ESFRI Physical Sciences and Engineering Strategy Working Group
Neutron Landscape Group

Neutron scattering facilities in Europe

Present status and future perspectives

ESFRI SCRIPTA Vol. 1

ESFRI Scripta Volume I

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Neutron scattering facilities in Europe - Present status and future perspectives

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Cover image: Diffraction pattern from the sugar-binding protein Gal3c with lactose bound collected using LADI-III at ILL. Picture credits should be given to D. Logan (Lund University) and M. Blakeley (ILL)

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Foreword

ESFRI Scripta series will publish documents born out of special studies mandated by ESFRI to high level expert groups, when of general interest. This first volume reproduces the concluding report of an *ad-hoc* group mandated in 2014 by the Physical Science and Engineering Strategy Work Group (PSE SWG) of ESFRI, to develop a thorough analysis of the European Landscape of Research Infrastructures devoted to Neutron Scattering, and its evolution in the next decades. ESFRI felt the urgency of such analysis, since many reactor-based neutron sources will be closed down in the next years due to national decisions, while the European Spallation Source (ESS) in Lund will be fully operative only in the mid or late 2020s. It was necessary to analyse at the appropriate level the implications in terms of capacity and capability of neutron science in Europe, both during the crossover period of national reactors with the ESS, and in the longer term.

This rationale led ESFRI to create the Neutron Landscape Group (NLG), co-chaired by Prof. Colin Carlile (former Director General of the ILL and of the ESS) and Prof. Caterina Petrillo (now Vice-Chair of the ESS Council).

Some conclusions of the NLG report were published in the Landscape Analysis section of the Roadmap ESFRI 2016, published on 10th March

2016*. Here we publish as ESFRI Scripta the full NLG report since it has the character of a reference book on the neutron research infrastructures with implications and scenarios of the possible strategies for Europe in this field.

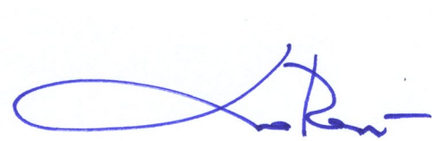
The Neutron Landscape represents an analysis of the European RI system that supports science based on neutron scattering and spectroscopy. This reinforces the ability of the PSE SWG of ESFRI to adequately fulfil its mission of providing a thorough Landscape Analysis of the research infrastructures ecosystem beyond the ESFRI Projects and Landmarks. The Landscape Analysis and its projection in the next decades, taking into full account the lifecycle of the existing and planned Research Infrastructures, forms a key part of the background for the evaluation of Projects and Landmarks.

ESFRI Scripta do not represent in any way the view or prioritization of ESFRI or of any Member State for commitments or future investments. ESFRI in no case acts as an advocate of specific potential future projects. The PSE SWG has reported about this publication to the ESFRI Forum on June 2016 and its Member Delegations have taken note of it.

I wish to thank the NLG and its Chairs for the high quality report, the PSE SWG and ESFRI Forum for supporting its publication, and the technical editors Marina Carpineti and Maddalena Donzelli for their professional making of the novel format of ESFRI Scripta.

Milan, June 2016

Giorgio Rossi
Chair of PSE SWG
Vice-Chair of ESFRI



* http://www.esfri.eu/roadmap-2016

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Introductory Statement

In the words of Giorgio Rossi, the Chair of the PSE Group and Chair-elected of ESFRI, "*The ultimate scope of ESFRI is to provide a coherent and strategy-led approach to policy-making on Research Infrastructures to the Competitiveness Council of the EU. In the domain of neutron science and analytical facilities, the strategy-led approach must be urgently formulated as no individual ministerial authority or owner-consortium of the current infrastructures is in the position to address it*" [1].

The work of the NLG has been conducted in that spirit and this report is written as input towards the fulfilment of this aim.

Executive Summary

1. **Neutrons play an important and distinct role in advanced materials science.** The neutron is a unique and irreplaceable probe, with characteristics that cannot be supplanted by other methods. Its use has provided, and continues to provide, information that other techniques cannot.

2. **Europe has led the field for ~40 years** in scientific studies using neutrons thanks to the versatile and broad network of neutron sources in Europe. These include the world's two leading sources as well as an array of high quality medium flux facilities located in several different countries. Relatively modest investment is necessary to maintain this position.

3. **Europe hosts the two world-leading sources** as measured by scientific output: the reactor-based Institut Laue Langevin, ILL, in Grenoble, and the accelerator-based ISIS Facility near Oxford, with access by the multi-disciplinary international scientific user community.

4. The next generation neutron source for Europe, **the European Spallation Source, ESS**, is now well under construction in Lund in southern Sweden. It promises not only to continue the flagship role in neutron scattering, but also to embrace exciting new opportunities

for science through yet higher performance instruments. It entered its construction phase in 2014, is scheduled to produce neutron beams in 2020 and the goal is to reach full specification by 2028, becoming the world's premier neutron source for science.

5. **The medium flux sources distributed around Europe act as breeding grounds** for new instrumentation, for the testing of scientific ideas, and for the training of the next generation of scientists, engineers, and technicians, as well as providing essential capacity for the research needs of an expanding and diversifying user community.

6. **The European user community is the largest and most diverse in the world** by far, numbering over 6000 scientists and engineers from academia, national and international research laboratories and institutes, as well as from industry, all of whom use neutrons as an essential tool in an increasingly wide range of research fields.

7. **Unique aspects of human capital are nurtured** by neutron facilities, in particular with respect to nuclear physics and engineering, and accelerator expertise. A reservoir of technological knowledge and uniquely experienced manpower exists that is not readily available elsewhere.

8. **Neutron sources place demands upon industry** and industry has expectations of neutron sources. Mutual benefits accrue. High-tech industrial design and production of unique, high-specification components for neutron sources with their multiplicity of state-of-the-art instrumentation enables modern industries to compete successfully in other high-tech fields. Cutting-edge materials knowledge helps to address important societal needs directly such as health, well-being and ageing; climate-change and energy sustainability; waste recycling, resource-management and pollution control. These activities feed economic activity and growth.

9. **This healthy position is however challenged**, despite the advent of the ESS. Two-thirds of all operational neutron sources in Europe were built in the 1960s & 1970s and the majority of these will close within ten years. Next generation accelerator-based sources of megawatt power, following the recommendation of the OECD in 1999 [2], are already operational in the USA and Japan and scientific output is increasing towards European levels.

10. **The major neutron facilities in Europe - ILL & ISIS - are fully mature**, comprehensively equipped, internationally-leading research facilities with a high scientific output, and they remain essential to satisfying the scientific community's research needs. But they are also ageing.

    (i) ILL has been operating since 1971 as an international facility. The reactor and the instruments have been constantly invested in and well maintained. The facility has excellent, modern instrumentation and highly efficient moderators and the reactor is reliable. Data rates have increased by a factor of 40 over this period thanks to this investment. Above all ILL has an impeccable safety record. It has the highest scientific output of any neutron source worldwide, and it remains indisputably the world's flagship facility, having graced that position for four decades. The scientific gap with respect to the output of other facilities is however narrowing visibly. Crucially, ILL depends upon highly enriched uranium for its fuel, a politically sensitive strategic material, as does FRM-II (MLZ) and other research reactors. The highly regulated and specialised supply chain for fuel elements, from ore to reprocessing, is a clear risk and represents a single line failure mechanism. The production pipeline for fuel elements is subject to the same intense scrutiny that reactors themselves experience, especially in the wake of the Fukushima experience and its political consequences. Costs, as a

consequence, are increasing very substantially. The 2016 report of the French Cour des Comptes (National Audit Office) [3] shows that the cost of maintaining nuclear reactor facilities has risen by a factor of 6 in the last decade and declare that even this is not sufficient.

