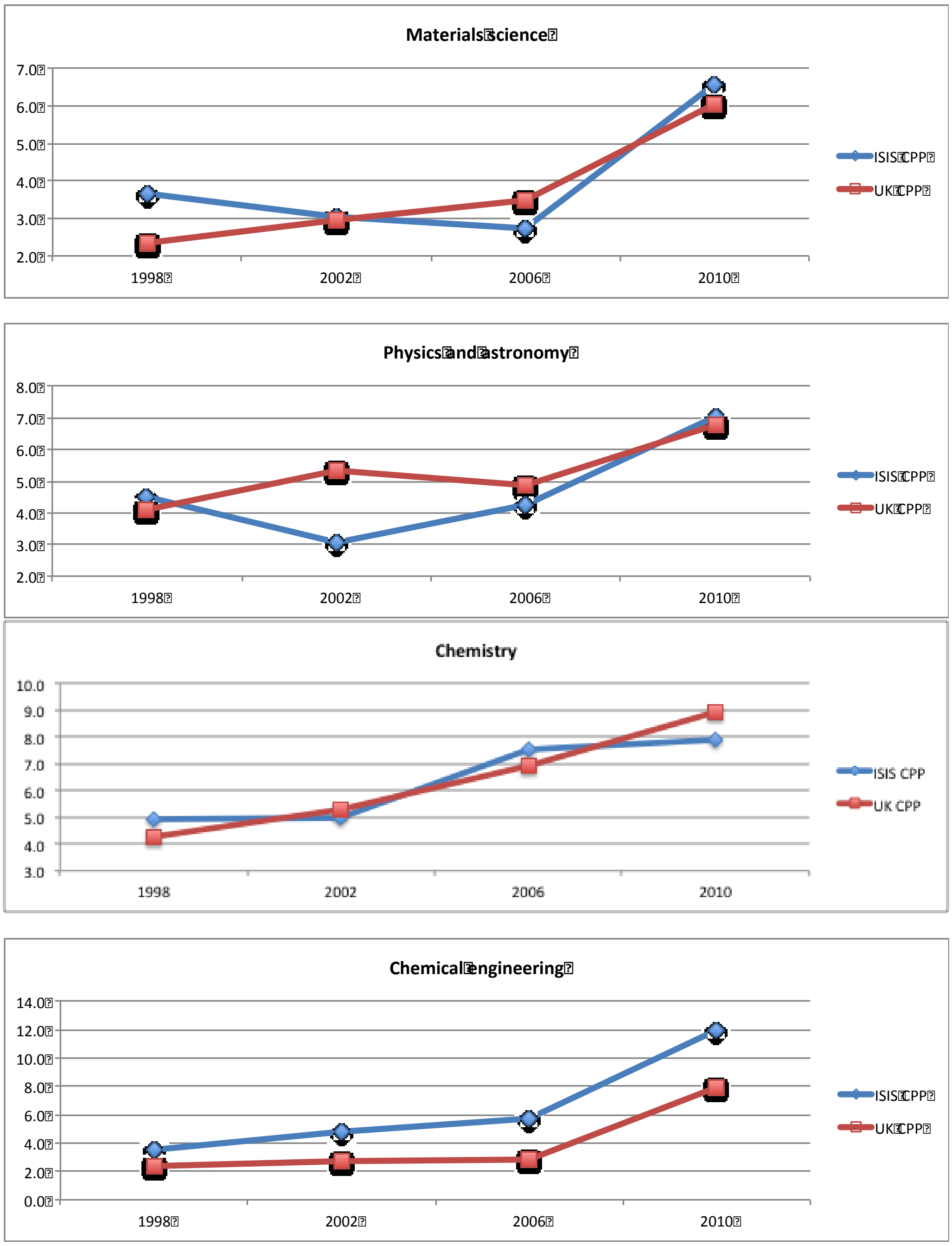
Figure 40 presents four profiles of ISIS publications, showing the proportions that are uncited, cited just once or more than once. As before, we have used the 3-year citation count as our basic indicator to allow comparison across widely differing publication years. The analysis suggests that 20-30% of ISIS papers are uncited in the given 3-year term, and suggests that this rate may be improving over time albeit the figures are a little erratic and the number of publications is rather small for 1998 (62). The trend looks rather clearer for the higher citation rates, however, world average and field average citation data would be needed to correctly evaluate the trend.

Figure 23 – Proportion of papers

Publication year	% uncited	% cited 1 time	% cited >1 time
2010	17.7	15.8	66.6
2006	29.9	15.5	54.6
2002	31.6	14.6	53.8
1998	25.8	19.4	54.8

To put the ISIS citation figures in context we have taken the four main areas of ISIS publication activity (as identified in Figure above), and compared the 3-year citation rates (average citations per publication – CPP) of ISIS publications and all UK publications in these fields in the selected years. The results are shown in the figures below – and broadly suggest similar citation rates for ISIS and all UK publications in the specified fields and years. In chemical engineering alone, the ISIS CPP is consistently above that of the UK for publications in each of the years shown.

Figure 24 - ISIS and UK publications - CPP for selected fields and years



Appendix F Survey of Academic Users

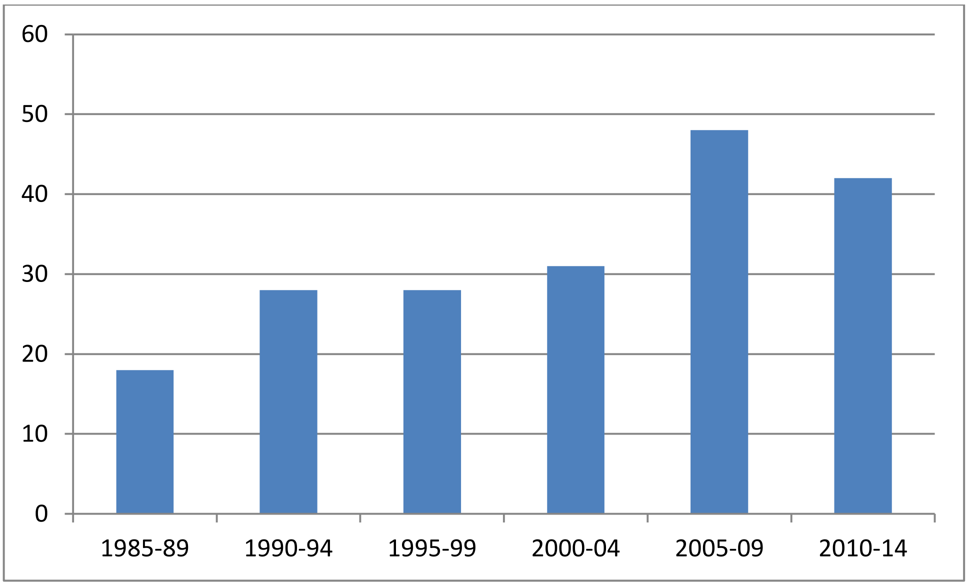
F.1 Introduction

The study team carried out a survey of ISIS's academic users in order to profile the facility's impact on research, skills and innovation, and to identify concrete examples of each where possible. We obtained around 200 responses to the online survey, the results from which are shown below.

F.2 Dates and frequency of usage

Users were asked to state the first year in which they made use of the ISIS facility. Figure 25 shows the distribution in the number of responses, in five-year periods.

Figure25 – Dates of first use of ISIS (n = 199)



Date of first use is rather uniform over the fifteen-year period up to 2005. A moderate increase in first-time users is noticeable post-2005, but the majority of respondents first used the facility ten or more years ago. A separate question requesting the date of most recent use indicates that over 85% of recipients had made use of ISIS in 2013 or 2014, suggesting that most of the early users have continued to avail themselves of the facility.

Users were also asked how many times they had used ISIS. Around three-quarters of survey respondents had used the facility five times or more, and about one-half over ten times. 15% of respondents had used ISIS more than 50 times, and 5% 100 times or more, with one (anonymous) user registering 1000 uses.

F.3 Use of alternative facilities

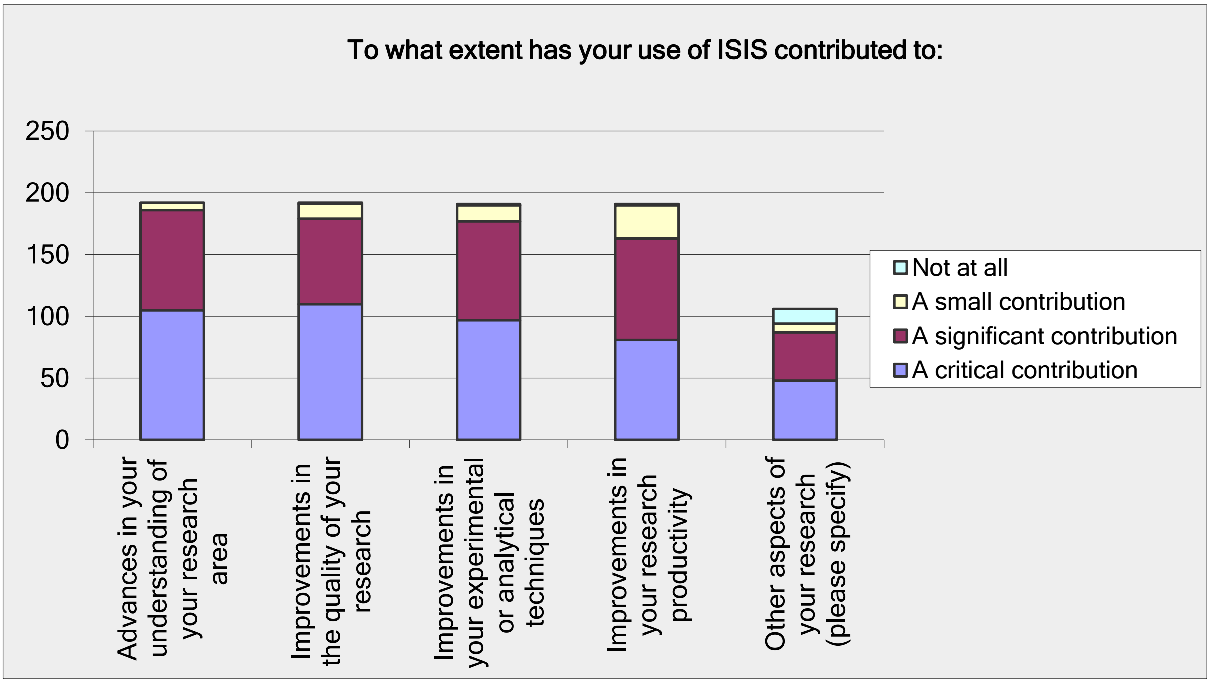
Survey participants were asked how their research would have been modified if the ISIS facility had not been available. About 60% would definitely have tried to use an alternative research facility (such as ILL), while a similar proportion would 'possibly' or 'definitely' have used a different type of technique or followed a different research path.

All responders considered that non-existence of ISIS would have negatively impacted their research to some extent. Two-thirds estimated the degree of impact to be 'large', one quarter to be 'medium' and the remaining 7% estimated the impact to be 'small'.

F.4 Contribution of ISIS to research

Survey participants were asked to estimate the contribution of ISIS to various developments in their research. Figure 26 shows the numbers of respondents estimating the contribution to each aspect as 'not at all', 'small', 'significant' and 'critical'.

Figure 26 – Contributions of ISIS to aspects of research (n = 192)



More than 85% of respondents considered the contribution of ISIS to each of the aspects to have been 'significant' or 'critical'. More than half considered contributions to advances in understanding to research quality and to improvements in techniques to have been 'critical'.

Respondents were asked to specify any 'other aspects of research' to which ISIS had contributed. Several users cited contributions to collaborative activity and networking, with new collaborations with industry, with researchers in other countries, and across disciplines being cited. Other contributions noted by more than one user were to the education of students and training of new researchers, and new research areas and directions that the facility enabled the users to explore.

F.5 Important advances attributable to ISIS

Most of the 173 responses to this open question contained detailed technical descriptions of the advances identified by respondents, often running to 100 words or more. These fulsome responses proved too challenging for us to codify with any degree of confidence, however, we judged them to broadly split 80:20 between advances in understanding of the world and improvements in measurement or measurement technique. We have extracted selected excerpts to provide readers with a flavour of the range of advances achieved.

Knowledge advancement*:* These include the discovery of previously unknown natural processes, improved understanding of processes, or the demonstration of chemical or physical mechanisms or properties of materials. Examples include:

- The role of carbon dioxide as a potential green solvent was enhanced by the finding of a simple, non-fluorinated and inexpensive hydrocarbon surfactant that can stabilise small water droplets within this awkward solvent
- Discovering a new structural motif in liquid benzene, which led to a new general understanding of pi-pi interactions
- Discovery of a new magnetic ground state, the valence bond glass, in the double perovskite Ba2YMoO6
- Development of a model for diffusion of nano-cogwheels
- We have proved that load sharing between the particles in a high temperature Ni superalloy depends on their size over a critical range
- Understanding of thermal stresses in organic light emitting diodes.
- Advanced understanding on molecular mechanisms of gas hydrate formation/transition
- We have determined how water molecules interact with water soluble ruthenium complexes that mediates homogeneous catalysis in water
- A greater understanding of overbased detergents: formation process, stability and acid neutralisation properties
- The biggest impact has been on our understanding of protein self-assembly mechanisms
- Understanding the role of hydrogen bonding has upon the elastic properties and stability of hydrous minerals
- Demonstration that polymer adsorption to nanoparticles was easily reversible

Improved measurement*:* These examples cover research made possible, or critically aided by, the equipment available at ISIS.

- ISIS has enabled us to determine the structures of energetic materials under extreme temperatures and pressures
- Neutron scattering allowed for the estimation of hydrogen self-diffusion coefficients in clay rocks
- Neutron diffraction measurements for a small amount of samples prepared by high pressure technique
- The ability to probe, and understand, solvation structure of materials dissolved in ionic liquids
- WISH diffractometer TS2 at ISIS has made the determination of subtle magnetic / structural ordering in 6H Ru perovskites possible in my work
- Through the use of ENGIN-X for the measurement of lattice strain, we validated our finite element based polycrystal model with very good agreements achieved between modelling prediction and neutron diffraction measurement
- Demonstration of the role of magnetic impurity on high-Tc superconductivity by using the Fermi chopper spectrometer MAPS
- By means of a long development period, inelastic neutron scattering can now most usefully be applied to investigate heterogeneous catalysts
- We have made state of the art measurements of Bose-Einstein condensation and of the atomic momentum in quantum liquids at ISIS

Development of an improved technique*:* Quoted examples of improvements in technique include:

- Development of a new method using muons for studying ion-dynamics in battery materials
- Development of reflectivity techniques to become a standard for all disciplines
- Construction of MAPS
- Demonstration of the irrelevance of the well-known dilatometry technique to monitor the phase transformations in steels at "high" temperature (>850°C)
- A new technique for the quantification and specification of bound hydrogen in materials

A number of respondents briefly described their on-going ISIS-based research that they expected to yield important results, but considered it too soon to present specific advances.

The above categorisation scheme is not ideal – no such scheme is perfect – and allocation of particular responses to categories is to some extent arbitrary. Nevertheless, it is suggestive of certain predominant features of ISIS-based research. For example, improvements in knowledge advancement and improved research dominate, suggesting that important advances mainly involve better understanding of underlying basic-science principles, concepts and structures, rather than more applied, 'close to market' developments.

F.6 Contribution of ISIS to personal scientific achievements

Survey participants were asked to estimate the contribution of ISIS to various developments in their profiles and careers. Figure 44 shows the numbers of respondents estimating the contribution to each aspect as 'not at all,' 'small,' 'significant' and 'critical.'

Figure 27 – Impacts of ISIS on users' research

Aspect	Not applicable (%)	Not at all (%)	Small contribution (%)	Significant contribution (%)	Critical/decisive contribution (%)
Your scientific impact within a field (e.g. publication of highly cited papers, invitations to talk)	5.4	1.1	14.1	43.5	35.9
Winning research grants	14.2	5.5	20.2	37.7	22.4
Promotion to senior academic post	27.4	15.6	14.5	29.1	13.4
Appointments to high-level advisory groups or governing bodies	37.9	14.3	16.5	20.9	10.4
Award of major scientific prizes	47.0	17.7	13.3	16.0	6.1
Attracting major industry contracts	42.5	16.0	19.9	15.5	6.1
Fellowship at national / international learned societies	55.9	17.3	14.0	8.4	4.5
Other (please specify)	80.0	3.6	1.8	10.9	3.6

Of the various aspects, 'scientific impact' and 'winning research grants' are perceived by 79% and 60% of respondents respectively, as 'significant' or 'critical/decisive' areas of ISIS contribution. 43% of respondents also attribute a significant or critical contribution to ISIS in their promotion to a senior academic post.

'Other' aspects cited by a (small) proportion of respondents included application to improved public engagement, science communication and school outreach, and contributions to launching a new research career.

We asked respondents that had rated their use of ISIS as 'critical/decisive' or 'significant' to explain briefly what the achievement was. Around 55% of respondents answered, citing a diverse range of achievements. Many quoted high-quality publications as a major achievement. For example:

- 'About 98% of my publications are coming from the results of my experiments in RAL'
- 'I have 13 papers cited 100 times or more: 9 of these arose from neutron diffraction studies, most of these at ISIS'
- '100% of my publications in the last 24 months have relied on, or been made possible by, experiments performed at ISIS'
- 'My h-index is 19, in less than 9 years after my first publication, all but one [of the contributing papers] featuring some ISIS input'[27]

Other achievements mentioned include awards of grants based to some extent on results from ISIS, furthering of personal international reputations, and invitations to give presentations.

