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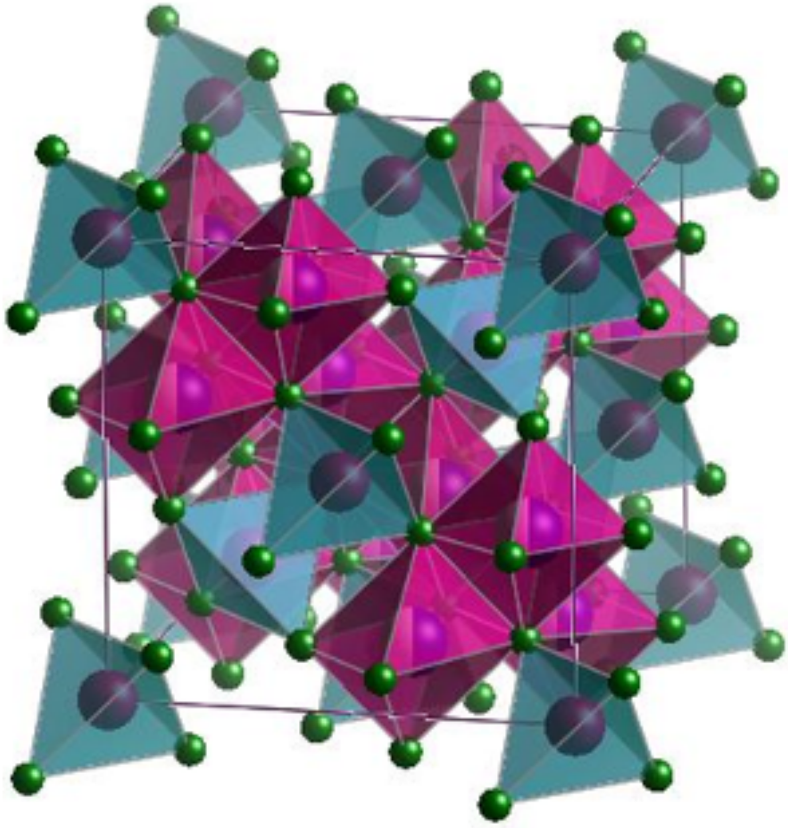
Neutron Science and Facilities

An Update to the 2017 Strategic Review

June 2020



Front cover: motionstock from Pixabay
Inner page: Crystalline structure of Co_2TiO_4, calculated using Neutron Powder Diffraction data from ISIS

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Executive Summary

In 2016/17 an independent panel carried out a Strategic Review of Neutron Science and Facilities on behalf of STFC. The Review made recommendations for ensuring that researchers could continue to access neutron sources in support of the UK's science and technology needs.

The status of neutron sources in Europe and across the world continues to evolve as older facilities close and new facilities and instrumentation are brought into operation. This report presents the findings of a panel commissioned by BEIS to carry out an update of the 2017 Review recommendations. This update will help ensure that the future neutron access strategy for the UK can continue to meet the needs of the research and innovation communities as well as supporting the UK's industrial strategy.

This update confirms that neutron techniques continue to be important research tools. They are being used for probing and revealing key characteristics and properties of materials and structures in many areas of the physical and biological sciences and engineering.

The UK's ISIS facility continues to be the most important source for most UK users. The update notes that the Institut Laue-Langevin (ILL) reactor source is now on a firmer operational footing and the prospects of ILL being able to extend its operations into the 2030's is brighter.

An important finding of the update is that the specification of the European Spallation Source (ESS), now at an advanced stage of construction in Sweden, has changed from that anticipated in the previous Review. At least in the initial phase of operation, the ESS power will be lower, reducing the total neutron flux, with a revised neutron moderator design to maintain the neutron "brightness". Achieving full operation of the initial fifteen instruments will also take longer than originally planned.

The update therefore recommends a neutron access profile that prioritises the ISIS facility and prolongs the use of ILL. This will mitigate against a slower ramp up of new capabilities at ESS. There is still likely to be a significant reduction in overall capacity from 2033 onwards. It is recommended that design studies for an ISIS replacement, together with research into laser driven sources, should continue as options for the long term.

The update also recommends a continued focus on enhancing the remote access capabilities for users at all the neutron sources. This will help to facilitate returning to full operations after the COVID-19 pandemic – as well as contributing to reducing their environmental impact.

It also recognises the increasing risk of an erosion of the specialist technical skills base in the facilities. If not addressed, this will impact on the operational efficiency of the facilities and the support that can be provided to the user communities in academia and industry – many of whom are not experts in applying neutron techniques.