(ii) ISIS has been operating since 1984. In 2009 a 2nd Target Station was built that focuses upon cold neutrons. The ISIS instrument suite is still increasing in both quantity and quality. ISIS was the first pulsed neutron source in the world that demonstrated beyond doubt that spallation sources could stand side-by-side with the most highly performing reactor facilities and indeed has out-performed them in certain areas. The ensuing competition between ISIS and ILL has had a beneficial influence on instrument excellence, scientific output and service to users on both sources. Experience on ISIS has fed through to the design of SNS in the USA and to J-PARC in Japan, allowing them to use this knowledge as a platform to achieve even more powerful facilities for science. ISIS in turn has benefitted from initiatives in the USA (IPNS at Argonne) and Japan (KENS at Tsukuba). However, because of restricted funding, ISIS has been obliged to operate well below capacity in terms of operating days for a number of years now. This under-exploitation represents a sub-optimal return on a large scientific and capital investment.

11. **ESS is scheduled to be fully operational by 2028**. It will then without doubt take over the mantle of the flagship facility. The published schedule is however explicitly stated as being technically defined. In other words it is highly dependent upon financial flow and sustained political support at the necessary levels. Equally well technical and conceptual excellence, coupled to high quality risk management, are critical to achieving this deadline, which is both aggressive and optimistic. This schedule must therefore be considered as the best possible scenario since the risk-mitigating

measures underpinning the schedule are challenging, and in particular the dependence upon in-kind contributions and multiple funding origins, represents a model which is breaking new ground. Historically, accelerator-based sources have required longer periods of commissioning than reactor-based sources.

12. **ESS will be very powerful** in all senses of the word. Its engine will be the world's most intense particle accelerator dedicated to analytical science. There is a palpable danger – indeed it is a tacit expectation at many levels of decision-making - that ESS is perceived as a like-for-like replacement for ILL. This is not the case and the Neutron Landscape Group wishes to underline this; the two international sources will be complementary in many important areas but the scientific overlap is neither complete nor proven by experience and, crucially, ESS's current funding envelope permits significantly fewer instruments than ILL has. The output of ESS, based upon current instrument plans, cannot exceed that of ILL, except in some unique frontier areas where its power will undoubtedly provide breakthroughs. The wise handling of the operational overlap period of the two sources, to be faced in the coming decades, will be pivotal to the continuing health of the scientific community in Europe who depends upon neutrons, partially or totally, in achieving their scientific goals.

13. **By 2025 Europe will, at best, have only 4 or 5 functioning neutron sources.** Most probably these will come from ILL, FRM-II (MLZ), ISIS, SINQ & ESS. Highly productive and still viable sources, such as LLB and BER-II, will already have ceased to operate. The decisions have already been taken unilaterally to close them down, and other national sources are destined to follow. By the beginning of the 2030s a likely scenario – unless mitigating actions are taken - is that Europe will find itself with the ESS and only one or two other neutron sources. Whilst this obviously will reconfigure the

scientific dynamics of neutron sources in Europe it will, even more importantly, focus the responsibility for supporting today's large scientific community and the instrumentation that it depends upon, on these few facilities. This responsibility is not simply for the provision of neutron instrumentation, but extends to all the peripheral and essential activities that are conducted so effectively by the smaller sources today. Crucially this includes nurturing and growing the user community. The ESS will have to be "all things to all men and women" and it is neither conceived nor resourced for this all-embracing role and neither is it perceived as such by the governing bodies.

14. **The longevity of ILL is a crucial issue** that must be handled with great care. It represents a pinnacle of achievement technically and scientifically. The closure of the ILL, whenever it will occur, will mean a very significant and instantaneous drop in neutron instrument availability, hand-in-hand with an equally significant drop in scientific and technical endeavour, accompanied by a damaging loss of technically and scientifically qualified personnel. It is difficult to overestimate the value that a reasonable overlap period of ILL and ESS represents, each operating at full specification, and accompanied by a proper strategy to oversee this transition. However, there is a real and tangible danger that Europe will simply drift into this void unless wise stewardship, openness, and a collective strategy - defined well-ahead of time - prevent the emergence of "a dark period". It would be unwise to consider closing down ILL without a very careful objective assessment of all the consequences of its loss. It merits a very wide consultation process, beyond its three owners. It is a decision that should not be taken hastily nor prematurely. ILL has been the unchallenged global leader for 40 years and its demise would certainly result in Europe relinquishing its world-leading position, possibly for decades to come, and especially so if the overlap period with ESS is not managed well.

15. **The clear consequence of all conceivable scenarios that we foresee is that there will be a marked reduction in availability of scientific measuring capability** using neutron beams in the coming years, and an undesirable loss of specialist human capital. Europe will lose its undisputed lead in many of the important areas of the sciences served by neutrons. Access to neutron instrument measuring time is highly competitive which means that even substantial increases in capacity result in demand being maintained, which attests to the untapped high quality scientific potential. Therefore Europe's competitive edge, deriving from this pursuit, not only in science but also in the associated technological know-how, and in its medium and long-term innovation potential, will be significantly degraded, unless pro-active policies are implemented by funding bodies, the sources themselves, and the user community alike. This is the *sine qua non* for the continued health of this productive scientific discipline. There is a clear choice to be made between protecting and building upon Europe's investment or allowing it to wither away through indecision and inaction. In a future Europe, with fewer national sources, it will be increasingly important to find ways to improve transnational access and to encourage coherent action/development between the sources. This is essential at both the European level and the global level.

16. Recalling Giorgio Rossi's words that "no individual ministerial authority or owner-consortium of the current infrastructures is in the position to address it" **we recommend that a European umbrella organisation be constituted** in order to provide a science-based strategy for neutrons as a key element for a coherent policy of all advanced analytical facilities including exploiting X-ray or electron beams in Europe. Without such a forum we foresee continued fragmentation of decision-making. Such a body would take responsibility for balancing the European neutron park and for moving into the era of global thinking for future neutron sources.

This umbrella organisation would be the natural body to set up activities relating to new sources either as replacements for closing reactors or conducting studies for an eventual successor to ESS.

17. **Imaginative efforts need to be made to enhance visibility and attractiveness of materials science** and the associated analytical facilities. Funding needs to be increased in this area. ESO, ESA & CERN commit substantial resources to public outreach and publicity - in a coordinated manner - thanks in part to their umbrella status. With all the high impact publicity given to astrophysics and high-energy physics they are very evident in the public eye. Neutrons must make increased efforts to do the same.

18. In comparison to synchrotron sources, **neutron sources in general give a less high-tech impression.** If neutron sources are to attract the next generation of scientists and engineers they must make efforts to lift their level of attractiveness. Again this requires additional funding above the 6% ratio of annual operating costs to installed capital value.

19. With so few new neutron sources being built, inevitably a "safety first/low risk" attitude amongst funders prevails with respect to embracing new ideas. This was not the case in the past, for example with ILL where new ideas – neutron guides for example – were the very foundation for success. **This "safety first" attitude must be resisted by the ambitious use of under-employed methods** – polarisation, robotic techniques for operations and maintenance, remote access, radical solutions for industrial access, stronger interactions with universities for staff exchange and student teaching. A process of reinvention is needed.

20. **Neutrons sources need to critically examine whether their procedures are fit for purpose and state of the art.** A lot can be learnt from benchmarking against other disciplines and embracing

best practices. **Open access to data**, so common and productive in astronomy but resisted by neutron users, is long overdue. This freedom of access has led to significantly more scientific output from telescopes, which is quantified by the Hubble Telescope. The jealous ownership culture of data in the neutron field leads to data being only partially analysed and scientific publication delayed, to the detriment of the user and the source itself, and indeed the whole discipline suffers.

I.