Respondents were invited to rate the impact of ISIS on a very simple scale ('not at all', 'small' or 'large') on each of eight categories of what we termed their 'research experience,' ranging from

[27] The h- (Hirsch) index combines quantity (numbers of publications) and quality (numbers of citations) into a single measure- an index of x indicates at least x citations each for x published papers. According to Hirsch, a 'successful' scientist would be characterised by an h-index equal to or greater than the number of years he/she has been scientifically active. This and other bibliometric measures of scientific output are discussed elsewhere in this report.

career progression to international collaboration, as listed in Figure 28, showing the distribution of responses by gradation of adjudged impact for each category; 183 people answered this question.

Figure 28 – Impact of ISIS on aspects of research experience

Aspect	Not at all (%)	To a small extent (%)	To a large extent (%)
Opportunities to collaborate	0.0	17.0	83.0
Your domain knowledge	1.1	21.7	77.2
The breadth of your experimental experience	0.6	22.7	76.8
The skills of your research students	9.9	21.1	69.0
Opportunities to work with international partners	7.1	25.3	67.6
The breadth of analytical methods you use	1.1	37.0	61.9
Your career progression	12.1	34.6	53.3
Opportunities to work with industry	49.2	33.5	17.3
Other (please specify)	75.0	10.7	14.3

The analysis shows that ISIS is widely regarded as having had a very positive impact on various areas of research experience: collaboration; domain knowledge; and experimental experience. Strongly positive impacts on career progression are a little less widely reported. Around half of all respondents stated that their work at ISIS had provided some opportunities for working with industry, with almost 20% reporting a strongly positive impact on their industrial collaboration. The only significant impacts identified in the 'other' category relate to equipment – specifically, significant impacts on the development of new equipment, and validation of other equipment.

Respondents also provided feedback as regards the extent to which the use of ISIS had impacted positively on their research group, from reputation to industry links, as shown in Figure 29. As before, ISIS impacts on users' research groups are generally seen to be very positive by the majority of respondents (177).

Figure 29 – Impacts of ISIS on users' own research groups

Impact on	Not at all (%)	To a small extent (%)	To a large extent (%)
Its international reputation	2.3	25.9	71.8
Its capacity and skills	1.1	27.6	71.3
Its international networks	4.6	30.3	65.1
Its attractiveness to other researchers / students	8.7	43.0	48.3
Its links to industry/business	46.8	35.3	17.9
Other (please specify)	71.0	19.4	9.7

F.7 Important benefits attributable to ISIS

Most of the responses to this open question relate either to the value of ISIS as a powerful, even unique, research facility, or to collaborative opportunities following from use of ISIS. Examples of the first of these include:

- 'The ability to perform high-pressure in-situ neutron measurements is unique to ISIS and critical to my research group …'
- 'ISIS has some of the best-engineered instruments in the world (low background, high resolution) and several of the neutron scattering experiments we have successfully performed at ISIS and have obtained extremely high-quality data would simply not have been possible anywhere else in the world'
- 'The large facility offers a unique place for performing studies impossible elsewhere'

Regarding collaborative opportunities:

- 'Being from Australia, the international collaborations with Europe that have come from using ISIS have been highly significant'
- 'Our access to ISIS has led to several collaborations with international groups whose expertise lies in areas other than neutron diffraction'
- 'The opportunity to collaborate with the ISIS staff members, who are some of the finest scientists in the world'

In addition, one respondent notes that:

- 'My use of ISIS has developed significantly my skills in neutron scattering techniques, some of which cannot be done elsewhere. I see my students are now taking this advantage too'

F.8 ISIS and technology transfer?

Respondents were asked to rate the importance of ISIS in facilitating aspects of technology transfer, research contracts and start-ups on a 1-5 scale as shown in Figure 30, where 5 is critical.

Figure 30 – Importance of ISIS to different aspects of technology Transfer (%), (n=153)

	N/A	1	2	3	4	5
Industry research contracts	61.3	9.4	7.7	7.2	9.4	5.0
Launching start-ups	83.3	5.6	3.3	3.3	3.3	1.1
Patent applications	81.2	7.7	3.9	2.8	3.9	0.6
Licence agreements	87.7	6.1	3.4	1.1	1.1	0.6

Scores here are generally very low, with 'not applicable' being overwhelmingly the largest category of response. This reflects in part the academic community's emphasis on advances in understanding, and suggests that ISIS' role in the direct commercialisation of academic research carried out at ISIS has been limited in extent. The most widely reported TT outcome relates to contract research. With the benefit of hindsight, the question is perhaps poorly framed as academic users may be required to look to their own institutional TT offices for any support with research commercialisation. This is not a function that ISIS fulfils on their behalf.

We also asked respondents to estimate the number of knowledge-transfer-related outputs (for their research group) that are linked to research done at ISIS. KT outputs were categorised as shown in Figure 48, which also indicates total numbers in each category cited by respondents.

Figure 31 – Knowledge-transfer outputs

Output category	Number or value
Number of industry research contracts	128
Approximate value of this contract research	> £15M
Patents applied for	28
Licence agreements entered into	4
Number of these licences that have generated income	1
Start-ups launched	18

The great majority – over 90% – of respondents indicated that no patents had been applied for, of the 28 applications cited, 10 were from one research group. Three groups had entered into any licensing agreements. Values of the 128 research contracts were very uneven – five groups held contracts with total value exceeding 1m euros. The 18 start-ups were distributed between 12 research groups. Respondents specified several other types of knowledge-transfer outputs linked to research done at ISIS:

- Public talks/lectures given at various venues, cited by three respondents
- Training students
- Contributions to popular science journals

F.9 Specific knowledge transfer achievement attributable to use of ISIS

Around one-third responded to this question – positive responses include:

- 'Studies on energetic materials have been of significant benefit to UK MOD/DSTL and have provided the UK Government with leverage in exchanging information with US and other NATO partners'
- Establishing that we could produce individual single-walled carbon nanotubes in metal-ammonia solutions was patented, and led to a licensing agreement with Linde'
- Transferring neutron Compton scattering knowledge to the European NMR community, resulting in a series of common papers with the use of both techniques'
- Aside from academic publications, public outreach events at the Natural History Museum'

One negative response was simply 'I don't do knowledge transfer achievements'. Another respondent provides an interesting comment regarding knowledge transfer:

- 'Our group is (still) not focused on knowledge transfer or patent applications. This is therefore not a failure that could be attributed to ISIS. Had we decided to apply for patents, the work done at ISIS may have contributed to the reinforcement of our experimental demonstration of utilities …'

F.10 Impacts in other social and economic realms

The socio-economic areas covered, with proportions of responses in 'no effect', 'small impact', 'large impact' and 'no view' categories are shown in Figure 32.

Figure 32 – Socio-economic impacts

Area	No impact	Small impact	Large impact	No view
Education and skills	2.4	17.6	72.1	7.9
Innovation	7.4	30.2	51.2	11.1
Productivity	21.7	26.7	28.0	23.6
Employment	18.9	37.8	27.4	15.9
Industrial competitiveness	22.8	30.2	22.8	24.1
Environmental sustainability	23.9	31.3	20.2	24.5
Economic output	25.2	32.5	16.6	25.8
Policy development	32.7	18.5	12.3	36.4
Health gains	33.8	21.9	10.0	34.4
Other (specify)	33.3	3.7	9.9	53.1

Of the areas covered, 'education and skills of young people' has the highest proportion (72%) of 'large impact' responses, tending to reinforce findings elsewhere in the survey. Impact on innovation comes second, with over 50% of respondents estimating this to be large. Compared with these, socio-economic impacts in other areas are estimated to be small.

'Other' socio-economic impacts cited were:

- Inspiration and education of the public
- Increased recognition of work carried out at leading-edge facilities
- Preservation and conservation of the heritage
- Development of cheaper/cleaner products
- Deeper understanding of physical laws, multidisciplinary and blue-sky research

Question 18. Can you point to one concrete example of an economic or social impact that has resulted (in some part) from your use of ISIS?

Only a small minority of the 209 respondents answered this question, with fewer than 30 specific examples cited. The majority of these were advances in understanding or employment outcomes for young researchers. There were only two or three examples of specific commercial developments arising directly from the academic users work.

Examples include:

- Improvements in scientific understanding.
- Training and employment opportunities for young researchers
- The subsequent attraction of grants

Question 19. Are you aware of any university REF submissions (Impact Case Studies) that mention ISIS research?

Positive responses, with titles, were submitted by about 20 respondents; about 10% of those surveyed.

Question 20. On a 1-5 scale, please rate the importance of ISIS to your research, your research community in the UK, and the international community in your field.

Results are shown in Figure 33.

Figure 33 - Importance of ISIS to research communities

Importance to:	1	2	3	4	5
Your research	0	5.6	12.2	26.7	55.6
Your research community in the UK	0.6	6.7	12.8	24.4	55.5
The international community in your field	0.6	4.5	13.6	31.1	50.3

The pattern of responses is similar for each of the three areas. More than half of respondents rated the ISIS contribution as 'absolutely essential' to their own research and to both UK and international communities, and over three-quarters rated it at 4 or 5 for all three communities.

Question 21. Do you expect to apply to use ISIS again in the future?

None of the 180 users who answered this question replied 'definitely not' or 'probably not'. 90% would 'definitely' apply to use the facility again, and the remaining 10% would 'probably' do so.

Question 22. Are you / have you ever been a member of an ISIS Facility Access Panel (FAP)?

62, slightly over one-third (34.4%) of those replying to this question, responded 'yes', 61.7% responded 'no', the remaining 3.9% replying 'don't know'.

We used this question to identify FAP members before going on to ask this sub-set of all respondents for their judgement regarding the impact of ISIS on their field overall, which was intended to complement the feedback from the larger group of academic users as regards their own research or that of their immediate research group.

Question 23. If Q22 is answered 'yes', which panel were you a member of, and over which period?

A wide range of panels were represented among the respondents, the heaviest representations (about ten each) being on FAP3 (Large-scale structures) and FAP5 (Spectroscopy). Most memberships covered a period since 2000, although only about 12 are current (2014).

Question 24. Thinking more broadly about the area covered by this FAP, to what extent has ISIS contributed positively to the following aspects for this field overall?

The twelve aspects, and the percentage ratings, are shown in Figure 34.

Figure 34 - ISIS contributions to the field overall

Aspect	Not at all	A small contribution	A significant contribution	A critical contribution	No view
Advances in understanding	0.0	0.0	13.6	84.7	1.7
Improvements in experimental techniques	0.0	1.7	28.8	67.8	1.7
Developing the skills of early career researchers	0.0	5.1	32.2	61.0	1.7
Specific scientific discoveries	0.0	1.7	33.9	59.3	5.1
Developing experimental skills	0.0	1.7	40.7	55.9	1.7
Improving the quality of doctoral training	0.0	5.2	37.9	53.4	3.4
Developing analytical skills	0.0	8.5	40.7	49.2	1.7
Improvements in research productivity	0.0	5.3	42.1	49.1	3.5
Improvements in analytical techniques	0.0	5.1	47.5	44.1	3.4
Developing domain knowledge	1.7	3.4	33.9	42.4	18.6
Developing collaborative skills	0.0	10.2	45.8	39.0	5.1
Developing project management skills	3.4	32.2	30.5	15.3	18.6

Scientific advances figure prominently here, with ISIS scoring particularly highly as a vehicle for 'advances in understanding'. Contributions to training and skills development also figure highly.

Question 25. Similarly, for this area overall, to what extent do you believe ISIS has impacted on the following:

Categories covered in this question, and percentage survey responses, are shown in Figure 35. The question was answered by 60 people that are or have been involved with one or other ISIS Facility Access Panels (FAPs).

Figure 35 – Impact of ISIS

Aspect	Not at all	To a small extent	To a large extent	No view
The UK's international reputation	0.0	3.4	94.9	1.7
The field's attractiveness to students	0.0	15.3	83.1	1.7
International cooperation / networking	0.0	15.3	78.0	6.8
International partnerships	0.0	18.6	78.0	3.4
Employability of researchers / students	0.0	20.3	71.2	8.5
International mobility (inbound)	0.0	22.0	61.0	16.9
Prioritisation of the field in UK policy	0.0	25.4	57.6	16.9
International mobility (outbound)	1.7	32.2	44.1	22.0
Industry engagement/collaboration	3.4	46.6	41.4	8.6
Industry investment in the field	6.9	48.3	24.1	20.7

The most widely perceived 'big impacts' relate to the UK's international reputation, attractiveness to students and international cooperation. Less positive are perceived impacts on industry engagement and collaboration, and industry investment in the field.

Question 26. What is the best example of impact (on science, skills, economy, society) resulting from this research community's use of ISIS?

Impacts cited as the most important can be broadly divided into:

Specific scientific achievements:

- Residual stress measurements at ENGIN-X have revolutionised the field and underpin a significant amount of manufacturing
- Research done at ISIS on correlated electron phenomena in particular quantum and frustrated magnets, quantum criticality, high-Tc superconductors and iron-pnictide superconductors have been critical for the current understanding of the physics of those materials
- Degussa's application of inelastic neutron scattering to investigate industrial grade heterogeneous catalysts is world leading and has advanced the art of catalyst characterisation

Collaborations and community building:

- The creation of an international community of theorists and experimentalists actively using deep inelastic neutron scattering to calibrate their theories and explore new phenomena in condensed matter physics not previously accessible
- Neutron knowledge has been transferred to other research communities to create interdisciplinary science
- A very positive impact on international scientific collaboration with Japanese universities related to research activity using ISIS

- The employment of researchers trained at ISIS by facilities elsewhere across the globe, and their use as international advisors

Skill development and training:

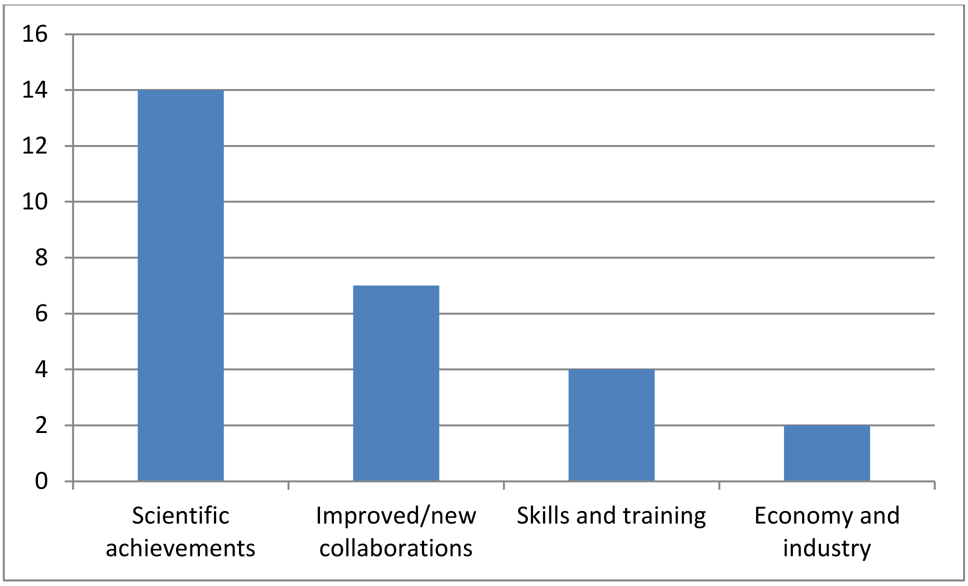
- Training of PhD students and young professionals (academic and national laboratory/industry)
- Training students in the cutting edge use of technology to solve problems
- Enabling students to describe complex new solids

Economy and industry:

- Understanding formulations and applying this knowledge to industrial problems
- PhD students being employed by industry as a direct result of work carried out at ISIS
- No specific wider social impacts are mentioned, beyond advances in understanding

The distribution of responses of 'best example of impact' by these categories is shown in Figure 36. In line with responses to other questions in the survey, scientific achievements are cited by most respondents as being the area of most significant impact, with impacts on collaboration also featuring significantly. Skill development and training is considered the most important impact by some respondents while only two cite the impact on industry and the economy. The subsequent employment of ISIS PhDs in industry, considered important by one survey participant, is however interesting and may justify further examination of this issue.

Figure 36 - Numbers giving responses in various categories as the 'best example of impact' from use of ISIS



Finally, survey participants were asked if they would be prepared to participate in a short follow-up interview to discuss particular responses. 82 provided a phone number, while 114 did not respond.

Appendix G Questionnaire survey of ISIS Industry Users

G.1 Introduction

Several hundred companies are known to have been involved with ISIS through the mainstream user programme, however their involvement is always managed through the academic lead partner. As a result of this arrangement, ISIS has no formal record of industrial partners and was therefore not able to provide the study team with a list of named contacts or even write to those industry contacts on our behalf to notify them about the impact assessment exercise.

Instead, the Director of ISIS kindly agreed to write to all academic users asking if they might forward a request to participate in a survey to their ISIS industrial collaborators. This request was made separately and in addition to our request to those same academics to provide a response on their own account. This indirect strategy was not especially productive, and just 10 industry responses were received in total.

G.2 Respondents

Information collated by ISIS suggests that the number of individual companies that have connected with ISIS through academic partners in the past year is around 60, and that there were nearly 800 proposals for beam time in the last three years that made explicit mention of industry involvement – including multiple mentions of the same companies. However, due to our indirect approach, we have no idea of the number of industrial users who received the survey invitation. As such, the 10 responses received cannot be compared with the size or features of a total population, however the feedback was instructive nevertheless.

The 10 respondents came from companies active in a range of different sectors, including: energy (3), chemicals (2), aerospace (2), automotive (1), materials (1), and micro/nanotechnology (1), and included both SMEs and large multi-nationals.

G.3 Use of the ISIS facility

Respondents to the survey were asked whether they had made direct use of the ISIS facility themselves. Most (7) said that they (or close colleagues) had been involved directly in one or more experiments at ISIS, while the remainder (3) had only made indirect use of the facility (i.e. through partnership or collaboration with a researcher or scientist from another institution).