Introduction

Neutron facilities enable unique experiments to be performed on the structure and dynamics of materials at the atomic scale, thereby underpinning a broad range of scientific disciplines, including physics, chemistry, materials science, biology, pharmacology, engineering, and the environmental sciences. Neutron techniques are used to address grand societal challenges (in energy, health care, the environment etc.) and provide innovative solutions for industry. The UK neutron user community is one of the largest and most active in Europe, supported by access to two world-leading facilities: the spallation source ISIS (the UK's national neutron and muon facility at the Rutherford Appleton Laboratory) and the reactor source at the Institut Laue-Langevin (ILL) at Grenoble.

As well as ISIS and ILL, there are several other neutron facilities world-wide. However, reactor-based sources are likely to reduce in number over the next 10 years (several having already been closed over the past 2-3 years) as they come to the end of their working life and regulatory pressures grow. At the same time, accelerator-based neutron facilities are being constructed or upgraded – e.g. in the US (SNS), Japan (J-PARC), China, and the next generation neutron source, the European Spallation Source (ESS) in Sweden (which the UK is contributing to).

In this changing international landscape, it is important that there is a clear direction in the UK for the appropriate level of provision of neutron facilities. This will guide future developments and access arrangements to align to the UK's key scientific objectives and maximise the broader benefits of neutrons to the UK science base and economy.

In 2016, STFC commissioned an independent review of neutron sources to begin to determine a future UK strategy[1]. In the light of the subsequent changes in neutron source operations and progress at the ESS, it is timely to update the findings of the previous review so that access arrangements and funding requirements can continue to meet the science, technology, and innovation needs of the UK's science and industrial user communities.

This update has been carried out by a panel appointed by STFC on behalf of BEIS, with the following terms of reference:

- Review and update the current and future science and innovation challenges that can be addressed with neutron techniques as identified in the 2017 report.
- Review the current status and future plans (in terms of capacity and capability) for the three main neutron sources used by UK researchers and industry (ISIS, ILL, and the forthcoming ESS).
- Assess the opportunities for accessing other international sources and the potential for new source types, and how this may impact the UK's portfolio of neutron investments.

[1] https://stfc.ukri.org/files/neutron-strategic-review/

- Identify an optimal timeline of neutron source provision for UK researchers and industry to 2040 that can maximise the opportunities for science and technology gains.
- Identify any actions that can facilitate realising the identified neutron access needs and update the recommendations of the 2017 report on the priorities for UK access to neutron sources.

The membership of the Review Update panel is given in Annex 1.

The panel was provided with detailed reports on the status, recent developments and future plans prepared by the three main facilities (ISIS, ILL, and ESS) and a summary of the status of the other principal facilities operating around the world.

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Advances in Research and Innovation Enabled by Neutron Techniques

The conclusions of the 2017 report remain broadly valid in terms of the science and technology challenges that neutron science techniques are being used to address. There has been significant progress in several areas that support the needs of the UK's industrial strategy. Some of these are highlighted in the examples below.

There have been quantitative and qualitative improvements in the instrumentation available to the user community. This is enabling new science to be undertaken and broadens the applicability of neutron techniques to new user groups (see below). Maintaining this positive trend will require that the neutron facilities continue to be aware of the differing needs of the growing communities and respond to them in their operational and development programmes.

Neutrons have continued to prove the benefits of their unique capabilities as probes of atomic scale structure and dynamics across a broad range of material classes, and in imaging applications. However, it is also increasingly clear that the maximum scientific gain is often achieved when they are deployed as part of a suite of complementary techniques (including x-rays, electrons and NMR). All these techniques need to develop in-step to maximise this complementarity.

Following the aims of the industrial strategy, the UK government is investing in new research centres to focus efforts on key research and technology challenges. Of particular relevance to the use of neutron techniques are: the Faraday Institution (novel battery technologies); the Henry Royce Institute (advanced materials); and the Rosalind Franklin Institute (new technologies for the life sciences). These new centres are growing their science communities and there are opportunities here for wider engagement with neutron science, to more fully exploit these techniques to address these societal challenges.

Over recent years there has already been some broadening of the UK's neutron user community – both within academia and industry. This means that there are now expert users and researchers that make occasional use of the facilities and techniques. However, in some areas, for example in the biosciences, pharmaceuticals, and engineering, some of the potential user groups do not fully appreciate how neutron techniques could be applicable to their research needs, or how to utilise them. To support the expansion of the use of neutrons, the facilities need to continue to target new groups and help the growing number of non-expert users to achieve their research aims. This may be particularly needed in the industrial communities where the specific expertise needed can be thinly spread.

With the formation of UK Research and Innovation (UKRI) in 2018, bringing together the seven Research Councils, Innovate UK and Research England, there is an opportunity to place neutron techniques more centrally in the research and innovation pantheon – addressing a wider range of research needs and supporting a broader user community.

The high impact publications track record of ILL and ISIS continues to provide evidence that strong science and technology outputs are being achieved (as shown in figures 1 and 2).