The Current Situation with neutron facilities in Europe

I.1 Introduction

"The wellbeing of our society depends on meeting grand challenges across several fronts embracing energy and the environment, healthcare and information technology. Progress in each of these domains depends critically on the development of new materials and processes, and this in turn requires precise insight into their structure and dynamics at an atomic, molecular and magnetic level. One of the most incisive tools to explore these properties is the neutron and the manner in which it is scattered by such materials. The power of the technique is derived from the key defining characteristics of the neutron, which complement well those of other probes such as synchrotron X-rays, electron diffraction and NMR. Research teams with access to state-of-the art experimental facilities using these probes as a complementary set can furnish materials technologists with the information they need to develop the new materials necessary for tomorrow's world."

The above paragraph is adapted from the strategy for neutrons of the ILL Associates, published in 2013 [4], in which the importance of materials research is underlined. Although materials research does not have the captivating images that astronomy has nor the newsworthy appeal of the Higgs Boson, it has however something of real and direct societal value that is often unsung. That is the part that materials research plays directly in developing solutions to society's needs when it comes to tackling the major challenges that humanity faces today. These are related to energy sustainability, to resource management, to climate change, to rebalancing the inequalities of the planetary population, and to health and wellbeing.

Neutron scattering has been pre-eminent, along with other powerful and complementary methods such as synchrotron radiation, electron microscopy and nuclear magnetic resonance, in unravelling step-by-step the mysteries of condensed matter. This complementarity renders

it possible to develop new materials from evidence-based research rather than by trial and error, as happened to a great extent in much of the 20th century. As such the role to be played by neutron scattering in the future is a topic worthy of careful analysis, especially since neutron sources are expensive, there are few of them, and the technique is flux-limited. Is it in fact obvious that neutron technologies should continue to be invested in? In reality, do we have sufficient neutron sources, and are there more cost-effective methods and capabilities to provide the information that researchers seek and that industries depend upon for their developments? The answers to these questions are some of the goals of this review commissioned by the Physical Sciences and Engineering strategy work group (PSE) of ESFRI, the European Strategy Forum for Research Infrastructures. The answer to the first question, derived from this present review, is clearly "yes", neutrons must continue to be invested in, and the answer to the second question equally clearly is "no", the research community does not have sufficient neutron sources nor more cost-effective methods: investment is needed and neutrons have unique qualities.

What is the health of neutron supply and utilisation, what scenarios might present themselves in the future and to what extent is Europe positioned to realise these scenarios? It was considered timely by ESFRI to undertake such a review of neutron scattering capacity and capability now, given the strong showing of the European research community, and its precarious dependence upon an ageing fleet of neutron sources in Europe. The advent of the European Spallation Source, which formally entered into its construction phase in September 2014 after 25 years of preparatory work, will safeguard the needs of the researcher communities to a great extent but will not subsume the activities and impact of the current diverse park of neutron sources in Europe. A very significant change in the dynamics of neutron scattering is therefore on the horizon and it is important that the remaining sources and the user community itself are prepared for that. This, together with changes

in the way in which scientific problems are tackled, with increasing automation, integration of different techniques and exponentially increasing data sets, coupled to the open access to this data that must occur, means that an evolution of the sociological aspects of carrying out neutron investigations must occur rapidly, in order for the discipline to continue to flourish.

The terms of reference and the membership of this review body were defined and agreed by ESFRI and are presented in Appendices I and II of this document. The letter from John Womersley, current Chair of ESFRI, to the Directors of Europe's neutron sources is given in Appendix III together with their coordinates in Appendix IV.

I.2 The importance of Materials Science

The unique properties of neutrons as a powerful probe of matter are particularly well aligned to many of the key scientific and societal problems we are facing today and will face tomorrow, for energy, transport, communications and computing technology, as well as for the environment and healthcare, as can be seen in *Figure 1* which categorises beam-time requests by societal impact for ILL, ISIS and LLB.

Progress in all of these fields depends on discovering new materials and processes, understanding their properties, how they function, and learning how to exploit them as efficiently and effectively as possible.

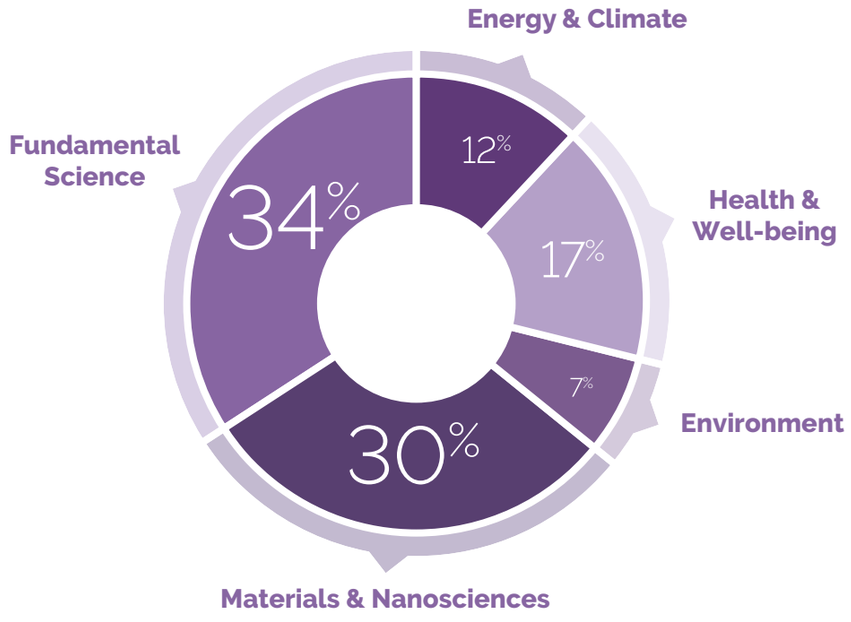


Figure 1. Neutron Beam-time usage according to Societal Impact

Recent requests for beam-time apportioned according to societal impact of neutron-beam facilitated science, averaged over ILL, ISIS & LLB. Adapted from image courtesy of ILL, 2013 [4].

The first step in this process - the search for new materials with specific desirable properties - increasingly involves more complex substances, often composites or hybrids, or soft materials based on colloids or polymers, whose functions depend on hierarchical processes over many scales of length and time. The substantial increases in brightness offered by next-generation neutron sources such as the ESS, in combination with the isotopic contrast and polarisation techniques that are accessible only to neutrons, will enable the structure and dynamics of such complex materials to be studied over a much wider range of thermodynamic variables, such as temperature or pressure, and under real conditions of synthesis or operation. More brilliant beams will reveal, for example, the details of fluid dynamics or the assembly of structures in the microfluid devices that are transforming polymer and pharmaceutical processing, while faster measurements will enable transitions in soft, self-assembled systems such as polymer hydrogel films to be studied and optimised as the basis of novel nanoscale sensors.

Many of the essential processes of life at the molecular level - and pathological ways in which these are disrupted during illness – are also governed by complex, self-assembled or folded macromolecular structures. Advances in X-ray sources, Free Electron Lasers, Electron Microscopy, NMR etc. will also hugely increase our understanding of such phenomena but, as is always the case, more answers also lead to new questions and, given the uniqueness of neutrons, the availability of more intense neutron beams will ensure that neutron spectroscopy will play its part. All of these techniques, collectively and individually, are necessary to address the challenges of materials that face us in the 21st century.

The substantial increases in brightness offered by next-generation neutron sources such as the ESS will open up the study of systems *in operando*, particularly in materials and processes where light atoms such as hydrogen and lithium play an essential role where their motions are perfectly matched to the dynamic range of advanced spectrometers. Pinpointing much more precisely where such atoms are and how they move

under operating conditions will be crucial in developing next-generation batteries and hydrogen storage media through direct measurements of ionic or molecular transport during the charge-discharge cycle to extend stored energy and durability. Bright, high-resolution spectrometers will also provide unique insights into chemical transformations on catalysts under real operating conditions, complementing optical spectroscopy, which generally finds such systems to be opaque. Thus new pathways will be signposted for key European industries to increase energy efficiency and reduce costs as well as to develop processes based on new feedstocks that are not derived from crude oil.