They were also asked to estimate the number of years that both they and their wider organisation had been making use of the ISIS facility, either directly or indirectly. The respondents themselves had been making use of ISIS for anything between 2 and 22 years, with an average of 10 years experience of the facility across respondents. Most suggested that their organisation had been making use of the facility for the same length of time, except in a few cases where the organisation's use pre-dated the respondent's, or vice versa (presumably where the individual had been using the facility in a previous position). The average length of time that the respondents' wider organisations had been making use of the ISIS facility was also 10 years.

Each respondent also explained briefly the main area of research where they had been making use of the ISIS facility. These were (relevant company sector in parenthesis):

- *Measurement of supermirrors with neutrons (micro/nanotechnology)*

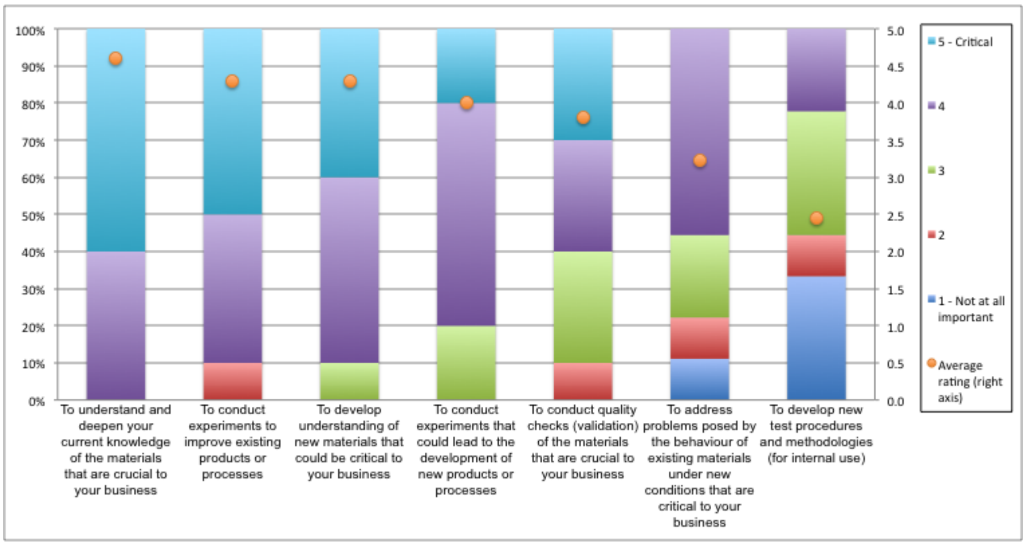
- *Measuring residual stress in metal wires (energy)*
- *Detection of phase transformations and strains (aerospace)*
- *Investigating solution quality and concentration for carbon nanotubes (materials)*
- *Development of lubricant additives (surfactants & detergent particles) (chemicals)*
- *Residual stress analysis (automotive)*
- *Inelastic neutron scattering to characterise Fischer-Tropsch catalysts (chemicals)*
- *Residual stress measurement on welded mock-ups of components (energy)*
- *Neutron scattering and reflectance of polymers, surfactants and colloids (energy)*
- *Texture measurement, residual stress measurement in thick sections for novel / advanced manufacturing and joining techniques, lattice strain evolution during in situ loading / fatigue tests (aerospace)*

G.4 Criticality and importance of the ISIS facility

Industry users were asked how important ISIS had been for their company in undertaking a range of different types of research activity. The distribution of assessments for each function are summarised in the figure below. An 'average rating' of criticality is also shown.

The most important use of ISIS across respondents appears to be in understanding and deepening current knowledge of crucial materials. However for six of the seven areas listed, a majority of respondents rated the importance highly (a rating of 4 or 5). Even in the two areas not seen by any of the respondents as critical (developing new test procedures / methods, and addressing problems posed by the behaviour of existing materials under new conditions), a majority still rated these as of some importance (i.e. a rating of 2 or above).

Figure 37 - Importance of ISIS to companies in undertaking different activities



Respondents were further asked to describe the one feature that makes ISIS of especial value to their business. Their responses were often very specific and so are each shown in full below:

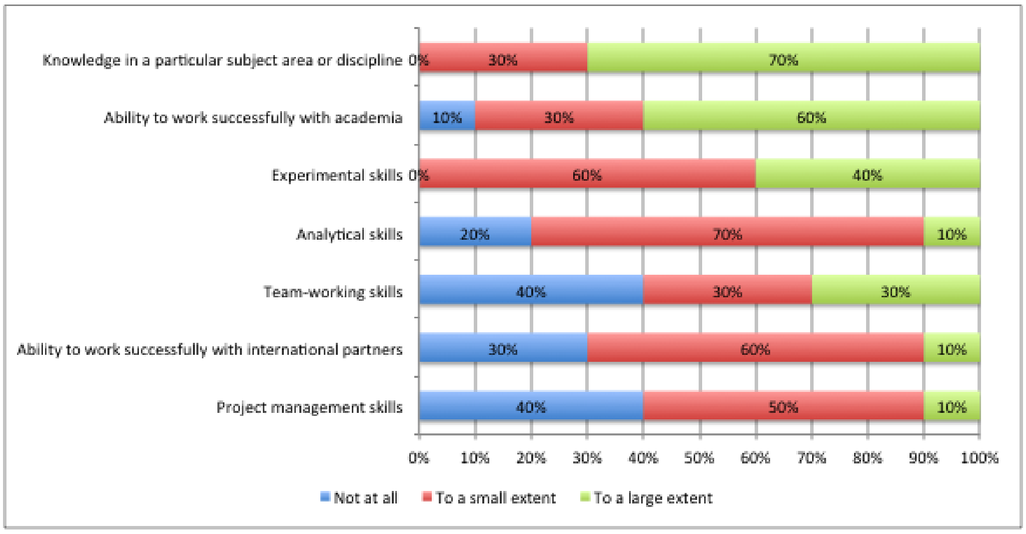
- *Neutrons are the only possible method to measure the parameters we need*

- *ISIS provides the advanced technologies for evaluating residual stress in manufactured products that could not be evaluated by other means. These evaluations are extremely useful for us to increase the utilisation of current materials and the capability of our products without compromising safety*
- *It provides an alternate means of validating our theory based on in-situ measurements and this theory has been developed in solving a particular problem.*
- *It enables experiments to be run to gain deeper understanding of materials that would simply not be possible anywhere else. The results obtained at ISIS enabled us to prove the quality of our product and move forward with commercialisation*
- *We are located 3 miles from ISIS. Having the diversity of instruments so close is a real advantage*
- *The ability to measure residual stresses on complex engineering components*
- *The expertise of the ISIS scientist in setting up the equipment to enable our experiments and in the interpretation of data*
- *The technical characteristics of the instrument used and sample environment capacity to measure residual stresses on big components*
- *Study of small structures in opaque materials*
- *Data quality from 'large' volumes*

G.5 Impacts on skills and capabilities

Respondents were asked to assess the extent to which their organisation's use of ISIS had a positive impact on its skills and capabilities, in various areas. The spread of responses is shown in the figure below. All respondents reported some level of impact on both domain knowledge and experimental skills, while a majority reported impacts in each of the other skills / capabilities listed. A majority of respondents also reported a *large* impact in both domain knowledge and the ability to work successfully with academia.

Figure 38 - Impact of ISIS on industry's skills and capabilities



They were then asked to describe the single most important benefit to their organisation's skills and capabilities, which is attributable to ISIS. Again, their responses were very specific, and so are shown in full below:

- *Gain of physical knowledge of our products and the manufacturing process*
- *The use of expert knowledge in academia and access to novel techniques and experimental facilities to solve industrial problems*
- *Being able to develop scientists in industry through running experiments at ISIS and gaining insight into new/ existing products*

- *Increased academic collaboration*
- *An understanding of the capacity of inelastic neutron scattering to address an issue key to much heterogeneous catalysis, namely carbon deposition*
- *Good knowledge of welding parameters and weldment geometries' impact on residual stresses of industrial components, and finite element analysis to predict more accurately the residual stress state of nuclear power plant components*
- *Encouraged collaboration with UK academics*
- *Residual stress measurement knowledge and expertise*

G.6 Impact on science and technology

Industrial users were asked to name and describe an important advance made possible by their use of ISIS, and to explain the role and importance of ISIS in the example. Seven of the respondents did so, and the information they provided is summarised in the table below, with the relevant 'advance' in the first column, and reflections on the role and importance of ISIS in the second column.

Figure 39 - Examples of important advances made possible by the use of ISIS

Advances made possible	**Role and importance of ISIS**
The effect of residual stress on the service integrity of inflexible pipes is an issue that was not properly understood. This became an obstacle in developing new pipes for high-pressure deep-water applications. Work at ISIS will help to understand this effect and to design future pipes with high confidence of integrity.	ISIS provides valuable experimental facilities and expertise on measuring residual stress.
Fully understanding the properties of a solution to prove scientific theory.	ISIS experiments simply could not be undertaken anywhere else - this is an invaluable resource.
Understanding the evolution of particle size in the synthesis of overbased detergent particles and the factors which influence size and properties	Preps were performed at the company and samples taken throughout. These were driven to ISIS to be sized by SANS immediately.
Ability to map residual stress in complex engineering components. This could lead to improved manufacturing processes and cost reductions in the future.	Through the use of the EnginX instrument at ISIS we were able to measure residual stress in the interior of turbo charger components non-destructively.
A more detailed understanding of the mechanism of action and decay of current commercial catalysts	Only through ISIS could we access neutron scattering, which in turn enables a molecular description of hydrocarbonaceous deposits on working and spent catalysts. The nature of this material makes the use of other techniques impossible.
Development of new welding processes and welding repair techniques	ENGIN-X at ISIS has mostly contributed to an exhaustive characterisation of big and representative components in terms of residual stress states to validate numerical models and fabrication processes.
Understanding texture evolution in titanium alloys	High quality data sets available from large volumes of material - which is difficult / impossible via other techniques

G.7 Commercial impacts

Industry users were asked to assess the extent to which their use of ISIS had a positive impact on various aspects relating to their organisation's <u>RTD capabilities, activities, and reputation</u>. A 5-point scale was used to indicate the adjudged degree of impact, where a score of "1" signifies "no impact." The distribution of responses given is summarised in the figure below. An 'average rating' is shown in the final column to help understand where impacts where most significant and widespread, and the table is sorted accordingly.

The first thing to notice is nearly all respondents suggested that there was some degree of impact from their use of ISIS (indicated by a rating of 2 or above) across each of the aspects listed. And in relation to four of the areas, all respondents indicated that there had been some impact from their use of ISIS.

A rating of 4 or above suggests a particularly significant impact in an area. Impacts on the company approach to R&D stand out, with two-thirds of respondents providing a high rating. However, significant impacts were also reported by 50+ % of users in three other areas: innovativeness, efficiency of products and processes, and approach to innovation management. Therefore, not only are impacts widespread, but also the extent of impact is often significant in many cases.

Figure 40 - Extent to which use of ISIS had an impact on…

	1	2	3	4	5	n	Avg rating
Your company's approach to research and development	11%	11%	11%	56%	11%	9	3.4
Your company's technology partnerships	0%	11%	44%	33%	11%	9	3.4
Your company's innovativeness	0%	22%	22%	56%	0%	9	3.3
Your company's approach to innovation management	0%	25%	25%	50%	0%	8	3.3
Your company's technology strategy	0%	11%	44%	44%	0%	9	3.3
The efficiency of your company's products and processes	11%	11%	22%	56%	0%	9	3.2
Your company's international reputation	11%	22%	22%	33%	11%	9	3.1

Respondents highlighted a number of other important types of impact (not listed) that are attributable to ISIS. These included: improved product safety, improved knowledge for the wider community, a better basis for making commercial decisions, and highlighting the science done by UK industry and the importance of central facilities to their product development.

Industry users were also asked to consider outcomes of their use of ISIS, in terms of wider commercial implications. Again, respondents used a 5-point scale to indicate the extent of commercial impacts. Responses are summarised below. The average ratings are in general slightly lower, compared with the more direct and internal outcomes discussed above. Nevertheless, there are still indications of reasonably widespread and / or significant implications from the use of ISIS across the various commercial aspects listed. In particular, more than two-thirds of respondents suggested that use of ISIS had had some impact on competitiveness, productivity, and share value, while at least half reported some impact in all other areas listed. The most significant impacts (ratings of 4 or 5) were most commonly reported in relation to competitiveness (56%) and productivity (38%), but were also suggested by a smaller number of respondents in five of the other areas listed as well.

Figure 41 - Extent to which use if ISIS has contributed to…

Sales	1	2	3	4	5	n	Avg rating
Competitiveness	22%	11%	11%	22%	33%	9	3.3
Productivity	13%	25%	25%	38%	0%	8	2.9
Savings	25%	13%	38%	25%	0%	8	2.6
Sales	25%	50%	0%	25%	0%	8	2.3
Exports	50%	13%	13%	13%	13%	8	2.3
Environmental footprint	38%	25%	25%	13%	0%	8	2.1
Employment	50%	38%	0%	13%	0%	8	1.8
Share value	29%	71%	0%	0%	0%	7	1.7

Respondents were further asked to estimate the total value of additional sales underpinned by their use of ISIS, and to note the period over which this has arisen. Two key points emerge from the responses given:

- For some, it is too early to put an estimate on the value:
  - *We are still in the commercialisation process with the technology and so sales are still low – however ISIS helped us get to the point of choosing to commercialise the technology*
  - *The value is not yet known*
  - *The understanding gained has yet to be implemented – the operation is carried out on a huge scale and there is a process to go through before implementing any process change*
- For others, it is difficult to attribute a value to the use of ISIS:
  - *It is difficult to estimate any evolution of sales underpinned by the use of ISIS, since most developments where the company has made use of the facility are related to R&D projects.*
  - *Process improvements have resulted in improved product stability – it is difficult to estimate the value of this*
  - *Understanding material behaviour during processing and service is at the heart of industrial application to safety critical hardware – the value of this directly associated with ISIS is very difficult to estimate*

However, one respondent did put a value of £5m on additional sales, another estimated ~£500k over three years, and two further respondents suggested the value to their companies would be in the millions of pounds per year.

Appendix H Survey of suppliers to ISIS Target Station 2 (TS2)

H.1 Introduction

The ISIS administration assembled a database of external organisations that had supplied ISIS during the design and construction of Target Station 2 (TS2). The list focused on suppliers of higher value items relating to the construction of instruments for TS-2, with a combined value of around £30M, where the full cost for TS2 amounted to more than £150M. The list included major work-package contractors as well as the suppliers of various other more complex goods and services.

Around 250 different organisations were listed. Many of these organisations have supplied ISIS with goods and services on other occasions, however, details on the timing and value of other ISIS-related procurement contracts was not available and as such it is perhaps best to think of this current supplier survey as an exploration of the benefits of working for ISIS more generally, albeit with a focus on higher value and more complex services.

In most cases the name of the company, its postal address and (in around 50% of cases) an email address were provided. However, the email addresses were often of a generic nature (e.g. sales@...), and no named contact was given. The study team attempted to identify email contacts for organisations where these were missing, and thereby increased the number of usable contacts to 177.

On 28th July a letter was sent from the Director of ISIS to the 177 supplier organisations (where email addresses were available), requesting their participation in a short online questionnaire. Responses were requested within a two-week period, and a reminder was sent on 13th August to further encourage a response. As of 18th August, a total of 47 responses to the survey had been received. That is a 27% response rate for the 177 suppliers with email addresses and 19% of the original 250.

Given the nature of the contact information, and the fact that for many of these suppliers, sales to ISIS will constitute a small proportion of their total business, the response rate to the survey is very good. Nevertheless, it does represent less than 20% of all suppliers for TS2 instruments, and a smaller (but unknown) proportion of all suppliers to ISIS. It is also possible that our voluntary survey attracted a larger number of responses from organisations that have a strong relationship with ISIS as compared with those that didn't respond (non-response bias). We cannot therefore assume that the responses provided can be simply extrapolated to a wider population.

Notwithstanding these methodological remarks, the results do provide insight into the experiences of a meaningful number of different sorts of suppliers, whose aggregate responses concerning the impact of ISIS, on their income and employment, may reasonably be assumed to constitute the lower bound as regards the benefits realised across the full portfolio of suppliers.

H.2 Outcomes from sales to ISIS

Suppliers were asked to assess the extent to which their past sales to ISIS had an impact on various aspects relating to their organisation's internal capabilities, activities and reputation. A 5-point scale was used by respondents to rate their judgement as to the scale of the impact on their organisation, where a score of "1" denotes "no impact at all" and a score of "5" signifies a major impact on the business.

Figure 59 shows the distribution of the number of responses, by score, along with the number of people that provided a response to that specific impact question. An 'average rating' is shown in the final column to help the reader to more readily identify the types of impacts that were most widely judged to have been significant, and the table is sorted accordingly.

The first thing to notice is the large proportion of respondents suggesting some degree of impact from their sales to ISIS (indicated by a rating of 2 or above) across each of the aspects listed. In relation to five of the areas, the vast majority (70+%) of respondents indicated that there had been some impact from their sales to ISIS. In particular, impacts in relation to the organisations' reputation for technological quality were most common, with only a handful of suppliers reporting that there had been no impact at all on this aspect. Recruitment was the only area where a majority of respondents (63%) judged there was no impact.

A score of 4 or 5 signals a particularly significant impact. Again, the impact on suppliers' reputation for technological quality stands out, with over half (55%) of all respondents providing a 4 or 5 rating. However, substantial impacts were also reported by 20-40% of suppliers in three other areas: reputation for innovation, in-house technological capability, and the development of innovative products and services. Overall, the survey results show that this group of ISIS suppliers has derived substantial benefits in manifold areas of their business.