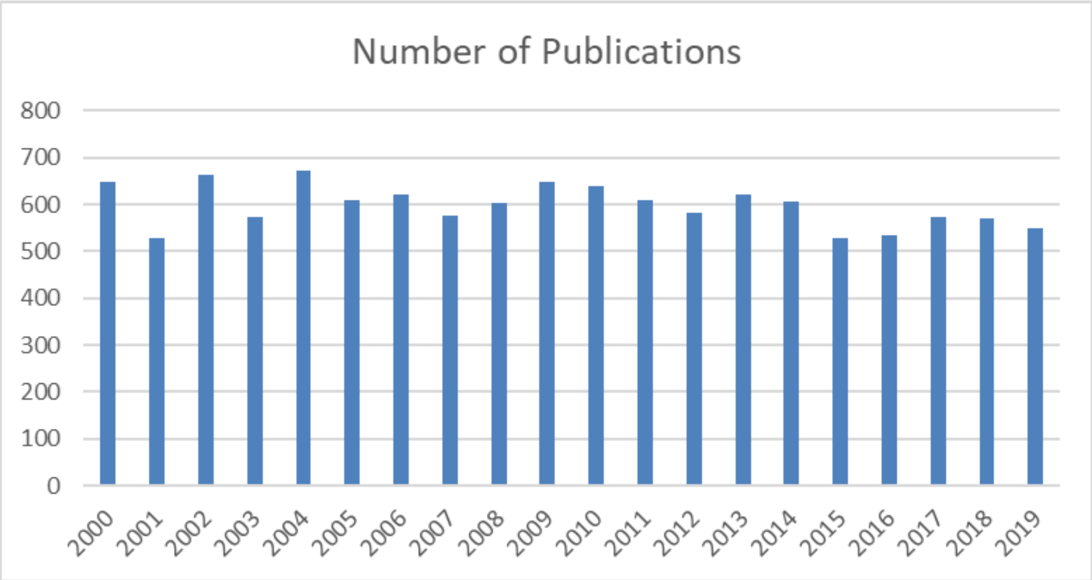

Figure 1: ILL publications

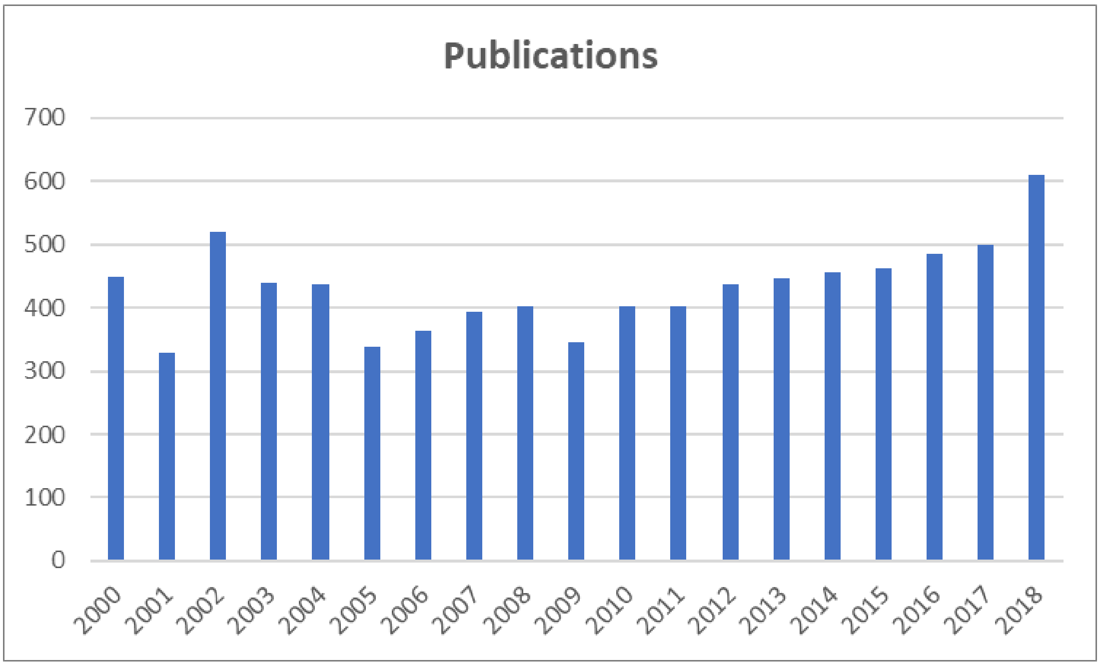

Figure 2: ISIS publications.

Examples of Science and Innovation Highlights

Neutron scattering - An integral part of the medicines design, delivery and diagnostics tool box

Neutron techniques are becoming important components of the development pathway for medicines and diagnostics, offering unique insights into the therapeutic agents themselves, as well as aiding the optimisation of the medicines the patients will receive or the diagnostics used to inform their treatment. Increasingly, the pharmaceutical science and technology industries are realising the potential of a range of neutron techniques that are able to impact on product development.