Novel quantum states in magnetic and electronic materials are a new and exciting frontier of science. They challenge our understanding of the different states of matter, and will be at the core of future functional devices that will furnish our households, offices and factories. An example of such a state is an entirely new magnetic structure found by neutrons in a crystal of manganese silicide – a grid of magnetic vortices called skyrmions. These vortices may be moved and sensed using very low levels of electric power, providing the basis for new data storage technologies with very high density and energy efficiency. More brilliant, magnetically polarised neutron beams will provide the most incisive, direct probe – often the only probe - to sense such systems and explore the subtle interplay between electronic and magnetic degrees of freedom and the way they may be influenced by low-dimensionality or nanostructuring or strong quantum effects. Future sources promise to provide the best means of understanding some of the longest-standing problems in physics such as the origin of high-temperature superconductivity, as well as to establish new paradigms for future technologies based on spintronics or qbits for quantum computing.

At much larger length scales, there is also the challenge of developing lightweight, multifunctional materials as well as components that must operate in very harsh environments, in advanced engines or turbines, for

all forms of mechanised transport and for new power stations to meet ever more stringent environmental regulations, and to make better use of increasingly scarce resources. Here the penetrating power of neutrons provides the deepest insights into high-performance alloys for example. Future sources will enable such work to be conducted in greater detail and far more rapidly on more complex, multicomponent materials, under realistic fabrication and operating conditions.

The most exciting – but also the most challenging – potential materials for future technology are complex systems whose function depends on structural properties and dynamical responses over many scales of length and time, and over wide swathes of temperature and pressure, magnetic and electric fields or harsh acidic, alkaline or radioactive environments. Some scientific investigations require conditions where not only the sensitivity to subtle effects is enhanced, but also encounter situations where the feasibility and length of the experiment is mainly determined not by the neutron flux but by the availability of advanced sample environment (for example *in situ* experiments) not forgetting the time required to vary and stabilise these conditions (temperature, electric and magnetic fields, pressure, pH, flow rates, etc.) together with the skill and ingenuity of the researcher/instrument scientist experimental team. Not surprisingly the most advanced capabilities cluster around the highest flux sources, but not exclusively so if we take as an example the impressive high-field magnet newly installed at BER-II.

The swiftest progress in discovering such materials, and understanding how to manufacture and manipulate them most effectively, will be made through the use of a portfolio of complementary techniques, combining advanced neutron spectroscopy with synchrotron radiation, electron microscopy, or NMR and all brought together with powerful, integrated computational studies. Here, the whole is very much greater than the sum of the parts, and each and every one of the different experimental techniques plays an essential role.

I.3 The strengths of the neutron as a probe and aspects of its complementarity to other probes

The characteristics of the neutron that make it such an effective and unique tool are summarised in *Box IA* and *B*, where the neutron's scientific properties are described together with its societal impacts, thus indicating how neutrons can contribute towards solving society's grand challenges.

NEUTRONS ARE UNIQUE

They have extraordinary properties that
make them indispensable in modern research

Neutrons h ave wavelengths and energies that **allow us to obtain information on structural patterns** from 10^{-10} m to 10^{-2} m and dynamic events from 10^{-12} s to 1 s

Neutrons are deeply penetrating, **providing information from the hidden interior of a sample as well as from its surface** without the effects of beam-damage as encountered with electron or X-ray probes

Neutrons are the only scattering probe to **provide isotopic contrast**, providing a unique tool in deciphering the organisation of biomedical and soft-matter systems

Neutrons possess a magnetic moment making them an **irreplaceable probe for the study of magnetism**

The scattering of neutrons can be calculated exactly, making neutrons a **precise, quantitative probe of matter**. This property underlines the value of neutron experiments coupled to methods of computer simulation and modelling

Box IA. Scientific properties of neutrons

Taken from The Science Case for ESS [5].

NEUTRONS ARE UNIQUE

They have extraordinary properties that **help addressing society's grand challenges**

ENERGY

Energy storage, transport, conversion all benefit from neutron research. The investigation of properties of new energy storage materials relies heavily on neutron scattering. Suitable storage materials are analysed ***in operando*** using neutrons, for instance for transportation. Neutron scattering can help improve lithium batteries. The development of superconductors for energy transport relies on information from neutron scattering. In photovoltaic and solar energy research, neutrons are used to study the performance of solar cells

INDUSTRIES & MATERIALS

Countless materials are produced every day to make our life easier. Cars, planes, trains, turbines, cosmetics, laundry detergents, drugs, all are improved both in efficiency, quality and price thanks to information provided by neutrons experiments. Futhermore, developing advanced materials that support new technologies depends in scientists' ability to manipulate their properties at the atomic level, and neutron science is a key to these efforts. **Industrial innovation and competitiveness** rely on fundamental knowledge provided by neutrons on the behaviour of molecules, or the determination of inner stresses to develop components with higher performance

ENVIRONMENT

Thanks to their tremendous capabilities for analysis, neutrons contribute to the development of **clean technologies.** Neutron scattering helps scientists to fight pollution and develop eco-friendly processes that release fewer contaminants into the environment. Neutrons can provide information about rare elements and serve as a way to detect contaminants. Neutron techniques can help define the intrinsic nature of pollutants and its relationship with the substance they are polluting. Neutrons give insights into the role of clouds in global warming and play a role in the battle to curb carbon emissions

HEALTH & LIFE

Research is fundamental to fight diseases. Neutron scattering provides vital information that cannot be acquired using any other technique. Neutrons provide structural information of relevance to degenerative diseases such as Alzheimer's. Biological function and enzymatic action benefit from critical detail provided by neutrons on hydrogen bonding and hydration. Drug delivery benefits from neutron scattering studies which may result in new therapeutic approaches in the future. Fast neutrons can be used for the treatment of malignant tumours. Neutrons are also used for the production of radionuclides that are used in **medical diagnosis and radiotherapy**

ARTS & CULTURAL HERITAGE

Neutrons are an invaluable tool to analyse precious archaeological objects: they are **non-destructive** and can penetrate deep into cultural artefacts or beneath the surface of paintings, to reveal structures at the microscopic scale, chemical composition or provide 3D images of the inner parts of the artefacts. For heritage science purposes, whole artefacts can be placed in the neutron beam and analysed at room conditions, without sample preparations. Analysis can also be done under vacuum or other conditions, such as high or low temperature. The measurements are made in real time, which can be useful for testing conservation materials and methods

Box IB. Societal impact of neutrons

Taken from ENSA publicity at ECNS, Zaragoza 2015 [6].

(i) Its neutral character

Thanks to their net zero charge, neutrons are able to penetrate deeply into bulk matter and to delve into its properties, unlike a number of other probes that, although they investigate the same distance and energy (time) scales, are however predominantly surface probes in character. These scales range from 0.05Å to 1000Å and from 1 μeV to 1 eV (1 sec to 10^{-12} s) as shown in *Figure 2*. The interaction of the neutron with matter is both gentle, not imparting damage to the sample under study, and yet sufficiently probable that sensible-sized samples can be used to obtain scientifically unique data. Bulk behaviour can thus be probed at the atomic, molecular and magnetic levels. These characteristics also minimise the practical problems related to the study of samples over wide ranges of thermodynamic parameters. For instance it has become commonplace to carry out experiments under extreme conditions - very low or very high temperatures, high magnetic fields and high pressures, or with highly radioactive or toxic materials - or

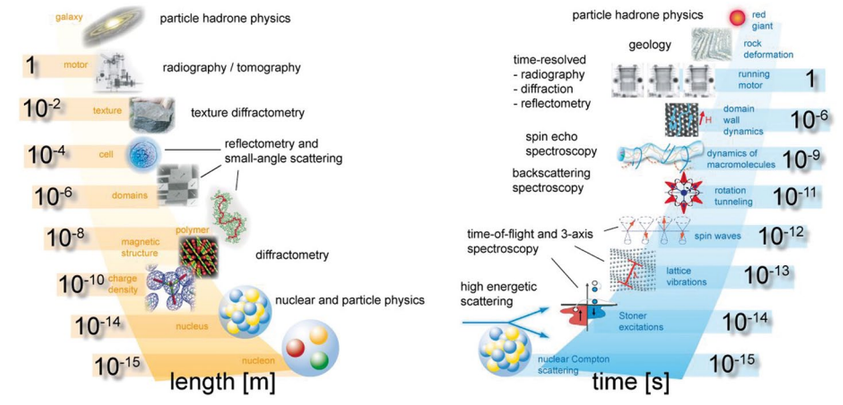


Figure 2. Lenght and time scales of neutron techniques

The length and time scales accessible to neutron techniques: scattering, imaging & fundamental physics. Image courtesy of the German KFN, 2011 [7].

studies of materials under manufacturing conditions - the extrusion of polymers or fully functioning electrolytic cells for example. Equally well the interpretation of data is highly tractable, since the neutron interacts with point nuclei or magnetic electrons rather than with the more diffuse electronic cloud.