Figure 42 - Extent to which sales to ISIS had an impact on…

	1	2	3	4	5	n	Avg. rating
Your reputation for technological quality	9%	11%	25%	36%	18%	**44**	3.4
Your reputation for innovation	18%	26%	18%	26%	13%	**39**	2.9
In-house technological capability (know-how)	16%	23%	28%	23%	9%	**43**	2.9
The development of innovative products or services	19%	26%	31%	17%	7%	**42**	2.7
Your collaborations	30%	16%	35%	16%	2%	**43**	2.4
Your recruitment	63%	10%	18%	10%	0%	**40**	1.8

Excludes those who responded 'n/a'

Suppliers were further asked to consider the outcomes of their sales to ISIS, and in particular the extent to which those contracts had wider commercial implications. Once again, respondents were asked to use a 5-point scale to indicate the degree to which they had derived wider commercial benefits as a result of their sales to ISIS, where a score of "1" was used to signify "no impact" and a score of "5" indicated a substantial commercial impact. Figure presents the summary of responses.

The average ratings are in general slightly lower, compared with the more direct and internal outcomes discussed above. Nevertheless, there are still indications of reasonably widespread and / or significant implications from sales to ISIS across the various commercial aspects listed. In particular, a majority of suppliers suggested that their sales to ISIS had had some impact on new products or services (83%), increased domestic sales (73%), increased quality (71%) and increased productivity (62%). Around 40% of the 46 responding suppliers reported some degree of positive impact on third party sales of products/services originally developed for ISIS, 30% report an increase in international sales and 20% report an increase in employment.

The most significant impacts (ratings of 4 or 5) were most commonly reported in relation to new products and services (21%) and increased quality (20%), but were also suggested by a smaller number of respondents in all five other areas listed as well.

Figure 43 - Extent to which sales to ISIS contributed to...

	1	2	3	4	5	n	Avg. rating
New products / services	17%	34%	28%	19%	2%	47	2.6
An increase in quality	29%	27%	24%	20%	0%	45	2.4
An increase in sales nationally	27%	47%	18%	9%	0%	45	2.1
An increase in productivity	38%	24%	36%	2%	0%	45	2.0
3rd-party sales of products / services developed for ISIS	50%	15%	28%	7%	0%	46	1.9
An increase in sales internationally	54%	17%	20%	7%	2%	46	1.8
An increase in employment	50%	28%	20%	2%	0%	46	1.7

To add some texture to the voting, respondents were asked to describe briefly the single most important impact from their work for ISIS. Free-text replies were provided by 36 suppliers, and often highlighted one of the aspects listed above. The responses given have been grouped together into five main areas of impact below (with the number of responses in parenthesis):

- Direct increase in sales / turnover / profit / employment (11)
  - *Increase in sales turnover; Increase in sales; Keeping turnover up; Boost in revenue during the time that the orders were placed; Boost to company growth; Boost to company growth; Boost to company growth; Increased profitability; Increase in our sales; Employment of more people within the company; Manufacturing opportunity and provision of goods*
- Establishment of long-term customer / relationship (5)
  - *Company stability; Consistent work with little or no issues; We work closely with ISIS development engineers to achieve leading edge products - we have provided this service for many years and are experienced on the needs of ISIS; ISIS have given us a solid customer who we work regularly with; Regular yearly business for 2-stage products and service*
- Increase in technical capability / know-how (5)
  - *Development of techniques; Improvement in our company's technical capabilities; Gained expertise in working with unusual materials, such as titanium zirconium; The most important factor for us is the ability to develop new product and resolution for problems we may not face in normal industry; We supply a number of vacuum pumps to ISIS, from the back of this we have developed a number of training courses to help you onsite*
- New products (6)
  - *Development of new products and technologies; Entering the market for our product after our company was established; New product development; New customer and 2 new products (from generic process); To have confidence in offering new products; New materials*
- Increase in reputation and third-party sales (10)
  - *Boost to reputation; Reputation and esteem; Technical Reputation; Furthering our reputation within vacuum housing; Increased reputation as a supplier to big science; ISIS as a customer is a prestigious organisation and is good to have within our customer portfolio; ISIS is a well known company and hence a valuable reference for us when trying to find new customers; Manifesting our global reputation as a high quality supplier; Ability to use it as an example in our credentials for working with large facilities - we have successfully won projects with other similar institutions on the back of work with ISIS; Allows us to approach other major scientific establishments with knowledge and confidence*

These comments show that while for some ISIS has been most important simply as a customer providing revenue (direct benefits), for many suppliers, the capabilities, products and reputation developed have been most important – often leading to wider opportunities and sales (indirect benefits). This kind of reputational benefit – a kind of accreditation by the market – is widely reported by large international scientific facilities like CERN or intergovernmental agencies like ESA, and as such ISIS and STFC are in very good company.

H.3 Counterfactual

Finally, suppliers were asked what the implications would have been if their contract(s) with ISIS had not been awarded. In total 35 responses were given, of which 54% highlighted that there would have been a significant loss of direct revenue (with implications for employment, growth and profitability), and 26% went as far as to suggest that there would have been wider implications (in terms of business growth and market position, which had been aided or enabled by ISIS sales). Examples of the comments provided in the latter category are shown below:

> *Minimal on the total budget but significant for our reputation and partnership with STFC; Longer timescales to making sales with other national laboratories; Difficult to say - but perhaps slower growth; More difficult to recruit and attract potential apprentices; Undermined our reputation as market leader; We would probably not have offered the products; Could not use the gained experiences and competences as leverage for other projects and orders; It is possible that we would have gaps in our knowledge and understanding of the use of our products at the extremes of their use; Unable to develop a new product*

The remaining 20% of respondents suggested that there would have been little or no adverse effect from the loss of their ISIS sale(s).

Appendix I ISIS supplier case studies

I.1 Applied Scintillation Technologies

Applied Scintillation Technologies[28] (ATS) is a UK company located in Harlow alongside GlaxoSmithKline, Nortel Networks, Pitney Bowes and Raytheon. The company employs around 45 people and had a turnover in the range £3M-£5M in 2013. ATS manufactures scintillation materials and technologies for the imaging and detection market place.[29] This is a growing market (5-6% pa) and currently estimated to be worth several hundred million a year globally (e.g. in healthcare, security, power plants and science applications).[30]

ATS was founded in 1920 and was an early maker of phosphor (a substance that exhibits the phenomenon of luminescence) for X-ray machines and has been supplying ISIS with specialist scintillator materials for neutron detectors since 1988. Employment has grown fivefold in the period and further expansion is planned.

ISIS's success is dependant in large part upon the quality of it's detectors, which are used in many instruments across ISIS: neutrons pass through samples being tested and need to be detected as they leave, providing unique information about the structure and properties of the materials under test.

> *"ATS has supplied over 180 square metres of scintillator for the detectors of 17 of the 26 neutron scattering instruments currently operating at ISIS." There are other manufacturers of scintillator material, but ASTs is self-supporting and does not have to be deposited on a substrate. This property has been used to excellent advantage in the ISIS detector designs."*

Both ISIS and AST have benefitted from their close working relationship as it has lead to the development of world class neutron detectors, business expansion within AST (staff as well as international markets) and exploration of new scintillation conditions.

> *"There are about 30 neutron scattering research sites worldwide, but only a few of these are actively researching neutron detector development. Detector research at ISIS, led by Dr Nigel Rhodes, is at the forefront of such research."*

> *"Our long and valued relationship with the detector scientists at ISIS has helped keep us at the forefront of neutron detection technologies. Working alongside the neutron scattering community helps to open new doors via direct introductions and through indirect means such as citations in academic papers," says Stuart Quinn, Sales and Commercial Director at AST.*

Working with facilities scientists of the calibre of those at ISIS has helped AST's business to develop, contributing substantially to its strong growth in the past 15 years. As a direct result of supplying ISIS, AST now supply neutron scattering research centres in the USA and Japan. The

[28] http://www.appscintech.com/about-us

[29] Scintillators are luminescent materials, which re-emit part of the absorbed energy in the form of light. The emission can be of different types: fluorescence (prompt), delayed fluorescence and phosphorescence (delayed with different wavelength).

[30] There are a number of 'charged' market research reports available, which estimate the global market for scintillation materials and technologies may reach around $500M by 2020, see for example the free abstract http://www.researchandmarkets.com/research/jjx7sz/scintillator

substantial history of AST's scintillators at ISIS has helped to provide a respected track record of success for their products, which is underpinning sales internationally.

ISIS and AST are also collaborating on the development of new scintillators. Some types of neutron detector make use of the rare gas helium-3. As a result of a worldwide shortage of helium-3, the price has increased 15-fold and it is increasingly difficult to source. Alternative solutions are needed and ISIS is working with AST to push the properties of scintillator materials further to allow them to be considered as viable options to replace helium-3. Success in this area would give AST's growth ambitions and international presence in the scientific detectors market, substantial additional impetus.

I.2 Prototech Engineering Limited

Founded in 1991, Prototech is a small, precision engineering business based in Sutton Courtenay in Oxfordshire, a mile from ISIS. The company specialises in the manufacture of: prototype and small batch precision engineered components, process control systems and cryogenic and ultra high vacuum equipment. It provides a complete in-house engineering service from procurement of materials, machining of components, mechanical and electrical assembly, to welding and testing of finished products. Prototech is supplying businesses and laboratories in a wide range of application areas, from chemicals to scientific instrumentation.[31]

> *"The idea that small companies cannot work with big research facilities is wrong," says Prototech MD John Greenaway. "Small businesses can see huge benefits from the long term contracts on offer. Winning work from large world-class facilities such as ISIS gives us the confidence to pitch for other large contracts. And because our formal relationship with ISIS is set for four years, we can enjoy valuable long term stability at a time when the future of the UK economy is so uncertain."*

In 2009, Prototech was awarded a 4-year, £400K contract to manufacture the moderators for ISIS Target Station 2, which are extremely sophisticated components, and critical to the successful performance of the facility. If the moderator doesn't work then neither does the beam line. Each moderator costs around £50,000 to produce and is replaced every six months. The Target Station 2 moderator is a significant advance over the previous design, producing over four times the number of useable neutrons with a quarter of the power.[32]

Neutrons emerge from the ISIS neutron targets at near light-speed and with high kinetic energy, which must be reduced considerably before they can be used for science experiments. To do this, ISIS (and other neutron sources) uses devices called moderators to reduce the kinetic energy, which also reduces the speed of the neutrons. The high-energy neutrons are designed to collide with the moderator materials' nuclei, in this case hydrogen and methane, removing just the right amount of kinetic energy from the neutrons. Moderators are built like Russian dolls – containing several nested metal skins. A refrigeration plant cools the moderators to almost minus 240 degrees Celsius allowing them to hold reservoirs of liquid hydrogen and solid methane. Each skin is machined from a solid piece of aluminium to create an exact shape that cannot be out by more than half a millimetre in any direction. The correct design and choice of materials for the moderators is critical to the performance of the facility: if these components do not function exactly as specified, ISIS TS2 will not operate. Given the critical nature of these complex components, the moderators are inspected up to 40 times during manufacture

[31] http://www.prototech.co.uk/

[32] http://www.isis.stfc.ac.uk/about/target-station-2/moderator8302.html

Sean Higgins, lead engineer from ISIS on the project says that working with a local company has benefited both ISIS and the contractor.

> *"These components are incredibly complicated to manufacture. Being able drive down the road to Prototech to discuss progress and solve problems has reduced the cost of the project. Sometimes you can't solve problems on the phone – you need to sit next to each other and work it out. This was an incredibly complex piece of manufacturing and we are very lucky to have such skills available in the UK. But it is up to facilities such as ISIS to identify, and put them to good use. If we don't – we may lose them."*

I.3 JJ X-RAY

JJ X-Ray is a Danish SME set up in 1996 by a senior engineer from the Physics Department of the Riso National Laboratory and was based at the Centre for Advanced Technology (Riso) with close links to the University of Copenhagen. In 2006, the company was taken over by employees and relocated to a science park on the premises of the Technical University of Denmark.

The company develops, designs and produces highly specialised components and assemblies for scientific x-ray, synchrotron radiation and neutron instrumentation.[33] It is widely known for its high precision slits and collimators. Slit systems are used to divide off unwanted radiation and create a well-defined beam shape. Collimators are used for enhancing the angular resolution of the scattered radiation from a sample. JJ X-Ray was one of the few suppliers in collimators and slits, when it was first set up.

The typical customer of JJ X-Ray is an instrument scientist working at a synchrotron radiation facility, such as the ESRF or the European x-ray free electron laser (European XFEL) or at a neutron facility like ISIS. JJ X-Ray won a contract in 2012 – with the Danish Technological University – to produce one of the six beamlines that will be implemented at the European XFEL at DESY in Hamburg.

The collaboration between ISIS and JJ X-Ray commenced in 2000 following informal exchanges at conferences and networking events, but really took off in 2008 when JJ X-Ray won the contract to supply and install three sample-positioning stacks for the ISIS Target Station 2. The tender required a sample positioning system with a load capacity of 700 kg to be positioned in space with an accuracy and sphere of confusion of less than 20µm within a very small (800 x 800 mm2) footprint. JJ X-Ray's solution was selected: A customized 6-axis sample stage meeting the specifications.

According to the CEO, Dr Christian Bjerg Mammen, the collaboration between ISIS and JJ X-Ray has contributed to the latter's growth in several areas: (1) JJ X-Ray's *international* turnover, which has tripled since 2008, through sales to ISIS and other international laboratories in for example Germany and the USA; (2) its portfolio of customers (in 2008 JJ X-Ray supplied 50% of neutron & synchrotron research facilities globally, while in and today JJ X-Ray supplies 80% of the 50 synchrotron radiation research facilities and 25 neutron research facilities around the globe; and (3) employment for JJ X-Ray (increased in-house capability through hiring of mechanical engineers: 1 in 2008 and 5 in 2014).

Successful installation and performance of these sample-positioning stacks was enabled through collaborative design development between ISIS and JJ X-Ray. This was achieved through a number of face-to-face meetings at ISIS, which provided the opportunity for the JJ X-Ray team to refine the

[33] http://www.jjxray.dk/

design and to recognise the benefit of strengthening their in-house engineering design capabilities. By hiring a mechanical engineer, required iterations in the design process could be modelled through Finite Element Analysis / Modelling (FEA / FEM). Since 2008 JJ X-Ray has expanded its in-house staff from one to five mechanical engineers with capabilities in FEM modelling to work on similar projects.

The three sample positioning stacks from JJ X-Ray have been operating daily at the three beamlines since installation, leading to an order of two more sample positioning stacks in 2011 for two new beamlines.

I.4 Edwards

Edwards was a UK-owned company specialised in the development and manufacture of sophisticated vacuum products, abatement systems and related value-added services. The company became part of the Atlas Copco Group (Sweden), in 2014. It has a global turnover in excess of £1 billion and almost 4,000 staff operating in more than 20 countries. Its vacuum technology is used in very many industrial processes, from manufacturing LEDs to pharmaceutical; and for both scientific instruments and a wide range of R&D applications.

Edwards has been supplying goods and services to ISIS since the facility was first built, and that relationship is reported to be still on-going and strengthening even under new ownership.

Edwards is a 40-minute drive away from ISIS and close to both Pfeiffer Vacuum (Bucks) and Oerlikon Leybold Vacuum (Surrey), two other vacuum pump suppliers to ISIS. All three companies have particular strengths and specialities, which complement each other and provide ISIS with an excellent sales and support service around the many and various vacuum pumps being used. Just to give an example, we understand that ISIS purchases about 300 Edwards products each year, with costs varying between £3,000 and £4,000 for each product or around £1M a year.

While ISIS constitutes a tiny fraction of Edwards' total annual sales, there is a business development angle, with ISIS's sometimes challenging requirements providing a valuable input for Edward's more general ambitions in growing its position in the scientific instrument / R&D sector internationally, mirroring other global vacuum pump manufacturers in focusing its attention on the development of application-specific products.

Over the past 12 months Edwards has been strengthening its relationship with ISIS by regular face-to face visits on site (every couple of months) and moreover the co-development of a training programme for the use of Edwards vacuum pumps.

This programme has been developed in close collaboration between Paul Raybould, Senior R&D Account Manager (Edwards) and Sunil Patel (ISIS Vacuum Group). This programme has been mutually beneficial as not only ISIS staff have been trained through it but Edwards engineers have also been undergoing this training internally. A rolling out of this training programme to global Edwards Vacuum Pumps staff (e.g. USA) is currently being considered. According to Paul: 'program content development in collaboration with ISIS assures a high standard of quality and thereby a stronger case for internal sign off'.

Edwards consider relationship building with its customers one its highest priorities and demonstrate this through its on-going support by sponsoring ISIS events and conferences (e.g. upcoming event 13-15 October at ISIS). And vice versa, ISIS values the relationship with Edwards and is always happy to provide references and introductions for future work.

I.5 Specialist Power

Specialist Power is a UK SME that manufactures and supplies a variety of secure and standby power systems, including uninterruptable power supplies (UPS) and standby generators. It provides turnkey solutions from sale of equipment to hassle free maintenance and support.

The relationship between ISIS and Specialist Power started in 2009 and has resulted in ISIS purchasing a variety of Specialist Power products and services over the past three years, which have an estimated value of between £50K and £250K a year. The relationship with ISIS has strengthened over time, with gradually increasing sales, albeit that has had only a marginal impact on the company's overall figures.

I.6 Inward investment of scientific instrumentation designer AVS

In 2010, ISIS invested around £3.3M in an upgrade to the Polaris medium resolution powder diffractometer, with substantially increased detector coverage and improved management of the incident beam and background signals from sample containment equipment. An additional £700k was made available by the Swedish Research Council, for the provision of advanced sample environment equipment. The upgraded instrument features a large vacuum vessel inside which all the detectors are mounted. Constructed out of stainless steel and having a volume of ~20,000 litres (a cylindrical flask of about 5 metres in length and 2.5 metres in diameter), this tank was designed in Spain by AVS and built by another Spanish engineering company, Cadinox,[34] as part of a multi-million pound "in kind" contribution provided to ISIS by the Spanish government.