The current portfolio of therapeutic agents is very diverse and includes traditional low molecular weight molecules such as paracetamol, intermediate-sized peptides for treatment of bacterial infections, through to large biomolecules such as monoclonal antibodies and other proteins and nucleic acids. All of these therapeutic agents can be very profitably studied using neutron techniques. For example, neutron diffraction studies of the single crystals of drugs are unique in being able to provide information about any hydrogen bonds involved in crystal formation, and can yield information on polymorphism, a very important piece of information as different polymorphs can exhibit widely different physical properties and thereby influence the behaviour of the medicine. Furthermore, neutron protein crystallography can be used to understand the interaction and affinity of a drug for its target protein and can greatly facilitate improved drug design.

The formulation of pharmaceutical products, particularly liquid and semi-solid ones such as gels, can be greatly aided by neutron studies, which can give insights that cannot be afforded by other methodologies. For example, small angle neutron scattering studies of monoclonal antibody preparations provide a very powerful means of obtaining structure in these very concentrated systems as well as establishing stability in the solid state (either after lyophilization or freezing), while quasi-elastic neutron scattering can give an insight into the dynamics of the systems as the addition of formulation additives, such as co-solvents, can have a dramatic impact on the dynamics and function of such molecules. In addition, neutron reflectivity techniques provide an invaluable means by which to establish how to reduce the absorption of monoclonal antibodies onto surfaces and thereby avoid their destabilisation and denaturation. Small angle neutron studies of drug delivery systems such as nanoparticles can furnish detailed structural information of great value in optimising the carrier architecture, also allowing identification of the preferred locus of drugs within the carrier, providing information on the mechanism of the drug's release, and the effect of the drug on the structure of the delivery system and its stability.

Finally, neutron reflectivity is particularly useful in gaining a detailed understanding of diagnostic devices based on antibody-antigen interactions such as are used in pregnancy test kits where it is possible to establish the amount and location of antigen bound to the surface-confined antibody.

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Neutrons are supporting advances in novel materials

Neutron techniques remain of critical importance in the study of magnetic materials, with significant scientific and technical strides. One example of this is progress in the quantitative magnetic profiling of nanostructures using neutrons. This is primarily driven through small angle neutron scattering, where there have been successful validations of experimental protocols to obtain clear, unambiguous results (see Nanoscale magnetism box). This is complemented by a renewed focus in magnetic field imaging.

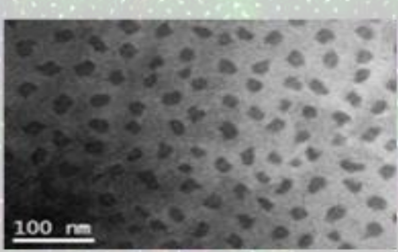
These capabilities will feed in to custom manufacture of nanostructures with specific magnetic profiles, for example functional core-shell nanoparticles. These have a range of potential applications, from catalysis to targeted drug delivery.

Neutrons provide highly accurate data, calibrated in absolute units, on magnetic correlations in materials. This plays an essential role in validating and developing new theoretical models of collective behaviour, with wide-spread applicability to other areas of science.

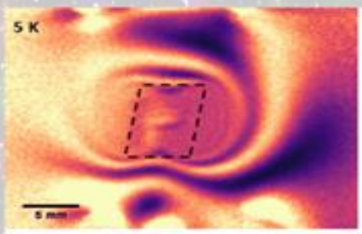
In the 2017 review, skyrmion studies were selected as a highlight. These studies can now be seen as a part of a broader appreciation of the importance of topology in classifying materials with novel electronic and magnetic behaviour (see Quantum spin liquids box). For example, certain low-dimensional materials provide a laboratory to explore the properties of exotic "quasi" particle (magnetic) excitations, with relevance not only to fundamental theoretical techniques, but also to the long-term quest to develop new materials for quantum technologies.

Nanoscale magnetism

The magnetic properties of an object depend on the material properties, but also the size, shape and interactions with neighbouring materials. We have many tools to control the size and shape of materials, but measuring the effects on individual nanostructures remains a challenge. Tom Farmer (STFC) and his collaborators at NIST were recently able to map the changes in magnetic properties in $CoFe_2O_4$ nanopillars – of the type illustrated below [1].



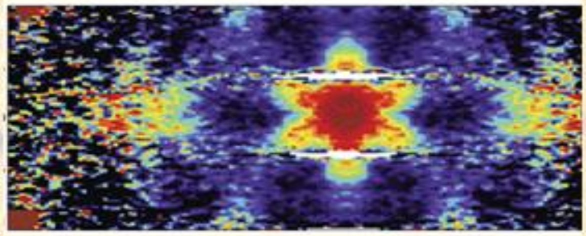
There has also been a renewed focus on magnetic field imaging, and with the advent of new imaging instruments, the resolution for magnetic field imaging will be pushed further and further – below is an image of flux pinning in a superconductor [2].