As neutral particles that interact relatively weakly with most atoms, neutrons can penetrate into materials very readily. This property allows structure and dynamics to be studied deep inside samples – for example large engineering components - or samples held within bulky apparatus, such as is necessary to study systems at very low temperatures, *in situ*, or *in operando*. Furthermore, the weak interaction with matter means that radiation damage is very low, enabling prolonged and detailed studies to be made of soft matter and biological materials under ambient conditions. The low degree of perturbation of such systems by neutron beams means that the theory and modelling of structure and dynamics can be performed more directly because the interaction between the incident radiation and the system is simpler and thus there are fewer artefacts in the measured data and fewer assumptions are required in the theoretical interpretation.

(ii) Its low energy and long wavelength

A major feature of neutron beams that makes them indispensable for materials research is simply the mass of the neutron itself – essentially equal to that of the proton. This means that, when slowed down to appropriate velocities in ambient temperature moderators, they have associated energies comparable to those of the motions of atoms and molecules in solids and liquids, and also have wavelengths comparable to interatomic spacings, a knowledge of which is essential to an understanding of all aspects of their functionality. These parameters can be probed simultaneously. Neutrons therefore naturally access a two-dimensional parameter space, unlike any other probe. These characteristics are particularly relevant for the scattering from

hydrogen, enabling neutrons to reveal diffusional or vibrational/rotational behaviour of complex hydrogenated molecules for example. The added power of deuteration and polarisation for augmenting or suppressing contrast adds further to the neutron's utility. Almost all information on the coherent excitation spectra in crystals in momentum and energy space – phonons - has been obtained from triple axis neutron spectroscopy or its analogue on pulsed sources. The precise measurement of phonon dispersion curves has been one of the most elegant contributions made by neutron scattering to solid state physics. Neutron spectroscopy is also applied to magnetic systems, providing the most quantitative information about collective magnetic excitations – magnons - which govern the performance of many functional electronic materials, including the mechanism of high-temperature superconductivity. Neutrons therefore provide insights into processes over a wide range of timescales and energies, sitting comfortably between those of synchrotron X-ray spectroscopy which is typically used for energies above 100 meV (although exceptionally down to about 10 meV) and NMR measurements for energies well below meV levels, typically in the MHz region and slower.

(iii) Its magnetic sensitivity

Besides the important aspect of electrical neutrality, the main strengths of the neutron scattering technique are based on other special characteristics of the interaction between the neutron and matter. A very important characteristic of the neutron is that it carries a magnetic moment with spin 1/2. In relation to this magnetic character, there is thus a further type of interaction other than the nuclear interaction, in this case between the dipole moment of the neutron and the magnetic fields originating from unpaired electrons in matter. This interaction opens up the unrivalled possibility of studying magnetic systems at the microscopic level, as well as collective magnetic excitations. Almost everything we know about the magnetic structure of materials at the

atomic and crystal lattice levels has been determined - accurately and precisely - by neutron scattering, revealing the behaviour, for example, of potential novel materials for new recording media, including the single-molecule magnets that may provide the qbits for future quantum computers.

(iv) Polarisation, deuteration and a powerful but gentle probe

A further consequence of the neutron's magnetism is that, by polarising neutron beams, and by analysing the polarisation after scattering, insight can be gained into other aspects of sample properties impossible to probe by other techniques. It is fair to say however that this unique property has not yet been exploited to its full potential and further effort must be expended in order to do so. If we restrict ourselves to low energies (cold and thermal neutron scattering with incident energies between 1 and 100 meV), neutrons interact primarily with the nuclei of atoms, in what are intrinsically very short-range interactions. The cross section (for scattering and absorption) is strongly dependent on the different elements and even the different isotopes of the same atomic species as well as the energy of the incoming neutrons. Furthermore the neutron can be polarised or unpolarised, enabling the separation of nuclear and magnetic signals. This gives access to an array of different properties of the samples under study. Light atoms (such as hydrogen or deuterium, lithium, carbon, nitrogen, oxygen…) present cross sections to neutrons that are comparable to or much higher than those of heavier atoms. This is quite distinct from other probes. There is an inherent contrast - from element to element and from isotope to isotope in a given element – that is available to neutrons. This characteristic of the neutron as a low energy probe having relatively benign interactions with what are often sensitive samples is the basis of studies in biology and soft condensed matter. Furthermore, these characteristics prevent the sample from being degraded as can occur with a very energetic probe as mentioned above. In general, by using neutron scattering, we are able

to study materials comprising mixtures of heavy and light atoms, with different isotopic ratios, in the bulk as well as on the surface, with clear identification of atomic location and element specificity, and in addition revealing the collective and local movements of these atoms or molecules in solid or liquid matter through coherent or incoherent studies.

(v) Prizewinning

The simple message of the value of neutrons as a probe to study matter is stated succinctly in the celebrated phrase from the 1994 Nobel Prize citation to C.G. Shull and B.N. Brockhouse: "Neutrons answer the question on where atoms are and what atoms do".

It is very important to underline the fact that neutron sources (and indeed synchrotron sources) have been instrumental in the award of many Nobel Prizes. The role of central scientific facilities in the bestowing of such honours is best exemplified by the award of the Nobel Prize for Physics to Peter Higgs of Edinburgh University and François Englert of the Université Libre de Bruxelles. Deserved though this recognition undoubtedly was, it could only have happened thanks to the fact that the Higgs Boson was discovered at CERN after many thousands of man-years of effort and many billions of euros investment. Using a footballing analogy, "goals" in the shape of Nobel Prizes are frequently scored by university researchers whereas the "goal assist" is due to the large facility. A case in point for neutrons is the Nobel Prize awarded to Pierre-Gilles de Gennes for the theory of polymer reptation. Without its experimental confirmation at ILL, reptation would have remained a theoretical concept and there would have been no such Nobel Prize awarded. It is fair to say that the goal assist is never valued as much as the goal strike - it is not as eye-catching - but both are essential for success just as much in science as on the football field. Science at this level is more often than not a multidisciplinary and international team game with players of different talents contributing. There are many examples of the above "assist" phenomenon at neutron and

synchrotron sources. It is not within the mandate of this group to survey comprehensively the fields of scientific endeavour that have benefitted from neutron scattering, however it is a necessary adjunct to our report and for this we look to the user community through the European Neutron Scattering Association, ENSA, as well as the neutron sources themselves to do what is clearly necessary.

(vi) A versatile particle with diverse uses

We now emphasise the important additional uses of neutron sources, both reactors and accelerators.

Isotope production

These uses include applications such as silicon doping, so essential for the semiconductor industry and radioactive isotope production for nuclear medicine. Isotopes such as technicium-99 for cardiological diagnosis as well as bone investigation; lutetium-177 and strontium-90 (a precursor for yttrium-90) both used in immunotherapy; and ytterbium-169 employed in the diagnostics of small joint injuries, also come to mind.
Cobalt-60 is extensively used as a so-called gamma-knife for the treatment of brain tumours in hospitals, for radioactive tracing in agriculture, and in imaging. Domestic and office uses of radioisotopes are for smoke detectors (americium-241) and for the tritium (or hydrogen-3) used in emergency exit lights, as well as in production control for the paper industry and the food industry.