The Spanish government's promotion of these two regional technology companies has enabled both organisations to develop a stronger position within the small but demanding international market for scientific instrumentation and vacuum flasks. AVS (www.a-v-s.es/) is expanding and now has operations close by big research facilities in France (CNRS in Annecy, close to CERN and ILL / ESRF) and Germany (in Berlin close to DESY and several other major laboratories) and in 2014 it opened an office on site at Harwell, with a view to developing its fledgling commercial relationships with ISIS in a broader set of interests with all the co-located facilities, including Diamond, and also gaining from the kind of knowledge spillovers (and recruitment opportunities) that should derive from its small local team rubbing shoulders with instrument scientists and visiting researchers. This is a good example of a high-tech inward investment, which mirrors the kinds of inward investment attracted by the UKTI R&D programme, and which should support employment growth on the one hand and the flow of UK technology and expertise to other major European scientific facilities, and in reverse too.

[34] Cadinox is a family-owned Basque company that carries out welding and machining for a variety of industrial sectors including large scientific installations, like ISIS or the ITER experimental fusion reactor that is being built at Cadarache in the South of France.

Appendix J Oxford Instruments and STFC

J.1 Introduction

Oxford Instruments is a leading UK technology company with a turnover in 2012/13 in excess of £350 million. It designs and manufactures high-technology tools and systems capable of fabricating, analysing and manipulating materials at the nanoscale. The company has worldwide sales to the science, energy, environmental, health and security industries.

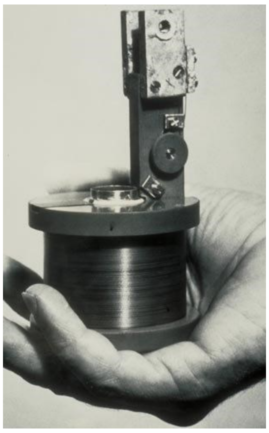
STFC is a public body funded mainly by the UK Government's Department of Business, Innovation and Skills (BIS). STFC supports fundamental research in the fields of particle physics, astronomy and nuclear physics; it operates or contributes to major UK research facilities such as Diamond Light Source; and it manages subscriptions to leading international science facilities including CERN and major astronomical telescopes overseas.

Oxford Instruments and STFC (and its predecessors[35]) have collaborated over many decades on topics including superconducting wire and magnets, particle accelerators and applications of cryogenic technology. Some of the resultant benefits are discussed below.

J.2 The Early Years

From the early 1960s, fundamental research was being carried out at STFC's Rutherford Appleton Laboratory (RAL) investigating how superconductivity could be applied to particle accelerators. From this work, much of it led by Martin Wilson, emerged a means of fabricating superconducting wire to make them practical for scientific and industrial use. This unique cable design is now known worldwide as a 'Rutherford Cable'. Some of the RAL research, particularly on means of joining superconducting wires, was an important enabling technology for Oxford Instruments' NMR and MRI businesses. The image below shows the first superconducting magnet manufactured by Oxford Instruments around 1962.

Figure 44 - The first superconducting magnet manufactured by Oxford Instruments



[35] In this document, STFC should be understood to mean the Science and Technology Facilities Council and its predecessor bodies including the Science Research Council (SRC), the Council for the Central Laboratory of the Research Councils (CCLRC), the Particle Physics and Astronomy Research Council (PPARC) and the Science and Engineering Research Council (SERC).

The significance of the work was summarised by Martin Wilson:

> *"I think it is fair to say that the development of filamentary wires by Rutherford … revolutionised the superconducting magnet business."*

In the mid-1980s, Oxford Instruments entered a lengthy and intensive collaboration with RAL and Daresbury Laboratory to allow the company to develop a product for IBM known as Helios – a compact accelerator that was intended to show how x-ray lithography could allow higher performance in semiconductors. Although further anticipated business did not materialise, the expertise gained was used to underpin Oxford Instruments' beamline business.

In a collaborative project which began its design phase in 1987, Oxford Instruments designed, constructed and supplied superconducting magnets to the Synchrotron Radiation Source (SRS) at Daresbury, expanding the range of applications to which the SRS could be applied. As an indirect result, research facilities, many of them overseas, purchased similar magnets for their synchrotron light sources.

J.3 Current Collaborations

Oxford Instruments is a key supplier to STFC's ISIS neutron scattering facility and Diamond Light Source, providing superconducting magnets to extend the capabilities of these two major international facilities. The design and manufacture of these magnets has been carried out with considerable exchange of knowledge between the facilities and Oxford Instruments.

The liquid cryogens required by the current generation of superconducting magnets is becoming increasingly expensive, and Oxford Instruments has invested considerable resource in cryogen-free refrigeration. ISIS has collaborated with Oxford Instruments to design and test this dry cryostat technology. As a result Oxford Instruments released a product in 2013 **called, ISISstat, which is being marketed for other neutron scattering experiments.**

Figure 45 - ISISstat

J.4 Looking to the Future

Collaborative, forward-looking programmes continue to involve both Oxford Instruments and STFC, for example:

- A joint project between Oxford Instruments, the Hitachi Laboratory at Cambridge, and STFC is developing platform technology for quantum computing, which could revolutionise computer performance. It uses Oxford Instruments' world-leading, cryogen-free refrigerators, which can reach extremely low temperatures.

The early research has also contributed to a major international programme:

- Nuclear fusion technology is being explored at ITER, a European experimental facility being constructed at Cadrache in the south of France. If successful, nuclear fusion will offer almost limitless energy, but practical applications are still very many years in the future. The process being used at ITER requires very strong magnetic fields, and Oxford Instruments won a major contract to supply superconducting strands to ITER. Although the structure of this strand has evolved considerably since the earliest multifilamentary wire designed by Martin Wilson and his colleagues at RAL, the design can still be seen as a long-term beneficiary of the innovations made there.

J.5 Direct Economic Impact

Listed below are examples, quantified where possible, which illustrate how contributions from STFC have led to direct economic benefits for Oxford Instruments. Throughout, it should be recognised that whilst significant research breakthroughs were made within STFC, it was only by the application of substantial development by Oxford Instruments and its partners that those inventions could be commercially exploited by Oxford Instruments.

It is estimated by the authors that over the last 40 years, technology which has had its origins in, or has been assisted by STFC has contributed to Oxford Instruments' product and service mix by at least £100 million of the company's revenue. This includes:

- Sales of the Helios lithography equipment to IBM, valued at about £18 million
- Sales of magnets and associated equipment directly supplied to the SRS, Diamond Light Source and ISIS Neutron Scattering Facility (all funded wholly or partly by STFC) amounted to more than £2 million
- Oxford Instruments' beamline business, which drew on expertise gained in the development of Helios, is estimated to have generated revenue of £20 million to £30 million over 5 – 10 years
- Building on the success of the sales to ISIS, Oxford Instruments has supplied similar equipment to comparable research institutions overseas, with benefits to Oxford Instruments revenue stream and the UK's balance of trade

In addition, it is estimated that the supply of superconducting wire to ITER, the nuclear fusion research facility, has contributed more than £30 million in revenue to Oxford Instruments. The design of such wire has developed greatly from, but still has its origins in, the early research at RAL.

J.6 Wider Social and Economic Impact

Collaborations between Oxford Instruments, STFC, academia and other companies have contributed to wider and indirect societal and economic benefits as well as the direct mutual benefits achieved by Oxford Instruments and STFC described above.

Although Oxford Instruments sold its share of the Magnetic Resonance Imaging (MRI) magnet business in 2003, the company was a significant early force in a business which now makes a direct value-added contribution to UK GDP of about £111million and supported 2,200 jobs in its supply chain in 2010. The cumulative contribution of the industry to UK GDP in the years 2011 – 2015 is estimated[36] by Oxford Economics to be of the order of £300 million, with over 2.5 million MRI scans performed in the UK each year. In addition, MRI has led to improved healthcare through its special capabilities in imaging soft tissue, particularly important for the diagnosis and treatment of conditions such as cancer and dementia. The Oxford Economics study also estimates that the economic impact of the availability of MRI for just one common condition (surgical treatment of prolapsed discs) is estimated to be around £166 million per annum.

Facilities, some funded by STFC, used Oxford Instruments' superconducting technology to support drug discovery, disease investigation and similar life-enhancing scientific developments.

The work at the SRS, using Oxford Instruments' magnets, allowed investigation of environmentally significant issues such as the determination of arsenic in plants and water, and the treatment of radioactive waste.

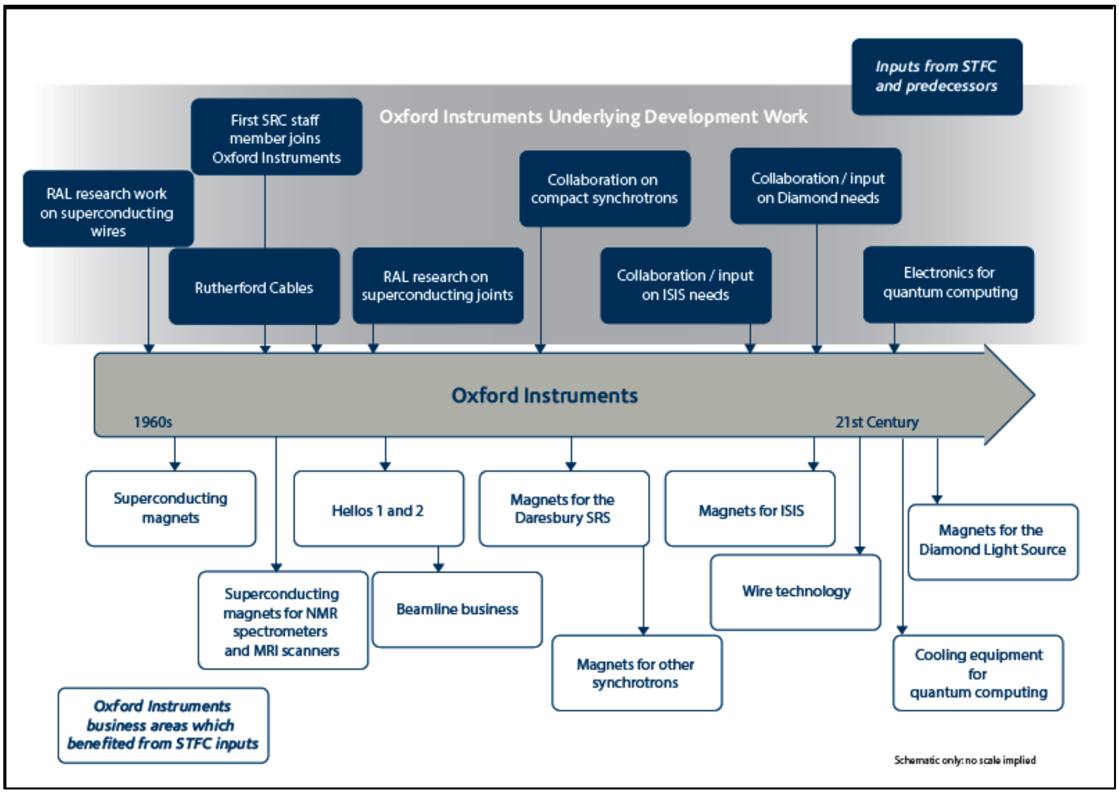
More generally, Oxford Instruments has invested in widespread public engagement and involvement including numerous publications, and 14 Queen's Award for Enterprise, seven of which related to technology described in this study. Many staff have also transferred between Oxford Instruments and STFC, including Martin Wilson, whose work was highly significant in making possible the commercial use of superconducting magnets.

J.7 Schematic overview of the OI and STFC relationship

The diagram below shows, in schematic form, a number of the inputs from STFC technology which have benefited elements of Oxford Instrument's business. This diagram does not show direct cause and effect, nor indicate magnitude of the inputs or outputs. It does show the multi-faceted nature of the co-operation over many decades, and the breadth of science and application areas made accessible by the two organisations working together.

[36] "The economic impact of physics research in the UK: Magnetic Resonance Imaging (MRI) Scanners Case Study", Oxford Economics on behalf of STFC (2012)

Figure 46 - Schematic Representation of STFC Inputs to Oxford Instruments



J.8 Conclusion

This case study illustrates how the UK's publicly-funded science base, coupled with the entrepreneurial technology-based companies such as Oxford Instruments, can result in visionary, world-beating technology, with consequent powerful economic and societal benefits.

Oxford Instruments has benefited by exploiting early stage, intrinsically high-risk, technology from early STFC research which had an uncertain outcome, unquantifiable benefits and no guarantee of any financial return at its conception. In turn, STFC has benefited from Oxford Instruments' growing capabilities not just in magnet research, but also in, for example, cryogen-free refrigeration. It is estimated by the authors that Oxford Instruments have gained a cumulative financial benefit in excess of £100 million, though it could be considerably higher.

The science emerging from the combined efforts of Oxford Instruments and STFC has been applied to a remarkably diverse range of uses, including elucidation of protein structures, design of novel materials and otherwise intractable medical diagnoses. The most notable impact from the collaboration has been the development of MRI technology, which has supported an industry which makes a direct value-added contribution to UK GDP of £111 million and supported 2,200 jobs in its supply chain in 2010. MRI also has significant social impact with 2.5 million scans performed in the UK each year, it is a key tool in the imaging and treatment of many conditions.

Oxford Instruments continues to be a significant supplier to STFC, using its expertise to expand the capability of some of STFC's large facilities – a collaboration which continues to the present day. It is expected that the societal benefits resulting from applications of these technologies will continue to be significant for many decades to come.

Appendix K Further information on training and education at ISIS

K.1 Education and training activities at ISIS

Figure 47 presents an overview of ISIS's main strands of education and training activities along with information about the type of beneficiary (e.g. PhD student), duration of the activity and the numbers of beneficiaries. The table distinguishes between ISIS schemes (e.g. the Neutron Training School) and STFC schemes that ISIS makes full use of (e.g. STFC Graduate Training Scheme).

Figure 47 – Summary of ISIS Education and Outreach activities

	Beneficiary Type	Years Running	Running time	No. beneficiaries over ISIS lifetime	Estimated beneficiary days over ISIS lifetime
ISIS Neutron Training School	PhD/postdoc	8	7 days	~ 192	~ 1344
ISIS Muon Training School	PhD/postdoc	9+	5 days	~ 162	~ 810
ISIS supervision of PhDs	PhD		3-5 years	~ 300	~ 1500
ISIS conferences and seminars	Various		Various		n/a
ISIS / Oxford Teacher Training	Teachers	1	1 day	~ 23	~ 23
STFC Graduate Training Scheme	Graduates	5?	Permanent	~ 25?	n/a
STFC Sandwich Student Placements	U/G	?	1 year	?	n/a
STFC Apprenticeships	Post-16	22	4 years	~ 57?	n/a
STFC Summer Placements	UG	?	4-12 weeks	?	
STFC Particle Physics Masterclass	A/AS Level	9	1 day	?	~ 5400

We have obtained estimates of the numbers of people attending or graduating where we can; we have gone on to reflect on a method for valuation, perhaps using market prices for courses or a cost-based approach to other educational support activities, where we have salary details and estimated mentoring inputs by ISIS staff. The results are not especially clear cut, however, where we have found pricing data, for summer schools for example, we see charges that range from around £100 a day for Oxford's neutron summer school through to £300 a day for non-academics attending statistics courses. The price – and cost of delivery – will vary depending upon the educational programme in question, with post-16 apprenticeships for example costing rather less in proportionate terms as compared with PhD supervision. As a first approximation, with ISIS staff delivering somewhere in the range 500-1,000 days of education and training support each year, we would argue that contribution might be conservatively priced at between £100K and £200K. If we assume ISIS has delivered on average 500 training days each year over its lifetime, working with the lower number in our range to reflect the facility's expansion over time, at an equivalent price of £200 a day, we arrive at a total estimate of £3M.

The table does not capture ISIS's most widespread contribution to skills development nationally, which is the 'on-the-job' training that early career researchers (postdocs and doctoral students) gain working alongside their senior academics and ISIS scientific staff. This type of capacity building is judged to be 'significant' by the very great majority of the respondents to our academic survey. From this perspective, ISIS is delivering many thousands of days of 'on-the-job' training to research students and post docs each year: post-docs and doctoral students constitute the great majority of all ISIS scientific users (i.e. 1268 of 1,412 scientific users in 2012/13, or c. 90% of the total). To monetise the value of their facility-enabled training delivered by ISIS scientists (in addition to the post docs' professors and academic co-workers), we assumed an average of 1,000 post docs / students have received the equivalent of 5 days experimental training each year at a unit price of £200 a day, which gives a figure of £30M across ISIS's 30-year lifetime.

ISIS has a strong training offer for staff, too. It is varied and unusual and compares well to industry schemes. This makes the individuals very employable (by others).

Returning to the table, it is clear from this analysis that ISIS has a broad educational programme, which has engaged many hundreds of students and scientists over the past 30 years. The neutron and muon training schools are well established and internationally recognised, with places heavily oversubscribed. ISIS has also added new initiatives along the way, with a new Teacher Training School picking up on the latest thinking about science education and the need to support teachers, as well as addressing students directly. The subsequent paragraphs describe each of these activities in a little more detail.

Neutron Training School

ISIS runs a Neutron Training School for PhD students and post-doctoral researchers with little or no previous experience of neutron scattering, but whose future research aims to make use of neutron scattering techniques.[37] The course is experiment-based and covers a number of topics, ranging from neutron scattering theory through to sample preparation and multiple diffraction and scattering techniques. There are optional modules too, to complement and build on the core topics, including computational methods and reflectometry.