[1] Farmer *et al.*, Phys. Rev. Materials **3**, 081401 (2019).
[2] Dhiman *et al.*, Phys. Rev. B **96**, 104517 (2017).

Quantum spin liquids

*Materials where the magnetic spins do not settle at the very lowest temperatures give rise to very interesting physics. Various candidates are being explored – the figure below is from measurements on $RuCl_3$ carried out at the Spallation Neutron Source at Oak Ridge National Laboratory [Banerjee et al., Science **356**, 1055 (2017)] which may potentially have excitations called Majorana fermions that arise in multiple contexts; they are one possible architecture on which quantum computing might be built.*



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Neutron Facilities

Current Technology Sources

General

The continued progress in developing the facilities' capabilities was welcomed and the subsequent growth in expertise in the UK community was recognised. This continues to add value to the international community through the collaborative work that is undertaken and, in many cases, led by UK researchers.

However, it was noted that there is a potential for loss of technical expertise at the facilities – both instrument scientists and support staff – and that this represents a serious risk to delivering reliable operations and maintaining the UK community and its international position. Maintaining technical expertise at all levels will be key to realising the UK's neutron strategy. However, it was also recognised that the facilities provide excellent training for young engineers and scientists. Some movement of these skills from the facilities to the wider academic and industrial sectors is of some benefit.

The user data indicates that there continues to be a steady demand for facility access. It was noted that it is difficult to determine the real level of unsatisfied demand for neutron facilities overall and specific instrumentation, due to the self-management by the user community on the number of applications to the facilities for beam-time.

There continues to be a sharp increase in the need for computational capabilities for data handling and analysis and interpretation. This trend was noted, and it is recognised that this is another area where the user community needs support from the facilities. It is suggested that there are excellent opportunities to build connections with the Ada Lovelace Centre and the Alan Turing Institute. This would also bring valuable training benefits for facility staff and the user communities.

There is a need to rethink access modes to the facilities, including a greater emphasis on timely and dynamic access and facilitating effective remote access with the necessary support by local teams to the remote users. This will potentially be a benefit in enabling safe operation in the aftermath of the COVID 19 pandemic. It could also support the future sustainability of facilities by exploring how the number of individual visits can be minimised with the resulting reduction in travel.

The mutual access model arrangements that exist between many of the national neutron facilities (e.g. ISIS, SINQ in Switzerland, SNS in the USA, etc.) work well and should be maintained. In this model, there is no access payment for researchers who win beam-time at national sources through peer-reviewed proposal mechanisms, with the implicit understanding that this is reciprocal. This model, which also applies for synchrotron radiation sources, has many advantages for both facilities and users. It is important that the benefits of this arrangement are clearly communicated as this is different to arrangements at large facilities in some other science areas. The “free access” arrangement can be misinterpreted as indicating that the facilities using this model are not valued, as a monetary value is not attached to individual experiments. It also needs to be recognised that some facilities, including ISIS, operate a hybrid access model with some cost sharing partnerships.

ISIS

The continuing high quality of ISIS as a core neutron facility in supporting the UK research and industrial community was recognised. Also, the leverage value of ISIS in enabling access to other national neutron facilities (and helping optimise the design of new facilities and instruments elsewhere) is strong and can sometimes be underestimated. This value will increase if the number of facilities around the world continues to decline.

It was noted that ISIS has been able to increase its operational capacity since the 2017 Review, delivering nearly 4,400 instrument-days in 2018 compared to 3,400 in 2016. ISIS reports that further increases in operations are now limited by available staff resources.

As already commented above, the facilities need a wide range of skilled scientific, technical and other support staff, not just to provide the core functions of operating the facility but also to support and engage with the user communities. The challenges that ISIS reports in securing and retaining its skilled workforce are a significant concern for the continued success of the facility. It is a fact that it is a highly competitive marketplace for specialised technical skills in many areas of the UK economy (including universities). An important part of the solution will be to keep ISIS as a leading-edge research centre and an exciting place to work. The planned Endeavour upgrade programme and other proposed developments, including the ISEC Engineering centre and design studies for future sources, can play an important role in helping ISIS attract and retain the skills it needs.

There is an opportunity for an enhanced vision at ISIS on how remote access could be expanded and this should be explored. It is accepted that there are some restrictions because of the nature of some of the instrumentation and that staff will be required to enable this. It is not suggested that ISIS should be moving toward becoming a fully remote access operation.

The progress that ISIS has made in developing its International partnerships and the benefits this has brought in terms of funding and increases in capability are welcomed. ISIS is right in being cautious about further expansion of its international partnerships so that the sustainability of its core operations do not become too vulnerable to fluctuations in the international income streams. Any future partnerships should be driven by strategic and sustainable gains to the facility’s capabilities.