Activation analysis

Neutron activation analysis, where samples are irradiated in neutron beams, is one of the most sensitive analytical methods with very wide applications in areas such as forensic science, and art and archaeology where it is the primary method of measurement for quantitative multi-elemental analysis with excellent detection limits as low as $\mu g\ kg^{-1}$, in other words one part in a billion sensitivity.

Fundamental physics

As a probe, very slow neutrons are employed very effectively for fundamental physics studies: for example to sense the quantisation of the gravitational field, opening up possibilities to understand in detail the characteristics of the gravitational force, inaccessible by other means. It should be noted too that neutron beams are used to study the fundamental properties of the neutron itself – such as its lifetime as a free particle, neutron-neutron oscillations, and the possible presence of a very weak electric dipole moment, all essential inputs to understanding the dynamics of the Big Bang and the evolving structure of the cosmos today. Neutron interferometry has convincingly demonstrated that all quantum effects exhibited by 'waves' and specifically light are also exhibited by 'particles' such as neutrons. This has been a spectacular success. Here the use of very slow neutrons - Ultra Cold Neutrons - which are produced predominantly at reactor sources, are essential. The information obtained has much wider implications for fundamental physics, touching, for example, on the validity of the Standard Model and complementing the work performed at high-energy physics laboratories such as CERN. In fact it was at ILL that the first experimental observation of the so-called reactor anti-neutrino deficit was made, that led to an understanding of the solar neutrino deficit and the award of the Nobel Prize in 2015 to Takaaki Kajita of the University of Tokyo and Arthur McDonald of Queen's University, Kingston. Today further work is being carried out at ILL to probe the existence of so-called sterile neutrinos, Majorana neutrinos that are their own anti-particle, proposed by some as a component of dark matter.

Muons, γ-rays, positrons and fission fragment beams

In addition, neutron sources are used for the generation of other particle beams. We have already mentioned neutrinos, but the production of positron and fission fragment beams on reactors as well as the use of high resolution γ-ray spectroscopy for nuclei shape analysis, yield

world-leading results. The production of muon beams on spallation sources and the development of muon instrument suites, notably at ISIS and J-PARC has produced unexpected insights particularly in localised magnetism studies. All this leads to an affinity and complementarity between slow neutron studies and the research carried out with secondary beams derived from neutron sources. These ancillary techniques and the fields of science they cover are significantly broader than materials science and give added scientific impact to what are often thought of as simply neutron sources for materials science.

Unique expertise

Furthermore a number of European neutron sources are unique repositories of expertise, for example when credible, authoritative advice is required for government departments on nuclear matters as well as for the media and the general public concerning events such as the accidents at Chernobyl and Fukushima. The Delft reactor facility is a good example of this, undertaking this role for the whole of The Netherlands as well as providing radiological training for hospital staff.

(vii) Complementary to other techniques

As we have indicated however, neutron scattering provides a remarkably powerful probe of the structure and dynamics of a wide range of materials at the atomic and molecular scales which is unique in many respects, and which complements other investigative techniques based on synchrotron radiation, electron microscopy and nuclear magnetic resonance.

We do not attempt here to assess comprehensively the advantages and disadvantages of these different probes but rather we concentrate upon the strengths and weaknesses of the neutron as a probe and its availability now and in coming decades in Europe, remaining within our mandate. Nevertheless a few comments are appropriate.

Photons

Photons generated at synchrotron sources range from X-ray wavelengths to the infra-red. Synchrotron radiation has many similarities to neutrons in terms of their usage and scientific applications. Indeed the increasingly higher brightness of photon beams and, as a consequence, the finer spatial resolution attainable means that, in general, synchrotron radiation can probe smaller samples or smaller volumes of materials much more quickly than neutrons can, and especially so since robotic measuring techniques have become commonplace. With neutrons, such methodology has not yet been embraced fully. The intensity of X-ray scattering, as a function of the atomic number of an element, rises continuously and strongly with the number of electrons in the atomic constituents of the sample: light elements scatter only very weakly and different isotopes of the same element have essentially the same scattering strength; heavier elements on the other hand scatter very strongly and can dominate the overall signal, overwhelming the signal from lighter atoms. This means that neutrons are particularly effective at determining the positions of light elements such as hydrogen. The location of hydrogen atoms is crucial to an understanding of the function of biological molecules as well as those technologically important materials required for hydrogen storage and transport in the development of greener materials for energy. It also means that, by exchanging hydrogen atoms (H) in a material by deuterium atoms (D) and thereby enhancing scattering contrast, the characteristics of those particular exchanged atoms can be studied with greater precision allowing specific properties or focussed regions of biological or polymeric systems to be explored.

Synchrotron radiation is nevertheless the method of choice in order to determine the skeleton and much of the flesh of a molecule or macromolecule despite the fact that, generally speaking, the protons are rendered poorly. Protein crystallography has been one of the most unexpectedly successful, high impact areas emerging from synchrotron radiation sources.

Electron microscopy and diffraction

Electron microscopy and electron diffraction also provide essential insights into the structure of a wide range of materials. Recent developments in the technology of electron detection are now allowing structure determination of soft and biological materials to near-atomic resolution, though only for very thin samples. For nano-crystalline samples (100 nm size range), single crystal electron diffraction can yield true atomic detail.

Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) has seen a rebirth in recent years, in particular thanks to advances in high magnetic fields, used not only to polarise the nuclei, but most importantly to drive quantum phase transitions. As a sensitive, element-selective, non-perturbing local probe, NMR often excels when demanding (field, pressure, or temperature) conditions are required, often making it one of the only techniques available. NMR is complementary to neutron scattering in many respects. These include the required sample nature and dimensions, the accessible time scales, the partial vs. full access to the spectrum of excitations, and in terms of both energy scales and momenta. Researchers therefore have a powerful tool to access new and unexplored phenomena.

I.4 Neutron sources and their performance - a comparison of fission sources and spallation sources - a comparison of pulsed sources and continuous sources

Of course the two greatest drawbacks of neutrons as a probe are intensity and availability: firstly because of the relative weakness of even the world's brightest neutron sources; and secondly because of the paucity of such sources especially - in both aspects - when compared to photon sources. The consequences of these drawbacks cannot be overstated and they are the motivation behind the striving for increased intensities of sources and improved performances of instruments.

(i) Fission, and Reactor-based sources

Neutron beams, at their most intense, are produced either via nuclear fission in a high power-density, purpose-built research reactor or by spallation using a particle accelerator driver, where a heavy metal target is bombarded with high energy protons. At the moment of generation, neutrons from both kinds of source are fast and highly penetrating, having energies ranging from MeV to GeV. To be useable for materials science the fast neutrons are slowed down to sub-eV energies in hydrogenous moderators held at different temperatures. Regardless of how they are produced, these slow neutrons have several defining characteristics that make them particularly versatile in exploring matter, as we point out above. Their velocities are associated to both a wavelength and an energy that correspond precisely to the scale of interatomic spacings and to molecular, magnetic and crystal vibrations. The colder the moderator, the slower the neutrons are in the emitted beams and the longer their wavelengths are, thus providing the flexibility for measurements on a single source to be matched to the needs of the scientific application.