The course is run once a year, typically with 24 students, and is seven days in length. The course is free to participating students and ISIS covers the costs of accommodation at Harwell and travel within the UK. Its hard to put a price on such a course, given the specialist nature of the people and facilities involved in its delivery, however, Oxford University runs a broadly comparable course (2 weeks, c. 85 students, more classroom based) and charges around £500 per person and the Canadians apply a broadly similar charge for their summer school.[38] These prices are substantially less than many other summer schools in the UK, which suggests that a figure of around £1,000 per person might be a more reasonable multiplier.[39] Moreover, each ISIS course is oversubscribed by a factor of five,[40] and produces strongly positive feedback from participants.[41]

K.2 Muon Spectroscopy Training School

ISIS has been running a Muon Spectroscopy Training School each year, since the mid-1990s, with the most recent training schools having been co-financed by the European Commission, through an FP7 research infrastructures grant, the EU Neutron and Muon Integrated Infrastructure

[37] http://www.isis.stfc.ac.uk/learning/neutron-training-course/

[38] The Canadian Institute for Neutron Scattering held its 12th Neutron Scattering Summer School at Chalk River on June 2 - 7, 2013. The school was organised by the Canadian Neutron Beam Centre and there was a fee of Can$400. Oxford University also runs a (biennial) 2-week neutron school for those new to neutron scattering, which has 50 residential places and 10 non-residential places. The course covers the theory and practice of neutron scattering – and includes a visit to ISIS – but does not have the experimental intensity of the ISIS course. There is a nominal fee for the course, which for the most recent course (2013) was £520 (€640) per residential student. For non-residential students, the school fees are £220 (€270), which includes teaching materials, drinks reception and gala dinner.

[39] University summer schools typically charge rather more than £500, with the well-regarded Essex Summer School in Social Science Data Analysis charging around £1000 to academics for a 5-day module and £1400 for non-academics (www.essex.ac.uk/summerschool/). The London School of Economics charges similar prices for its various modules, like Factor Models in Time Series with Applications in Macroeconomics and Finance (www.lse.ac.uk/study/summerSchools/Methods/Mathematics-&-Statistics/ME111.aspx)

[40] 24 students accepted annually but ISIS typically received more than 100 applications for the scheme.

[41] ISIS is planning a survey of ~100 past attendees to the training school in 2014

Initiative (NMI3).[42] The school is one of two in the world and provides practical training for PhD students and postdoctoral researchers on the use of muons in condensed matter research. The topics covered during the school are designed to enable participants to gain maximum benefit from future facility time as well as improving participant's knowledge in related fields such as computing and cryogenics. This school also provides students with hands-on experience of working at a large international facility such as ISIS. The school is run for a total of 5 days and typically accepts around 20 students annually (22 in 2014) and consists of a series of lectures and practical experiments by students using the four muon spectrometers at the ISIS facility; each student is provided with the opportunity to perform two different experiments.

The course is free of charge: European support has increased the numbers of overseas students able to attend as well as bringing in guest lecturers from the various other leading muon research groups and facilities in the consortium (e.g. Professor Elvezio Morenzoni, LMU Laboratory Head at the Paul Scherrer Institute [PSI] in Switzerland).

K.3 PhD Supervision

ISIS scientists are encouraged to maintain various external links and a substantial proportion of staff hold visiting fellowships at leading universities and are often providing external supervision to one or more PhD students. We understand from the senior management team that ISIS staff are co-supervising around 50 PhD students currently, which would suggest that 200-300 doctoral students will have benefitted from the insight and advice of ISIS over the past 30 years. The current cohort of students includes many young scientists from all over the world (e.g. US, Canada, Australia, India, Japan, Brazil and South Korea) as well as students at UK universities.

K.4 STFC Graduate Training Scheme[43]

The STFC operates a Graduate Training Scheme as a means by which to provide its various facilities with access to a stream of talented new scientists and engineers to join the complement of facilities scientists operating the various facilities and instruments. The new graduates will have completed a Bachelors (2.1 or above) or Masters degree in a relevant science or engineering subject within the last 18 months to work at the Rutherford Appleton Laboratory or ISIS (ISIS typically takes 6 graduates annually). The GTS appointees have permanent contracts, rather than the short-term fixed contracts that would be typical for postdocs in universities, and each is assigned a personal mentor who helps them to develop and complete their own individual learning plan.

During the first two years of the programme graduates will work alongside other graduates to complete a programme of in-house training courses and workshops in a variety of personal and professional skills. Each graduate will also have the opportunity to complete a placement in a department other than their field to help broaden skills as well as their understanding of the organisation. In addition to this, graduates also have the opportunity to take part on a personal development programme, which involves working with other graduates on a corporate project, and spend several days and nights at sea learning to sail a Tall Ship. This provides graduates with the opportunity to develop key skills essential in their future career, including communication, leadership and team working.

[42] ISIS is one of 18 partners (one of eight facilities) involved in the Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy (NMI3), which aims to improve pan-European coordination of neutron scattering and muon spectroscopy research, by linking all the research infrastructures in these fields in Europe. http://nmi3.eu/

[43] http://www.stfc.ac.uk/1389.aspx

K.5 STFC Sandwich Student Placement Scheme

The STFC runs an Industrial Placement scheme. This offers undergraduates enrolled on a sandwich degree the opportunity to spend 12 months, working as a paid intern (c. £17K p.a.) at one of the STFC's several sites, Rutherford Appleton Laboratory (RAL), Daresbury or Polaris House in Swindon. We understand that ISIS has hosted a significant proportion of these interns over the years. The number of placements available varies year on year in line with project opportunities and include laboratory, media and software projects according to the facility's needs and the student's interest. For example, in 2013-4, 8 projects were advertised under this scheme, which included 1 media project, 3 software projects and 4 lab-based projects.

K.6 STFC Apprentice Training Scheme

The STFC has been running an engineering apprenticeship scheme – electrical, electronic, mechanical – in association with the Rutherford Appleton and Daresbury Laboratories for more than 20 years. During this time there has been an intake of 114 apprentices, split 48% mechanical, 35% electrical and 15% electronic.

Apprenticeships are four years in duration and involve attendance at Oxford and Cherwell College one day a week for the first year with the rest of the week spent in the laboratory. This provides apprentices with on-the-job training using the knowledge and skills of ISIS staff. Following successful completion of their first year, apprentices then spend the next three years working within various workshops at Harwell or Daresbury according to their chosen engineering discipline. At the end of the apprenticeship scheme, *all* apprentices are offered a job as a technician with around 50% of those new appointments being located at the ISIS facility.[44]

K.7 STFC Vacation Student Scheme

STFC Vacation Student Scheme provides undergraduate students with an opportunity to do a summer placement at one or other of its laboratories or technology centres for a period of between 4 and 12 weeks. ISIS is a major supporter of the scheme and provides 3-5 students each year with the opportunity to work on projects and gain practical experience relevant to their intended or current courses of study under the supervision of experienced ISIS staff in their chosen field.

School and work experience placements are also offered to GCSE students and ISIS typically takes 2-3 students annually to work on small projects typically 2-3 weeks in duration.

K.8 ISIS Teacher Training

The first Teacher Training School was run in 2013 and brought 23 trainee teachers from the University of Oxford's Department of Education to ISIS to hear from scientists on topics ranging from spider's silk, catalysis and magnetism to the latest in hydrogen storage and the effects of cosmic rays that they can then transfer to the classroom. The day was concluded by an explanation of how the ISIS accelerators work, a tour of the experimental areas and the opportunity to look at demonstrations of some of the physics involved in producing and using neutrons.

[44] Of the 76 apprenticeships completed during the period 1992 – 2009, nearly two-thirds (65%) are still in full time employment with STFC.

K.9 Particle Physics Masterclass

The ISIS facility takes part in the STFC's annual Particle Physics Masterclass, which typically attracts around 600 'A' and 'AS-Level' students. The aim of the event is too inspire students to pursue careers in science, technology, engineering and mathematics by providing them with 'real-life' experience of a working research centre. The event includes a mixture of talks given by researchers and a practical session including a computer workshop, which uses data from the Large Hadron Collider at CERN in addition to a tour of key facilities at ISIS.

K.10 Seminars, Conferences and Workshops

Seminars are run on an informal basis (normally several run a month) and cover condensed matter physics (experiment and theory), chemistry, neutron and muon instrumentation and other related subjects. ISIS is involved in and hosts a number of national and international conferences and workshops annually which attract researchers from all over the world.

K.11 Lecturing

A review of staff activities in 2011-12 found that they hold around 20 external positions at universities such as visiting professorships or other appointments. A number also give individual talks at external student events or contribute to university lecture courses. This is in addition to the help they provide with the various formal training schemes mentioned above (training schools, etc.).

Appendix L Siemens, ISIS and the ONIAC facility

L.1 Introduction

This case study describes a facility that was built at ISIS Target Station 2 in 2009 by Siemens, a large multinational engineering and electronics PLC headquartered in Germany with a strong base here in the UK. Siemens employs 370,000 people across 190 countries with global revenue of €78 billion. In the UK, Siemens' reported sales of around £3.3 billion and employment of 13,700 people in 2013.[45] Siemens has 30,000 employees worldwide working on its research and development programmes, with a budget of over €4bn.

L.2 Background

Siemens originally started developing technologies for proton therapy in 2008 with the high-energy components developed in Germany and the low-energy parts in the UK. Although Siemens eventually decided to pull out of proton therapy systems, it identified an alternative market opportunity for the budding technology: generation of radioisotopes for nuclear medicine. Siemens had defined the concept and started building a compact, energy efficient, low-cost particle accelerator inside the company's research facilities at Roke Manor (the former Plessey research labs in Hampshire) in 2008. They successfully tested the electrical configuration and vacuum performance of the system by 2010, but then needed to build the ion source and accelerator unit. Siemens' R&D capabilities were reaching their limits and the team started to look for a specialised facility to continue with the accelerator phase of the project.

BIS encouraged Siemens to approach the STFC about hosting its test equipment in order to continue developing the novel accelerator. STFC's ISIS facility is the home to a large proton accelerator. However, Siemens wanted to use the available radiation-shielded space in the new Target Station 2 and the highly skilled staff at ISIS rather than to gain access to the actual beam line. STFC was enthusiastic about developing the new technology and worked closely with Siemens to build the shielded bunker (the "white box") to host the test equipment within 3 months.

L.3 Technology for medical diagnostics

The aim is to build a prototype of a spherical tandem electrostatic accelerator that produces a 10 MeV proton beam in the smallest possible volume using an H-ion source, DC high voltage generator and a stack of concentric electrode shells, like an onion, hence the name ONIon ACclerator or ONIAC. The accelerated proton beam will be used to produce radioactive tracers for medical diagnostics. The production of such radioactive tracers is currently performed by central cyclotron facilities, which are large, heavy, complex and expensive to maintain. Siemens' proposed technology is potentially revolutionary and could provide a simple, lightweight alternative to current technologies. The challenge is to deliver the fast decaying radioactive tracers to hospitals in time for use.

For the medical diagnostic tool, positron emission tomography (PET), C-11 radioactive tracer would be ideal as it can naturally be incorporated in a biological molecule. However due to its short half-life (20 min), onsite production by a cyclotron would be necessary, which most hospitals

45 http://www.siemens.co.uk/en/about_us/index/facts_and_figures.htm

cannot afford. An 'unnatural' alternative is to use fluorodeoxyglucose (F-18) (with a half-life of 2 hours) that Siemens currently distributes to hospitals through its PETNET.

Technetium-99m (TC-99m) it the most commonly used radioisotope (est. 80% of scans globally) that can be imaged in tumour cells by single-photon emission computed tomography (SPECT). Due to TC-99m's short half-life (6 hours), it is Molybdenum-99 (Mo-99) that is supplied to hospitals (which can be used to produce TC-99m locally), currently generated in (ageing) nuclear reactors. In the late 2000s, however, the two reactors (Chalk River in Canada and Petten in Holland) that provide over 70% of the global supply of Mo-99 had to be shut down simultaneously, causing worldwide shortage of medical radioisotopes for several months.

L.4 ISIS – Siemens knowledge exchange

When Siemens sold off their proton therapy system, it also sold off the corresponding expertise with it. The small Corporate Technology group developing the novel electrostatic accelerator had defined the product concept, but they were not experts in all the areas required for a successful delivery of a 'proof of principle' prototype. Siemens had to find experts to collaborate with and identified the UK as being open to such collaborations in 2010. ISIS was seen as a unique 'ready-made' integrated facility with favourable rates to lease radiation-classified space and highly skilled workforce to help develop the novel particle accelerator technology. (Siemens also supports PhD students at various universities through CASE awards with STFC for radioisotope chemistry). There are currently two Siemens and two ISIS research engineers working on the project, part time, using preferred contractors. In addition, ISIS technicians provide vacuum, electronic and mechanical support when required. Siemens pays rental for the facility, covers the cost of staff time and covers the cost of any resources used on the experiment.

Professor Paul Beasley, Head of Strategic Development at Siemens Corporate Technology, says that there is always pressure to locate Siemens research in Germany. However he believes that Siemens could not get the same level of support in German national facilities as they do at ISIS in the UK. He thinks that industry input to a national laboratory is mutually beneficial. STFC is getting a first hand view of some of the intellectual property and novel technologies developed by Siemens, and can show interest if they want to engage in any other projects. On the other hand, Siemens can develop and test new ideas rather quickly in close relationship with STFC and utilise their existing expertise in ion sources and radio frequency (RF) technologies. Siemens certainly took seriously the partnership with senior managers from Siemens Healthcare visiting the ONIAC facility in 2012.

Building relationship with a leading engineering company is beneficial to ISIS, agrees Dr Dan Faircloth, the ONIAC project manager at ISIS. Supplying ISIS technology to industry demonstrates that it is a commercially-relevant user facility. Technologies developed through this project could ultimately enhance the performance of ISIS and provide value to the broader UK scientific community. As an example he mentions the diamond-like carbon (DLC) coating that is currently being tested on ONIAC. Dr Faircloth believes that engineers at ISIS benefit from applied science and learn through the R&D process. It also contributes to personal reputation working with Siemens, and, not the least, the joint project, if successful, will ultimately deliver benefit to society.

In addition, the ISIS-Siemens partnership is having a direct impact on UK businesses beyond STFC. Over 80% of the manufacturing for the ONIAC facility is contracted from UK companies; mostly locally in Oxfordshire, but the highly specific shells for the ONIAC facility were precision cut by laser in North England.

L.5 Future

Siemens measures progress of an R&D project using technology readiness levels (TRL) 1-9. The ONIAC project is currently at technology development phase (TRL 4), having completed the bulk of basic technology research and feasibility study. It is hoped that a prototype will be available in the next 3 years that will demonstrate the full opportunity of the project. However new components are still needed for the accelerator system and discussions with the STFC research network and others are already underway to complete the project. It is foreseen that the collaboration on the ONIAC facility will result in a Master Research Agreement between STFC and Siemens in the near future to extend partnership to other high-risk projects, such as developing solid-state microwave generators or solid-state drives.

L.6 Economic impact

It is not possible to determine an economic impact attributable to this collaboration with ISIS, in part because Siemens is looking to develop a product that does not yet exist in the market and in part because at this time and stage of development, the novel accelerator's technical and economic feasibility is still to be determined.

The new compact accelerator system designed by Siemens and under development at ISIS is intended to arrive at an affordable solution for any hospital and thus transform the economics of the onsite production of radioisotopes for medical diagnostics. This kind of distributed system doesn't exist presently, albeit Canada's TRIUMF facility believes it has an upgrade package that can be 'bolted on' to existing local cyclotrons in Canada, which are powerful enough to be used to manufacture certain types of isotope (e.g. TC-99m). There is an assumption that these distributed production facilities might cost a few million US, and so would be affordable for individual larger hospitals or groups of hospitals.

The global market for radioisotopes was valued at around $US 4 billion in 2012, and is expected to grow steadily at 5-10% a year over the next five years, driven by the increasing use of PET and SPECT scanners and patients growing awareness of the powerful diagnostic and medical applications. There are limiting factors, most notably the short-half life of the materials and stringent regulations. The materials are mainly supplied by five large, government-owned reactors, with Canada's Chalk River reactor supplying almost 50% of global requirements.

Chalk River will close in 2016, and the US government has launched a competition to identify novel production systems that can replace the conventional reactor source (the US has no domestic production of medical isotopes), with high-energy proton accelerators and cyclotron's as the main approaches being developed. These methodologies are similar in many ways to the Siemens strategy, and would all provide the basis for more distributed production of isotopes. Supply shortages is expected to increase the unit cost of the reactor-derived isotopes, providing more headroom for the novel technologies, however, there is no clear view on the economic feasibility of this approach. The main players are in the US, where the anxiety of reliability of supply is greatest and where very substantial funds have been invested in tech startups like Shine and Northstar, however, while the startups are raising tens of millions in investment finance, several large global businesses (e.g. GE, Babcock and Wilcox) have closed down the development projects due to uncertainties over the economics of the technology and future business.

This very rough estimate of a unit price suggests that the global market for compact accelerators could quickly develop into a market with a value of hundreds of millions a year within the next 5-10 years, as rising prices for conventional isotopes helps tip the scale in favour of more costly /

novel production techniques. In the longer term, the greatest demand will be from developing countries, but for now, it is Europe and North America. We have no view of where Siemens' technology stands in the international pantheon of accelerator technology, however, even if it is successful, the new systems are likely to be made in Germany and exported to the UK and other countries. The main benefit for the UK (and other national health services) of local production will be in the reliability in supply of isotopes and some protection against rapid price inflation that is expected to follow the closure of several of the ageing reactors that dominate production currently.

STFC continues to play an important role however and will host an international conference on compact accelerators for isotope production, at Daresbury (March 26-27, 2015). There will be presentations by people from CERN, ILL, Siemens, STFC, TRIUMF and various UK universities.