ILL

The successful completion, since the 2017 report, of the Millennium upgrade programme and additional safety enhancements under the Fukushima response programme and Key Reactor Components project was welcomed. It was noted that these safety enhancements have enabled new operating licenses to be agreed for ILL which is key to securing agreement on the next 10-year operating protocol and potentially even longer operations.

It was noted that UK users are currently achieving access levels at ILL above the approximate 25% funding share, which indicates a high quality of UK science submissions and a good alignment of ILL capabilities with UK research needs.

It was also noted that ILL has made good progress in supporting remote access arrangements.

ESS

It was noted that there have been significant changes to the ESS specification since the previous Review. The proton beam power has been reduced from 5MW to 2MW. Although this reduces the total neutron flux, ESS have been able to re-design the moderators so that the planned brightness at the instruments will be maintained. ESS consider that this will ensure that the scientific potential of the facility will not be impacted.

The updated construction schedule provided by ESS indicate that the 2MW beam power will be achieved by the end of 2025 with fifteen instruments operational by the end of 2026. This is approximately a two-year delay from the schedule considered by the previous Review. Despite the rescheduling, this is considered to still be a very ambitious programme and it was noted that the impacts of the COVID-19 pandemic on the supply of key components from the in-kind contributors has not yet been fully assessed.

The panel noted that, despite the reduction in beam power, the new moderator design and advanced specification of the instruments should still enable significant improvement in performance compared to similar existing instruments at current sources. It was also noted that ESS consider that the potential upgrade route to reach the 5MW beam power performance will not require a significant downtime in operations. The panel considered that undertaking the upgrade to 5MW with no impact on the science programme would be challenging.

It was reassuring to see how much of the UK’s expertise in spallation sources, and neutron science more generally, is now linked into the ESS programme so the UK community can potentially have greater influence.

Emerging and Future Technologies

Compact neutron sources are still at an early stage of development and their ultimate capabilities and cost compared to current sources remains uncertain. As a result, they are currently considered to have an unknown cost-benefit value to the UK community, compared to continued investment in and operation of ISIS and ILL. The progress at the pilot compact sources around the world should be monitored.

The capability of laser driven sources is not fully understood at the present time but should be watched with interest. The UK's new Extreme Photonics Applications Centre (EPAC) will be able to play a key role in enabling the necessary research on the laser technologies that will be required for any future laser driven neutron sources.

The concept of an ISIS II short pulse facility is exciting, and it has the potential to be very complementary to other sources. Continued exploration is strongly encouraged as a long-term option. Detailed analysis of the proposal is outside the scope of the current review, but the concept demonstrates visionary forward thinking and could create an exciting technical challenge to engage the whole UK community in.

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Meeting the UK's Needs for Neutron Capacity and Capability

Facility Considerations

Overall, the recommended portfolio of neutron facilities that the UK should access has not fundamentally changed since the 2017 report.

The panel confirmed that maintaining and developing ISIS should be the highest priority for the UK and ISIS should continue to be fully supported over at least the next 10 to 15 years.

To maintain the capacity for the UK user community it has become more important since the 2017 Review that the UK continues to be able to access ILL. This should be at least for the full duration of the 10-year 6th Protocol period (2023 – 2033). The improved status of ILL after its recent upgrades makes this much more feasible and a lower risk element of the portfolio.

The panel considered that the planning timeline provided by ESS to achieve full operational performance for fifteen instruments is potentially over-optimistic. The capacity that ESS will be able to provide to the UK in the medium term is likely to be limited. Even if there are no unforeseen delays, it takes time for the accelerator operation to reach its full potential and for instruments to move from start up to full operational capacity. In addition, the user community will need time to learn how to fully exploit the new capabilities. From experience elsewhere (e.g. at SNS and J-PARC) it can take up to 10 years for a new facility to become fully operational and deliver the anticipated science outcomes. However, it is recognised that ESS will become an important complementary and growing capability for the UK with new and unique capabilities as instruments become operational and user experience is gained.

The previous Review recommended securing a level of initial access to ESS that is commensurate with the UK contribution to the construction of the facility (~10%). Given the changes in specification and – until operational experience is gained - uncertainty over how this will impact on the capabilities, this level of access still seems appropriate. Future changes to the level of access could be reviewed once operational and user experience has been gained.

It is recognised that UK users continue to bid for modest amounts of access to several of the other neutron facilities around the world under the mutual access arrangements. However, it has to be noted that the likely continued reduction in the number of sources will make this access route even more competitive as almost all sources are oversubscribed. From the information available to the panel, it was noted that there is spare capacity at the OPAL reactor source in Australia. This source has comparable neutron characteristics and instruments to the ILL source, which could make it a potentially attractive option for UK users. If sources can continue to develop their remote access capability then sources such as OPAL may become a realistic option in the future, particularly in the event that there is a significant unplanned interruption to operations at one of the European sources.