The first nuclear reactor CP-1 was made critical in Chicago in December 1942, quite remarkably only 10 years after the discovery of the neutron itself by Chadwick in 1932. It was then a simple step to extract neutron beams from such a set-up in order to use them for the study of materials as a parasitic application. Initially the materials studied were those that featured in the construction of nuclear reactors themselves and, of course, in weapons. A knowledge of the vast but then unknown data base of neutron cross-sections as a function of energy, for both scattering and absorption processes, was very necessary. In parallel, electron accelerators, which generate neutrons by photofission, were also developed since, with their narrow pulses, they could measure the energy dependence of neutron cross-sections with high precision, especially in the troublesome keV region where undesirable absorbing resonances occurred. These resonances – their strength and their shape - had to be understood in order that their effects could be minimised in component design for nuclear devices. Reactors generate continuous beams of neutrons rather profusely, with polychromatic spectra, whereas electron linacs are sharply pulsed. By time-of-flight techniques, the neutron beams from linacs can be energy-sorted with precision and cross-sections measured. A parasitic use of electron accelerators was for pulsed neutron diffraction and spectroscopy and these instruments were the precursors of today's spallation source instruments. The big impediment of electron linacs is the intense flash of gamma radiation when the electron pulse hits the target, which is a limitation for short wavelength neutron applications. Nevertheless many of the instrumentation ideas for later spallation sources were prototyped on such machines.

Despite the profusion of neutrons created by neutron sources, only a small proportion of these can be used. Why? Well, neutrons are difficult to direct spatially. They are generated, to a first approximation, isotropically in contrast to synchrotron radiation which is delivered in finely collimated beams directly to the instruments. Broadly speaking

neutron instruments can access only those neutrons that are directed towards the beam lines or neutron guides from the source, following moderation. This is the fundamental reason why neutron sources are perceived as weaker than synchrotron sources and why continuous advances in neutron source strength and instrument capability and utilisation, and indeed the number of instruments on any given source, are primordial in order to be able to profit from the clear benefits of slow neutrons for materials science and, importantly, to be able to harness the complementary nature of the two different radiations. Neutrons are undoubtedly the method of choice for many areas of materials science. However, when one type of radiation source - in terms of quantity rather than quality - is dominated by another, the concept of complementarity can become meaningless, no matter what enticing properties one type of radiation may have compared to the other. For this reason taking every opportunity to enhance the data rate of neutron instrumentation enables the specific qualities of both radiations to be employed to mutual scientific benefit. One could cite the fineness of synchrotron radiation beams and thus the smallness of samples vis à vis the readiness of attaining high energy resolutions with neutrons as two orthogonal and mutually unbeatable advantages, to take but one obvious example of complementarity.

(ii) Spallation, and Accelerator-driven Sources

As the field progressed and accelerators were used to generate high-energy proton beams, their use for neutron production by spallation was pioneered at Argonne in the USA and Tsukuba in Japan, beginning in the 1980s when reactor sources were still of course very much pre-eminent. The quest for higher intensities at the instrument was the driver for this. Instrumentation at reactors was however far better developed than at pulsed sources since the high flux reactor sources such as the Brookhaven HFR and ILL were able to build upon earlier tried and tested developments at Oak Ridge, Harwell, Saclay, Delft, Studsvik, Risø,

Mol, Wuerenlingen, Casaccia, Budapest, Rez, Warsaw, Kjeller, Athens, Belgrade, Vienna, Jülich, Karlsruhe and many more places. There were many reactors, many instruments and, importantly, many instrument concept developers and builders. The era of a thriving, broad network of neutron sources, particularly in Europe, was at its pinnacle. When the first medium power spallation source came into being (ISIS in 1984) with its microsecond long pulses, a Venn diagram could be drawn at that time illustrating the relatively limited overlap of the two types of source that was thought at the time to be set in stone. The complementarity in those days was clear and reassuring. Reactors were for thermal and cold neutrons and pulsed sources were for thermal and epithermal neutrons. As experience was gained at ISIS and elsewhere, building upon earlier work on electron linacs and at Argonne and Tsukuba, it gradually became clear that the overlap of the two kinds of source was far greater than had first been assumed. Coherent excitations could indeed be measured on pulsed sources, rather beautifully in fact, and there was a profusion of cold neutrons, which resulted in the popular technique of neutron reflectometry emerging first of all from pulsed sources (initially at IPNS near Chicago and later at ISIS) rather than at reactor sources. There was an immediate impact with high resolution powder diffraction, and microelectronvolt excitations could, surprisingly, be rapidly measured. On the other hand the heralded extension into electron-volt excitations, opening up an unexplored application of neutron scattering, did not materialise with the advent of pulsed sources. This increasing overlap of the applications of the two types of source was a dynamic effect and changed considerably with time as further experience with spallation sources was gained and the received wisdom was modified. With the unexpected success of the cold neutron instruments at ISIS, and the consequent building of a second target station dedicated solely to cold neutrons, in parallel with the falling away of the applicability of epithermal neutrons, the Venn diagram today would show much more overlap between continuous sources and short pulse sources,

although this overlap is by no means complete. A significant degree of complementarity still remains.

(iii) Intercomparison of Specific Sources

As we can deduce from the above, the future potential or actual performance of different neutron sources cannot be properly represented by a precise number on a one-dimensional scale. Even more difficult is to attempt to render other complementary radiation techniques on this hypothetical absolute scale. The output of any given experimental investigation – what we can learn from an experiment - depends instead on a subtle combination of factors:

- the neutron production source, its intensity, its spectrum, any intrinsic resolution and its reliability;
- the neutron instrument suite in terms of quality and quantity;
- the ancillary scientific support facilities;
- the sample environment; the software needed both to control the instruments and to access, visualise and analyse the data;
- the access mechanisms; and last but certainly not least
- the human support and the chemistry that develops between the different actors.

Nevertheless attempts have been made to distill source performance down to a single number, and indeed this is frequently demanded when the case for new sources is being developed. This need has resulted in the Brugger-Price-Carpenter-Lander plot that has, despite its evident flaws, been reproduced and modified many times, as shown in *Figure 3* in the following page.

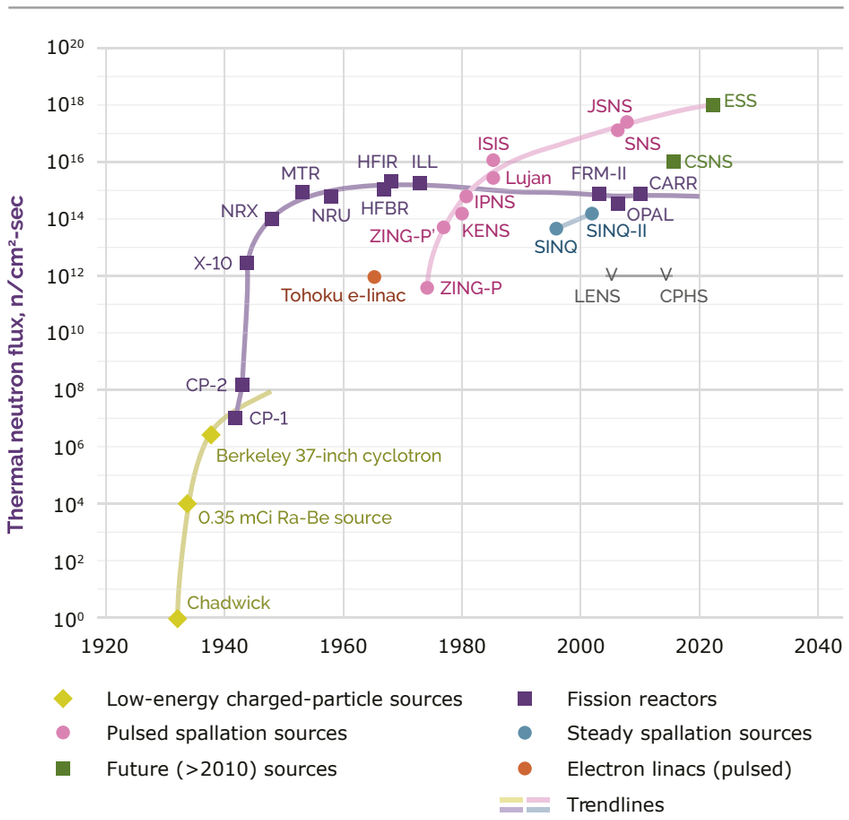


Figure 3. Thermal neutron sources fluxes

The evolution of effective neutron source fluxes as a function of calendar year, from the discovery of the neutron in 1932 to the time horizon of this report. HFIR, ILL, ISIS, SINQ, SNS, JSNS and FRM-II (MLZ) are still operational and CSNS and ESS are under construction. Adapted from image courtesy of Gerry H. Lander.