Appendix M Economic impact assessment methodology and analysis

M.1 Immediate economic impact

The first tier of economic impact comprises three types of economic impact that arise as a result of the economic activity *(wages and profits)* generated by ISIS operations:

- **Direct impact** – corresponds to the employment and activity directly generated by the expenditure made by ISIS during the construction periods but also throughout its operation over the last 30 years in terms of Value Added. Following an income approach, VA can be calculated as the sum of compensation to employees (payroll), organisations' gross operating surplus and production taxes (net of subsidies) in a given year. Production taxes on employment of labour, the ownership and use of buildings or other assets used in "production". Put differently, VA accounts for final income and excludes the purchase of any intermediate goods and services. Given than ISIS does not operate with profits, its VA can be approximated by the value of the payroll, i.e. overall staff costs, which include taxes to labour.
- **Indirect impact** – corresponds to the employment and activity supported down the supply chain as a result of the purchase of goods and services from its suppliers.

  Again, we will need to calculate the Value Added generated by those suppliers. Calculating value added is more complex in this case as it is not possible to obtain data on wages, profits and production taxes that are strictly related to the expenditure made by ISIS as a result of the purchase of goods and services. A sound approach to calculate VA is to estimate the income/turnover that flows from ISIS to its supplier and use secondary data that estimates the ratio between VA and turnover for all the economy. This data is published at regional and industrial level by the ONS.
- **Induced impact** - corresponds to employment and economic activity supported by those directly employed in ISIS and employed by their suppliers who spend their wages and salaries on goods and services in the wider economy. This, in turn, helps to support jobs in the industries that supply these goods and services (e.g. retail industry, banking sector, etc.). This final induced effect can be calculated using income multipliers. Ideally one would estimate these benefits using a bespoke input-output table for the different economic sectors and geographical areas covered by ISIS and its suppliers. However, creating such a complex framework would be far beyond the scope of this study the practicable solution, used in many cases, is to make use of the standard output and employment multipliers calculated made available in secondary sources, such as the ratios published by BIS.

It is important to note that these immediate (or first tier) financial impacts apply to *any* area of public expenditure, irrespective of economic sector and irrespective of the value of outputs, i.e. the goods and services resulting from the expenditure. The impacts from these three categories may be similar whether the expenditure is undertaken to address an important social need (such as education, healthcare or defence), or for activities with a more indirect benefit to society (such as R&D) (Technopolis, 2012).

M.1.1 Estimating induced impact using multiplier effects:

As explained above multipliers will serve to estimate the induced effect of economic impact generated by ISIS.

Multipliers are estimated using input-output (IO) tables. An IO table of a given industry is a matrix that maps all the sectors that participate in the supply chain of that industry (or segment of that industry) and quantifies the purchases of good and services that they make one to the other. It also estimates the number of employees that are part of the full supply chain.

We will rely on the information provided by BIS (2009c), which is based on the results obtained from different exercises on impact assessment for different type of interventions.

Figure 48 – Multipliers

	Number of obs.	Lower end range %	Upper end of range %	Mean %	Median %	+/- at 95% Conf level
Regeneration through physical infrastructure	**80**	**1.00**	**3.25**	**1.40**	**1.39**	**5.9**
Capital projects	41	1.00	3.25	1.42	1.39	10.8
Public realm	23	1.10	1.73	1.36	1.44	6.6
Transport	1	1.40	1.40	1.40	1.40	-
Promoting image/culture	6	1.30	1.73	1.55	1.57	15.2
Other	16	1.15	1.62	1.36	1.39	6.3
People and skills	**62**	**1.00**	**3.25**	**1.36**	**1.301**	**15.2**
Matching people to jobs	23	1.00	1.73	1.31	1.30	8.0
Workforce/skills development	26	1.00	1.60	1.32	1.30	5.9
Provision of level 3 or above qualifications	18	1.00	3.25	1.48	1.44	22.3
Supporting development of educational infrastructure	9	1.10	1.60	1.39	1.40	13.4
Other	6	1.10	3.25	1.59	1.33	72.4

Source: BIS (2009c)

M.1.1 Dealing with missing data

We have had access to almost complete time series for expenditure and employment spanning over a period of 30 years. The data presents some gaps and we will use standard methodology to fill up the missing data. For instance, in the case of income we will extrapolate a full time-series of income by (i) estimating the growth between missing years (e.g. 1993 and 2000) and (ii) assuming a progressive increase in each year for which data is missing. For instance, if income has increased by 45% between 1993 and 2000, then the estimated compound annual growth rate is 5.5% using the following formula:

$$\left(\sqrt[7]{Income_{2000} / Income_{1993}} - 1 \right) \times 100$$

M.1.1 Estimating attribution (from gross to net additional direct economic impact)

There are four elements or discounting factors that need to be taken into account when estimating the economic impact of any public investment programme. These elements and the methodology we explain below corresponds with the recommendations and suggestions made by the HM Treasury Green Book and the Magenta Book.

Deadweight

A key element when assessing the impact of a public investment is to understand what difference did it made. For instance, one needs to measure how different the final outcome (e.g. VA) would have been without the public investment. This is the so-called *counterfactual scenario*.

Put differently, we need to calculate what proportion of the outcomes would have happened anyway in the absence of the support provided by the public investment. That proportion is the deadweight factor.

In the case of ISIS, one can easily argue that the facility would not have gone ahead without the support provided by the government. Consequently the immediate impact, in terms of direct, indirect and induced economic activity, would have probably not been materialised.

Although is probable that employees will have been absorbed somewhere else in the economy, staff that is highly specialised will have been located in other similar facilities outside the UK (provided the UK did not invest in a neutron source at all).

Note that the concept of deadweight will also be applied to all different streams of impact included in our conceptual framework, including the effect on suppliers (innovative procurement) and the commercial and innovation impacts on industrial users.

Other discounting factors

The standard methodology also includes estimating other three key factors:

- Displacement - Extent to which the intervention/public investment has reduced other activities and benefits elsewhere in the economy.

  Displacement could happen when, for instance, public investment helps to support certain organisations and industries that compete with other players in the market. That support, while positive for the supported activities, could go in detriment of other organisations located in the same geography if they share the same market. In this case, the positive outcome could merely be a redistribution of market shares within the economy.

  Given the unique nature of ISIS we will assume that displacement is equal to 0.

- Substitution - Extent to which companies have substituted an activity or input for a similar one in order to take advantage of the support provided through ISIS.

  A proxy for this factor is usually calculated by asking supported organisations (in this case ISIS) if the support provided by a programme has resulted in them replacing one employee for another solely in order to take advantage of those benefits. Again, in the case of ISIS, this factor is not relevant, hence we will assume is equal to 0.

- Leakage – Extent to which does the public investment benefit those outside the geographical area of intervention. This factor is concerned with discounting any economic activity that takes place outside the 'area of intervention', in this the case the UK economy.

  To account for this issue ISIS has helped us to collect data on:

  1. *Number of staff* that are residents in the local area (i.e. Oxfordshire), elsewhere in the UK or abroad. At the moment, we only have information on residency for 2007. However, this information shows that only a small percentage of staff (6%) lives outside the OX postcode area or in a non-adjacent area. This means that the level of leakage outside the UK is equal to 0.

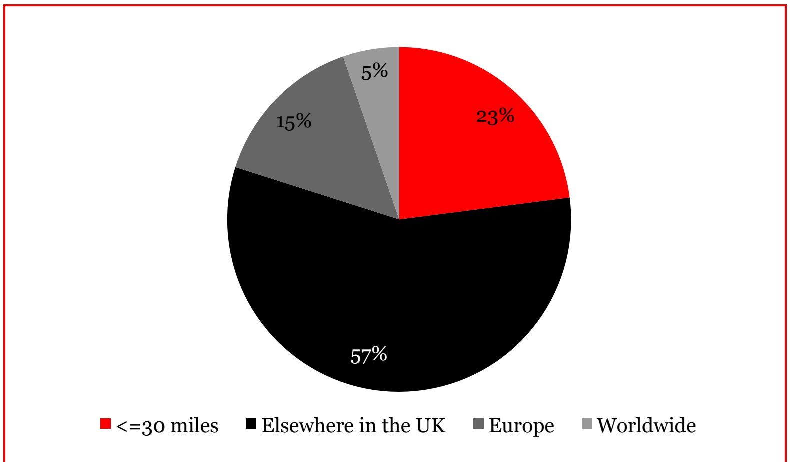
Figure 49 – Salaries by place of residence (2007)

Residence	Aggregate salary	% of total
OX11	£2,415,202.00	25%
Other OX postcodes	£5,209,847.00	55%
Adjacent to OX	£1,332,931.36	14%
Other	£521,797	6%

Source: SQW, ISIS

2. *Location of suppliers* – ISIS has also helped us to collect information on the expenditure made in the construction of TS2. A total of £35 million (excluding VAT) was spent on the construction of TS2 instruments[46] and Figure shows that 80% of that total expenditure was allocated to suppliers based in the local area (30 miles or less) or elsewhere in the UK (23% and 57%, respectively). This means that leakage of the indirect impact is small and this factor will be taken into consideration when estimating the immediate economic impact.

Figure 50 – Location of suppliers TS2



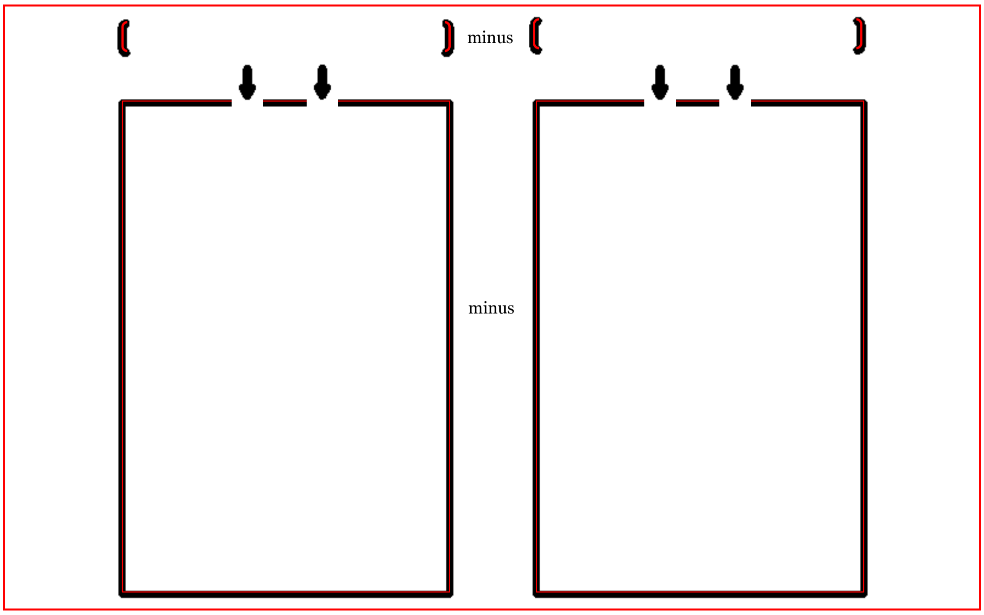
Source: ISIS

1.1.1.1 From gross to net effects

[46] The figures only correspond to expenses over £5K and do not include External Training, Copiers, Hospitality for visitors, Combined POs with companies totalling< £5kSelf Drive Cars, Fuel for hire cars, RAL Transport, Miscellaneous GPC transactions with companies totalling < £5k, STFC Telephony, and Poorly specified transactions.

Figure 51 shows a schematic representation on how the VA and these four factors are combined to get from *Gross* to *Net.*

Figure 51 - From *Gross* to *Net Additional* Direct Economic Impact



Source: Technopolis (2014), BIS (2009a, 2009b). *Gross impact, leakage, displacement and substitution of counterfactual scenario.

M.2 Estimations and analysis

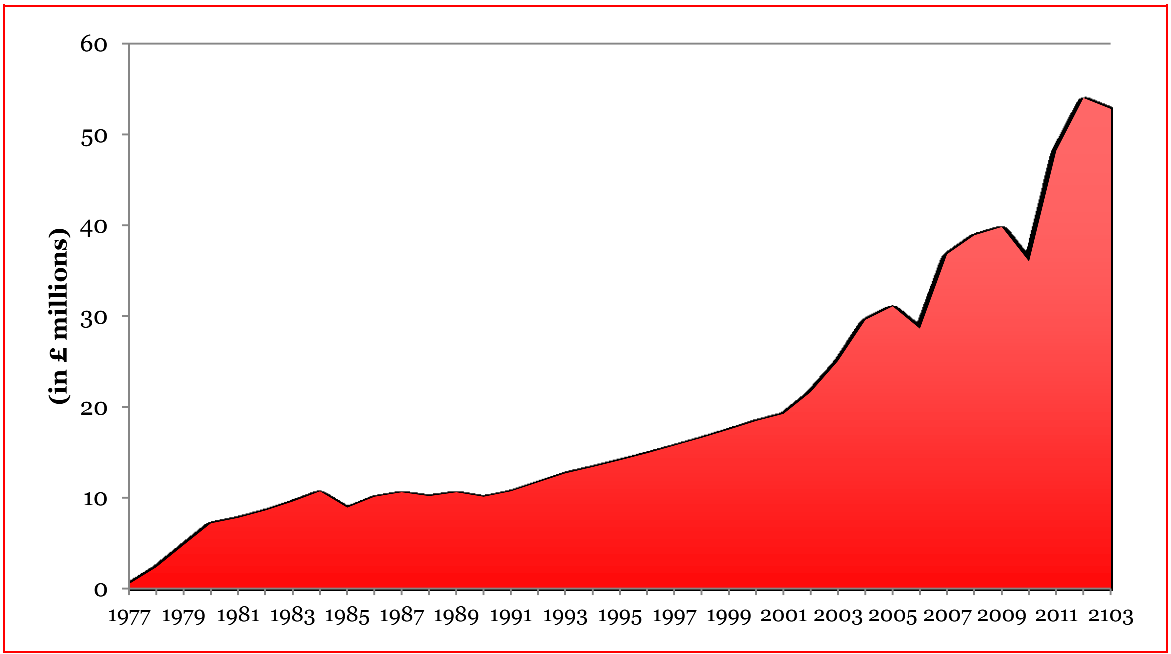
Income and expenditure

ISIS spent approximately **£700 million between 1977, when construction began, and the end of 2013.** Note that we use income as a proxy for expenditure for the period 1977-2003 given that it was not possible to estimate the time series for expenditure: ISIS has comprehensive records for income and for expenditure between 2004 and 2013, but annual expenditure data were not readily available for the earlier period.

Annual income/expenditure has increased steadily over the period, and showed a substantial increase after 2003 when the construction of TS2 started (2003), but had been building quite strongly in the mid-period before the implementation of TS2. This is due is to the development of new instruments and targets for TS1 (and subsequently TS2), and the energy requirements that the new state or the art instruments require.

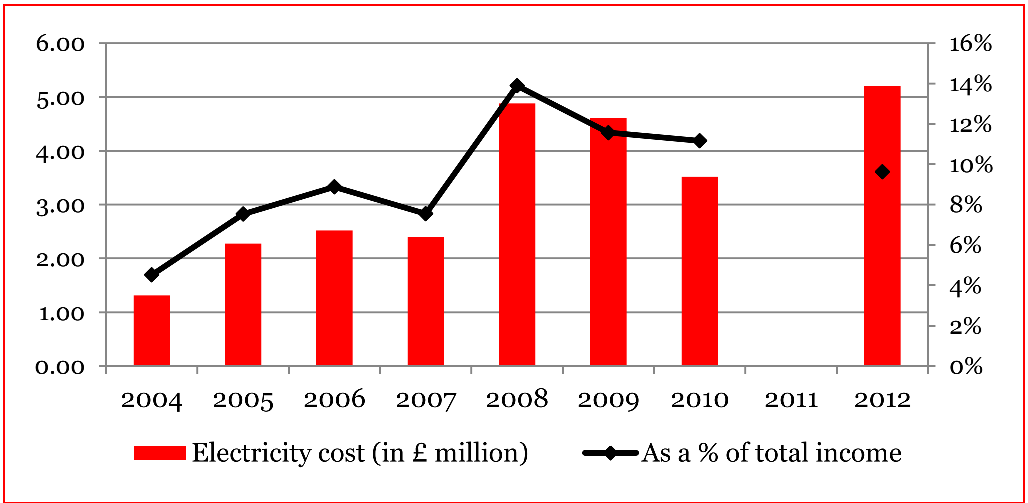
Figure 70 shows a steady increase in the relative importance of electricity costs over total income, between 2004 (5%) and 2008 (14%). This relative importance has decrease, though to 10% in 2012.

Figure 52 – ISIS annual income, 1977-2013 (non-deflated)



Source: Prepared by Technopolis with information provided by ISIS (2014). Figure from 2007-2013 correspond to expenditure (including operations and capital)

Figure 53 – ISIS electricity costs (£ million [cash terms] and % of total income)



Source: Prepared by Technopolis with information provided by ISIS (2014)

The UK government has provided the great majority of ISIS's £643 million in income, however, the facility also benefits from a steady flow of international investment of £2M-£3M a year.