Recommended Access Profile

An optimal neutron access profile is recommended based on the following elements:

- The ISIS source continues at least at its current capacity (~ 4,400 instrument-days/yr)
- The ILL source continues for the full ten-year duration of the 6th Protocol and the UK stays as a full Associate member (33% shareholding)
- The UK secures 10% of the ESS capacity as it comes online.

In order to manage expectations on how quickly high impact science outcomes can be achieved at ESS, the panel was conservative in estimating the ramp up in useable instrument-days. Guided by the experience seen at other new facilities it is suggested that the 200 days/yr operation with 15 instruments planned by ESS is factored into the profile as a linear growth over 10 years starting in 2024. If outcomes can be realised more quickly then that would be a bonus.

The resulting profile of UK access is shown in figure 3 below, together with the recommended profile from the 2017 report. This shows the change in available instrument-days relative to that expected from ISIS and ILL in 2020. Note that this does not include scheduled shutdowns for maintenance and upgrades and any ad hoc access to other sources by UK researchers.

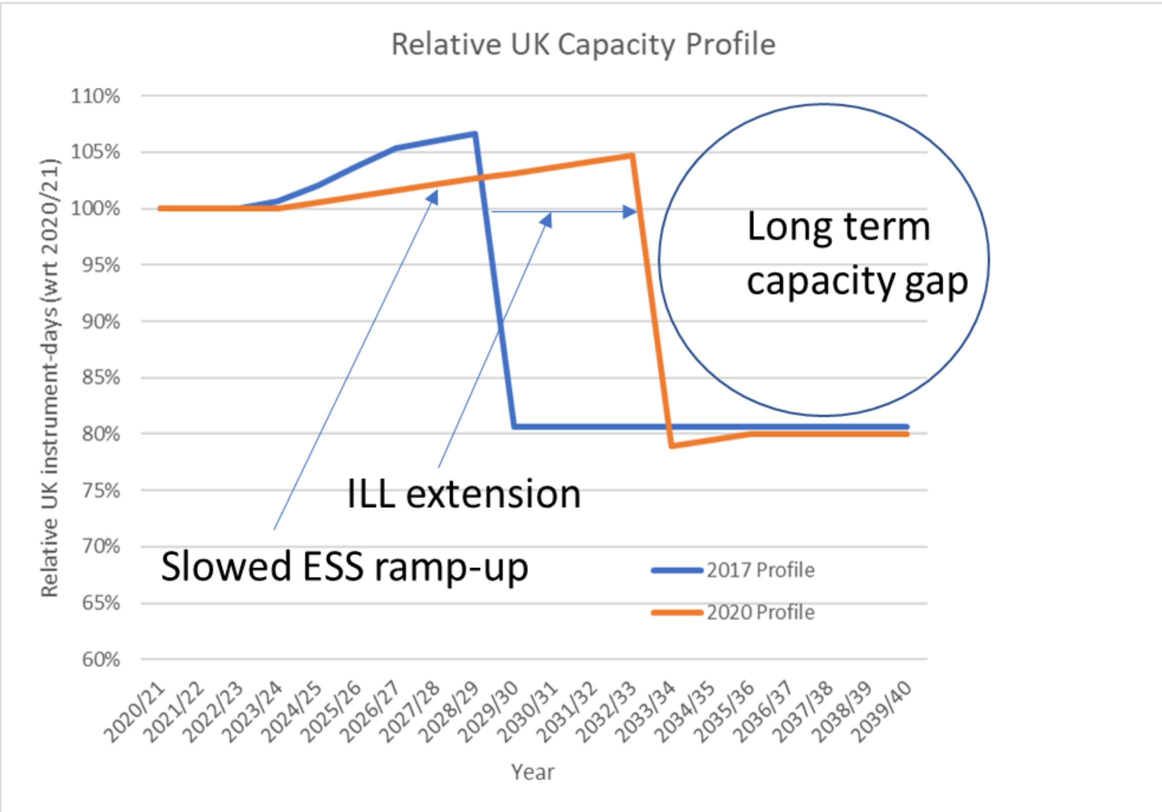

Figure 3 Access Profile

The options for addressing the long-term capacity gap are:

- A further extension to the ILL source
- Additional instruments at ESS (up to seven additional instruments have been identified by ESS)
- Building a new “ISIS II” source
- Developing a laser driven source or an alternative new technology.

Conclusions and Recommendations

Conclusions

Overall the findings of this Review Update agree with the 2017 Review.
Specific points identified by the panel include:

- Neutron capabilities are enabling key advances in research and innovation and support the goals of the UK's industrial strategy. This is likely to continue, particularly as an integrated component of different probe techniques.
- There has been good progress at ISIS and ILL over last 3 years in developing capacity and capability, confirming them as still being the primary sources for UK users.
- Retaining and building the skills base at ISIS (scientific, engineering and other support) is as big a challenge as maintaining the machine functionality.
- Successful upgrades and new operational licenses mean ILL has a brighter future.
- Noted the changes in the ESS specification with reduced power (2MW) and a two-year delay realising fifteen operational instruments.
- No significant alternative source options identified in the short/medium term but there is potential in the longer term.