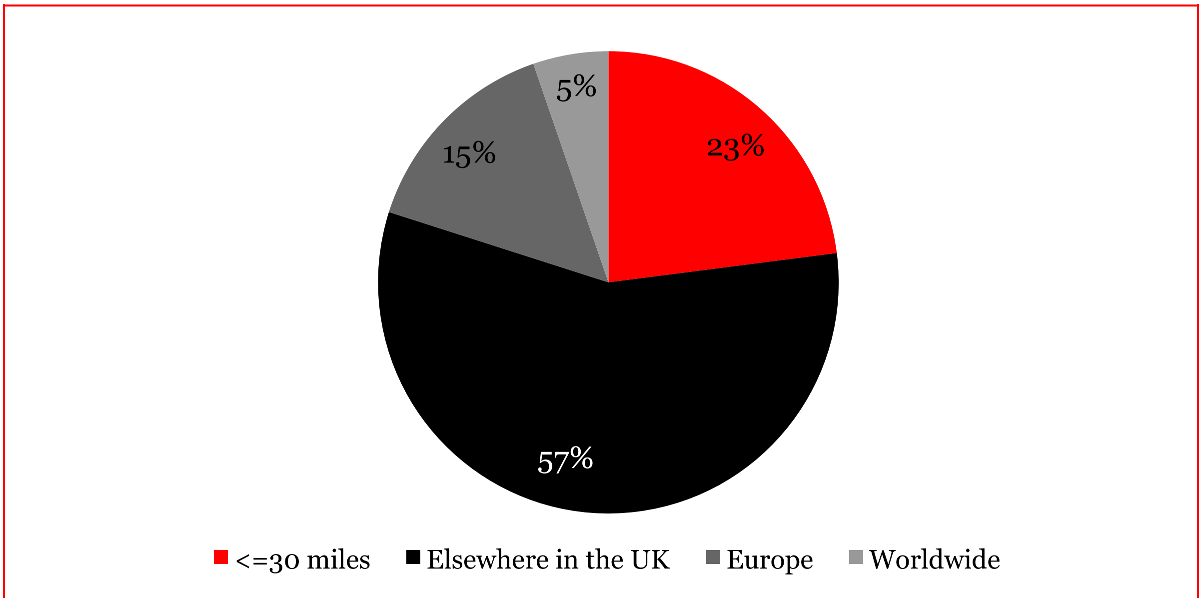
<u>Location of suppliers</u>

ISIS was unable to provide the study team with a complete historical record of its suppliers in a convenient digital form, and it was therefore decided to use the available (electronic) data about the suppliers to Target Station 2 as the basis for our geographical analysis of the facility's expenditure over the longer term.

On the assumption that ISIS's purchase of instrumentation and related systems would be the work packages most likely to produce spillover benefits and attract national and international competition, we chose to focus our analysis on the £41.5 million related to the purchase / construction of instruments for (2013, where the overall investment, including buildings and infrastructure, amounted to more than £150 million.

According to ISIS supplier records, **80% of the expenditure for the construction of instruments was spent with organisations with UK addresses**, either within the local area (<=30 miles from ISIS) or elsewhere in the UK (23% and 57% respectively). Figure 54 shows the distribution of purchases broken down by four broad territorial categories, with around a quarter of £42M of high value, complex purchases being won by contractors local to ISIS. This hints at the kind of local spillover benefits that derive from large science clusters like Harwell.

Figure 54 – Location of TS2 instrument suppliers



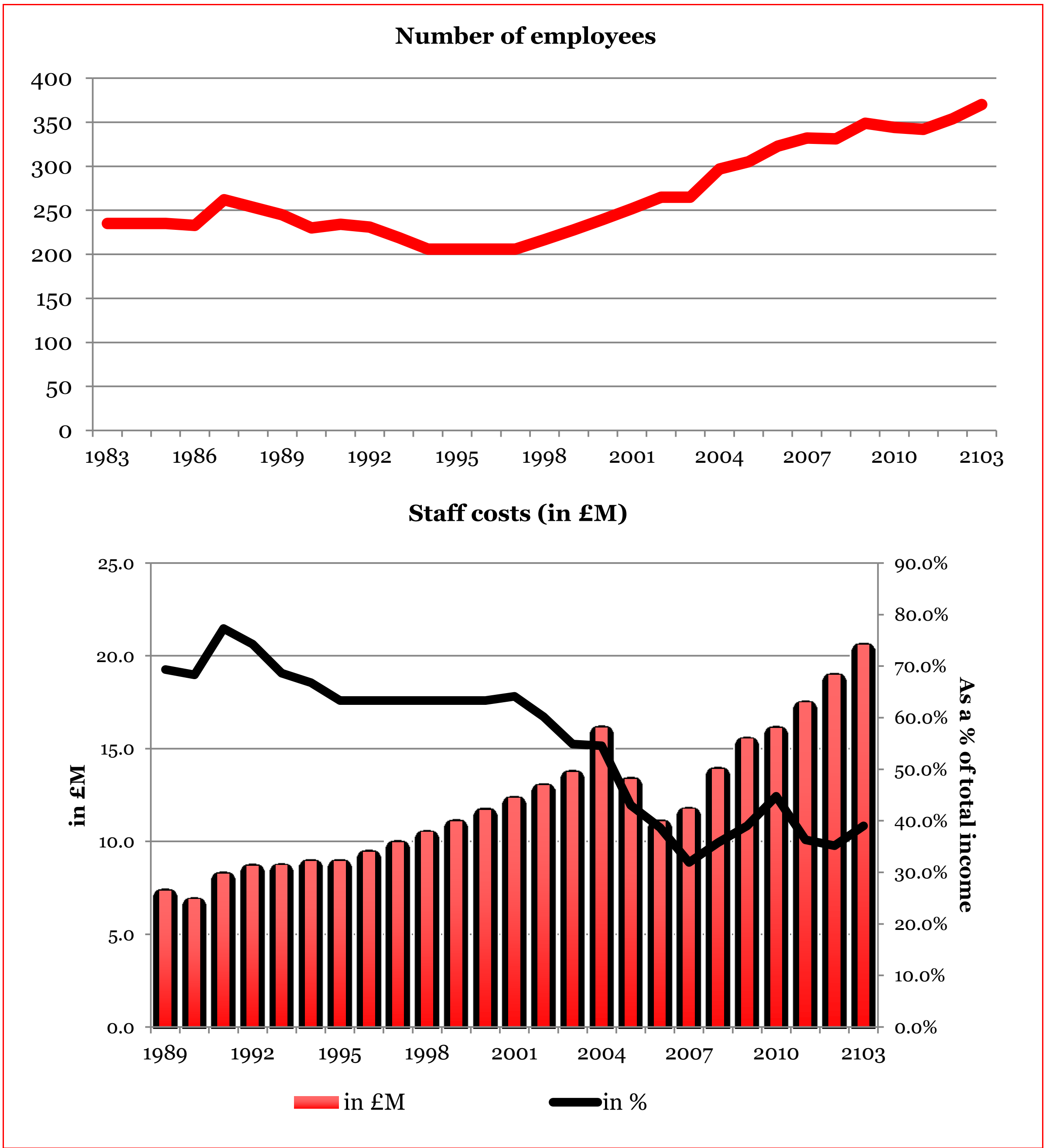
Source: Prepared by Technopolis with information provided by ISIS (2014)

Employment

ISIS currently employs around 370 people with most staff appointed on full-time contracts. Employment has increased gradually over time, from 200 in 1995 to current (2014) levels. Over the 30 years since its inauguration, **ISIS's total payroll costs amount to around £355 million** (in cash terms).[47] The relative importance of the payroll (staff cost) within ISIS's total expenditure has decreased over time, from around 70% of costs to 50%, driven in part by the lab's ability to administer a larger number of instruments with a proportionately smaller team of administrators, technicians and facilities scientists. The construction of TS2 has added a series of next generation instruments that require fewer personnel to operate, proportionately, helping to improve ISIS's basic labour productivity. As at 2014, the majority of employees (73%) belong to salary bands D-F (Figure 57) and the (weighted) average salary is c. £33K. Additionally, the majority of employees are male (Figure 58).

[47] We have information on payroll costs for around 15 of each of the past 30 years: 1989-1995, 2004, 2006-2010 and 2012. To fill the gaps between years, we used the approach explained in the methodology section. For the missing payroll information corresponding to 1977-1988, we used the information on income and assumed that the payroll was 69.3%, i.e., the percentage shown in the data for the year 1989.

Figure 56 – Employment (1983-2013)



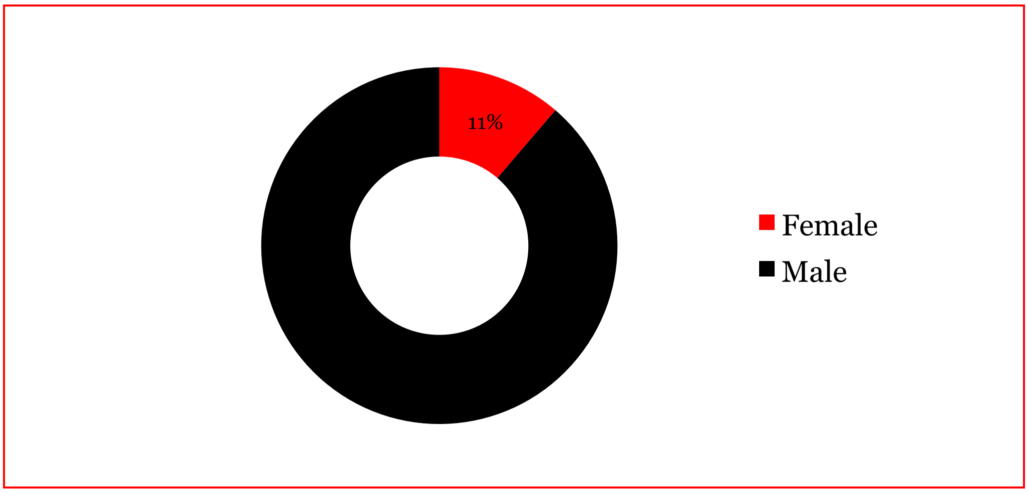
Source: Prepared by Technopolis with information provided by ISIS (2014)

Figure 57 – Employees, per salary band level (2014)

Band	Standard Pay	Percentage of employees under each band
B*	£18,222	4%
C	£23,442	19%
D	£29,566	29%
E	£37,534	31%
F	£47,521	13%
G	£60,627	2%
Senior	£75,359	1%
	(Weighted) Average	**£33,885**

Source: Prepared by Technopolis with information provided by ISIS (2014). B* includes 1 x Band A, Senior comprises Bands H, X and Y

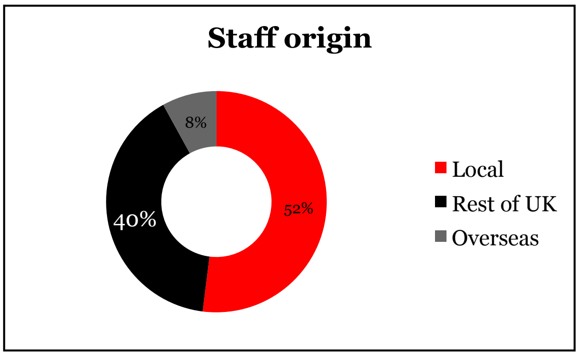
Figure 58 – Employees, gender balance (2014)



Source: Prepared by Technopolis with information provided by ISIS (2014)

The SQW report (2008) provides information on regarding personnel according the area of recruitment (in number of employees) and payroll per place of residence (see Figure 59). It is customary to use place-of-residence as a proxy for the geographical location where employees spend their salaries and, consequently, create a knock on positive effect on the local economy (induced impact). This assumption is perhaps overly generous as many staff will be home-owners with a substantial minority of total income going to mortgage repayments typically remitted to national banks and building societies rather than locally-based financial institutions. In any case, we see that 94% of all staff reside in Oxfordshire, or in a surrounding area. We do not have detailed information on the remaining 6%, but based on the overall distribution it is reasonable to assume that most of them reside within the UK.

Figure 59 – Distribution of ISIS staff by place of recruitment and current place of residence (2008)



Salaries by place of residence

Location	Pay roll (value)	Percentage
OX11	£2,415,202.00	25%
Other OX postcodes	£5,209,847.00	55%
Adjacent to OX	£1,332,931.36	14%
Other	£521,797	6%

Source: SQW (2008)

Immediate Economic Impacts

The direct impact of ISIS is measured as the Value Added of its activity, which can be approximated by the value of its gross payroll, including all elements of remuneration, including employer's NICs. Based on this approach, between 1982 and 2013, ISIS has had a gross **direct impact of £355.3 million.**

This implies a VA to income ratio of 54%, on average over the 30 years in which the facility has operated, a ratio (1:0.54), which is in line with the ratio for other analogous sectors of the UK economy, such a "professional, scientific and technical activities."

To estimate the total immediate impact, we need to make use of multipliers to quantify the further economic activity stimulated by ISIS's direct impacts. Multipliers take two principal forms: an income ("induced") multiplier, which is associated with additional income to those employed by the facility and a supply ("indirect") multiplier, which is associated with additional income due to 'local' supplier purchases (BIS, 2009). They are usually calculated using input-output (IO) tables, but that analysis was beyond the scope of this study. Instead, we have relied on the information provided by BIS (2009), which is based on the results obtained from numerous impact assessments for different types of public policy interventions. The *combined* multiplier for projects related to 'regeneration through physical infrastructure' is estimated at 1.40. This means a direct impact of £1M would have a final total impact (direct, indirect and induced) of £1.4M. Using this multiplier we estimate that the accumulated "Gross Intermediate Economic Impact" of ISIS to the UK Economy, over the last 30 years (1982 – 2013), is £497.4M. Furthermore, after applying the discounting factor related to the location of suppliers (we assume that 80% of suppliers are UK based), **we estimate that "the Net Intermediate Economic Impact" is £400M.**

Figure 60 – Immediate Economic Impacts (1982-2013)

	Calculations	£ Million (1982-2013)
Gross Direct (VA)	[A]	£355.3
Multiplier	[B]	1.4
Gross Indirect and Induced	[C]=[B]*[A]-[A]	£142.1
Total Gross Intermediate Impact	[D] =[C]+[A]	£497.4
Deadweight	[E]	NA
Substitution	[F]	NA
Displacement	[G]	NA
Leakage	[H]	80%(UK suppliers)
Total discounting factor	[I]=[E]*[F]*[G]*[H]	80%
Total Net Intermediate Economic Impact	[D]*[I]	**£397.9**

Source: Technopolis (2014)

1.2 Additional economic impact

1.2.1 Value of assets

We estimate that a total of £245 million has been invested in capital (building, instruments, equipment), based on capital expenditure between 2004-2013 and extrapolating those values to the entire life span of ISIS. Note that TS1 and TS2 have entailed an investment of circa £260M, however those figures include non-capital expenditure such consultancy projects with specialised engineering firms. As mentioned before in 1977, ISIS inherited buildings, equipment, power supplies and concrete 'shielding' blocks (together worth ~£130m) from NIMROD. If we take into account an annual depreciation of capital of 5%, in 2013 those assets have a value of £176M. Meaning that ISIS has maintained and capitalised those assets, with a combined balance sheet value of close to £200M that the facility can continue to exploit going forwards. We have not included the value of these assets in our formal impact assessment, however, it is important to remember that infrastructure has a retained value that enables relatively small recurrent / operational investments to deliver very much larger social and economic benefits.

1.2.2 Visitors' contributions to the local economy

In addition to user visits from researchers conducting experiments, ISIS also receives visitors throughout the year as part of their outreach activities. Based on information contained in the Annual Reviews, ISIS hosts 1,500 to 2,000 visits by non-users each year (see Figure 61). In 2013/14, these visits comprised 31% business visitors, 36% students (<18), 13% students (18+) and 20% other members of the public. These non-users tend to visit for the day in connection with business meetings or outreach activities, where they have the chance to learn about the research being conducted in ISIS. These visitors will each spend small sums in the local economy, for meals and local transport costs (e.g. taxis). Given the fact that many of these visitors will travel from outside the region, the costs of travel will tend to benefit other parts of the country or the UK overall (e.g. national rail).

Figure 61 – Annual number of day visitors (non-scientific users) to ISIS

Year	Day visitors (non-scientific users) to ISIS
2013	1,485
2012	1,861
2011	1,867
2010	2,002
2009	1,448
2008	886
2007	1,523
2006	1,335
2005	1,770

Source: Technopolis, extracted from ISIS Annual Reviews

There were almost 3,000 visits by around 1,500 scientific users in 2013/14, which is a typical number (a little lower than the previous year). Scientific users tend to visit ISIS for several days at a time, on average 6 days, and typically more than once in the period while their experiments are being run (c. 2 visits for every visitor, historically). These scientific users will tend to generate substantially more income for the local economy, as their stay will invariably include the cost of accommodation as well as expenditure on local travel and food while at ISIS. In the case of UK-resident scientific users, ISIS covers their travel and subsistence costs and this 'local economic contribution' is therefore already accounted for in the ISIS budget. International scientific visitors tend to bear their own costs, and while their major travel costs (e.g. flights) will typically be spent with carriers in the country of origin, their food and accommodation is a substantial expense that benefits Oxfordshire directly.

We have assumed that day visitors spend on average £20 a day (mainly on refreshments and local transport) each and that overseas scientific visitors spend around £780 for each visit, comprising accommodation and other subsistence and local travel, which suggests that ISIS visitors contributed around £0.75M to the local economy in 2013/14. If we use these estimates as the basis for estimating the total economic impact of ISIS visitors over the previous 30 years, we arrive at a figure of around £22M. Scientific and non-scientific visitor numbers have increased somewhat over the years, so given that fact and the other assumptions used in this calculation, we have included a figure of £20M in our overall estimate of ISIS's lifetime impacts.

Figure 62 – Visitors' contributions in 2013/14 and across ISIS lifetime

	Number of visits	Number of days (ave)	Economic impacts	Total (2013/14(	Total (1984-2014)
Day visitors	1,485	1	£20 per person per day for subsistence day	£29,700	£891,000
User visitors (researchers)					
National	1,945	6	UK visitors get their T&S costs paid for by ISIS so their costs are already included in the ISIS budget	£0	£0
Overseas	912	6	£100 accommodation / day £30 expenses / day	£711,360	£21,340,800
Total				**£741,060**	**£22,231,800**