Recommendations

The following recommendations are made:

- Continue to support ISIS as the core national facility underpinning the UK community, with particular attention to retaining its technical skills base.
- Secure future access to ILL for at least the 10 year 6th protocol period.
- Continue as members of the ESS project and secure access in line with the UK's contribution to the construction costs. Closely scrutinise ESS progress to inform any change to long-term levels of access.
- Encourage the facilities to develop flexible and agile access arrangements, and to continue to widen their user base.
- Encourage all facilities to increase their remote access capabilities – important for post-pandemic operations and improving sustainability credentials.
- Support research into the potential for laser driven sources.
- Support continued development of the ISIS II concept.

The panel also reviewed the recommendations from the 2017 Review. This is reported in Annex 2.

Annexes

Annex 1

Panel Members

Prof John Loughhead CB OBE (chair)	Chief Scientific Advisor BEIS
Prof David Rugg	Rolls Royce and Imperial College
Prof Elizabeth Blackburn	Lund University, Sweden
Prof Julie Yeomans	University of Surry
Prof Jayne Lawrence	University of Manchester
Prof Chick Wilson	University of Bath
Prof Desmond McMorrow	UCL
Prof. Christian Rüegg	Paul Scherrer Institute, Switzerland
Prof. Anke Kaysser-Pyzalla	Technische Universität Braunschweig, Germany

Annex 2

Commentary on previous review recommendations

The UK-funded facilities should continue to regularly carry out reviews of the capacity and capability provided. These need to be rigorous and transparent and include trends in demand in order to ensure that the supply matches the demand and changing priorities are identified early. ***Agree***

The UK-funded facilities should maintain and enhance their scientific and operational links to ensure best practice is shared and developments (e.g. in instrument design) benefit all and are not duplicated. A greater emphasis on computing and software is essential, and shared approaches to computing and software development should also be supported. ***Agree***

UK government and its agencies should continue to ensure adequate access to neutron facilities in order to meet the needs of important science areas. ***Meeting industrial needs is also important.***

Access modes need to evolve to ensure that agility is created so that academic and industrial users can effectively exploit the techniques to address high priority science and technology challenges. The UK can use its ISIS facility to lead on this. ***Agree***

There needs to be a continuing focus on seeking reduced costs of beam time. ***Costs were not specifically addressed in the update but agree with the recommendation***

Maximise the co-location benefits of ISIS being part of the Harwell campus, for example, in helping maintain world-class skills in the underpinning areas of expertise needed in topics, such as accelerator and detector technology. ***Not addressed but noted***

Neutrons are a key capability exploited by many research programmes supported by the RCs. Their provision needs to be considered within a balanced funding portfolio such that increases in funding for neutrons should not be at the expense of funding of the research programmes that exploit them. The panel recommends that the existing governance arrangements that STFC and the RCs have in place continue to tension this funding balance to ensure the best overall outcome for the UK is achieved. ***Not addressed but noted***

As a completely new facility, ESS is the highest risk element of this access option and the panel recognises the challenges faced in bringing this large and complex new facility on line. The panel recommends that STFC actively monitors the progress with ESS construction and commissioning. If necessary, the UK should renegotiate its costs and access if there are concerns about ESS performance, or if the scope for greater use is proven. ***Agree***

There should be a further review of neutron access once there is two years' experience of ESS operations. This review should address the extent to which ESS is proving to match the UK science requirements both in terms of capacity and capability and machine performance. ***Agree but timing of the review will depend on ESS progress.***

The panel recommends that if budget limitations mandate adopting a one source option, then ISIS provides the best capacity and capability for the UK and secures a national research capability. ***Not addressed but noted***

If UK access to ILL does not continue beyond 2023, then access to alternative reactor sources should be secured, with any necessary funding, to ensure that specific critical research needs can continue to be met. ***Agree but the aim should be to secure a full 10 year continuation at ILL. If this does not happen there needs to be an urgent and focused review of alternative options***

Ongoing investment in ISIS will be required to ensure it does not stagnate and also that UK science is equipped to fully exploit the new ESS capabilities as they come on line. ***Agree***

ISIS should be supported and encouraged to actively seek to broaden its user and funding base internationally and with industry and other UK funding sources. This will be crucial to helping close the likely gap to the available public funding and will also ensure that there is continuing innovation at ISIS. A small loss in access for UK users is considered to be an acceptable element of a wider plan to securing a sustainable future for ISIS. ***Note the risk of too diverse and variable a funding base – need to choose partners strategically***

Strengthen collaboration between industry and academia and upskill individual companies in neutron scattering by means of a significant cross research council and industry backed training scheme. ***Agree***

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