(iv) The European Spallation Source ESS

Nowadays, with the advent of ESS where its ~3 ms proton pulse will be 5000 times longer than the ~0.6 μs pulses of ISIS, SNS and J-PARC, the complementarity question arises once again. ESS is a so-called long-pulse source, with a longer pulse even than the recently refurbished IBR-II pulsed reactor. What is the perceived/predicted current/future

instrumental/scientific overlap between the present reactors and short-pulse sources on the one hand and a unique, first of its kind, long pulse source such as ESS on the other hand, and how might that evolve over the coming 20 years? If past experience is a reliable guide, there will be both unforeseen successes and unexpected failures within ESS's first suite of instruments. There is significant difficulty in predicting where the instruments on ESS will make most scientific impact partly since this new flagship source is its own prototype. There have been no medium or even low power long pulse neutron sources prior to ESS. IBR-II in Dubna is the closest example, where nevertheless its pulses are still only one tenth as long as at ESS. ESS will undoubtedly define its own areas of high impact as the years pass and experience is gained. These uncertainties will require a high degree of acceptance by both the governing and funding bodies and the user community itself if ESS is, ultimately, to realise its undoubted scientific potential and set a new world standard. Inevitably the rebuilding of some instruments will be necessary, as was true at both ILL and ISIS, and this must be viewed as part of the process.

The central question then is whether and to what extent ESS can be expected to replace all of the functions of a major tried and tested source such as ILL and how predictable this process is, and on what timescale. ILL has delivered admirably over decades and remains the recognised world leader. Indeed the user community looks to ESS to explore and break through into new, exciting and unknown areas that current sources cannot address, and what are these areas? The answers to these questions are of course impossible to predict but what further mitigates against the commonly held premise that ESS is a replacement for ILL is that ESS will have only 22 instruments, and only 16 of these are currently within the capital funding envelope. The remaining 6 are proposed to be funded from the annual operating budget, which adds a further element of uncertainty to the attainment of full specification. We recall that ILL has ~40 different instrument stations. Whilst the enhanced quality and

increased intensity of ESS is undoubtedly important, this is balanced by the more limited number of beam-days and an inevitably relatively slow rise to full specification.

Therefore with 16 instruments, and even with 22 instruments, it is asking a lot of ESS to take over the mantle of ILL in the medium term and three conclusions emerge:

(i) A vision for ESS must be laid down now that provides for many more instruments, securely funded;

(ii) Expectations for ESS must be calibrated to the probable reality;

(iii) ILL must be nurtured until such times as reliable experience has been gained on what are the high impact areas of ESS.

(v) More than simply neutrons

The raison d'être of a world-leading source such as ESS is to provide the best resolution and the highest intensity possible, far beyond what can be done today. This is key for the exploitation of neutrons in those high profile research areas of extreme environments, nanomaterials and life sciences, each of which is coupled to an important societal need. The new spallation sources are a key factor in this development but they have yet to surpass the integrated high quality scientific output of the most effective reactor sources, as underlined by the output of high impact papers from the leading global neutron sources shown in *Figure 4*. This figure also serves to show the rising scientific impact of spallation sources such as ISIS and SNS. However a broadly-based expert community of user-groups, each with a wide-ranging, grant-dominated research programme, cannot thrive with only a few sources and with a limited number of specialist instruments, without access to less powerful complementary versions to provide essential additional capacity. Just as is the case today for synchrotron radiation, it is important to bear in mind that a critical mass of experimental opportunities to access neutron instruments is essential in order to sustain the research community and

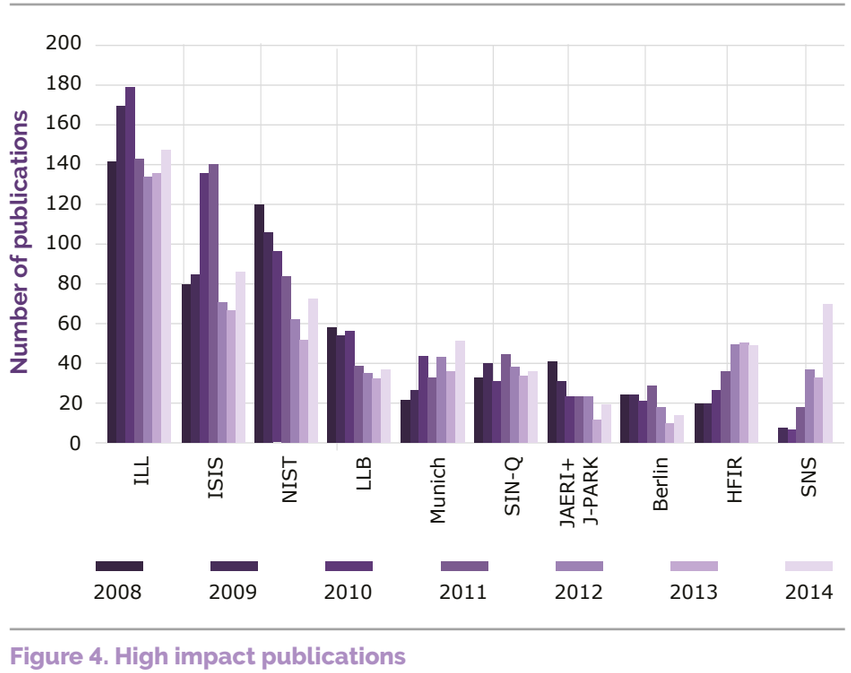


Figure 4. High impact publications

Number of papers published in high impact journals using data from leading neutron sources around the world, up to 2014. Adapted from image courtesy of ILL: Christian Vettier, Helmut Schober & Bill Stirling.

the technical expertise necessary to underpin any thriving scientific discipline. With fewer sources there is a need to provide proportionally more work-horse instruments at ESS.

Access to both neutron and synchrotron instrumentation is highly competitive, resulting in the fact that oversubscription remains at a high level even when capacity increases. This has been clearly demonstrated at ISIS when the additional instrument suite on its second target station was commissioned, and also at ILL where the Millennium Programme of instrument upgrades has resulted in a factor of ~40 increase in data rate over the whole instrument suite over the last 15 years. Demand has been maintained.

A key question then is 'how much capacity does the European research community need, and what would be the impact of a significant reduction compared to the current level of provision of neutron beam days?' It is sometimes said that the loss of instrument beam days in coming years that is indicated by our survey (see below) would merely result in the pruning of lower quality research which would, it is asserted, be a good thing and would result in a leaner and fitter research community. We do not subscribe to this view either in the case of neutrons or in the case of synchrotron radiation, since the evidence does not support such assertions. The level of oversubscription on neutron instruments has remained constant whenever there has been an increase in supply, indicating that the quality of scientific demand does not show signs of weakening. Some of the current capacity is also vital for more exploratory measurements – for example for researchers new to neutrons or from emerging disciplines, or to prepare the ground for more precise or incisive experiments at more powerful facilities and this makes much better use of the time there. A loss of a significant proportion of instrument beam days, as our survey indicates, would therefore inevitably result in a significant loss of high quality science as well as applying a brake on the future generation of users and we warn against this kind of thinking.

(vi) Decommissioning

Decommissioning nuclear facilities has a high cost and is a specialist undertaking. Motivation is key as is not delaying the process so that those staff knowledgeable about the facility can be engaged. Decommissioning of course not only removes the hardware but also will remove the expertise that has been built up over years and indeed decades. It heralds a period when annual costs do not fall significantly but scientific experimentation ceases, even though data analysis and publication of results will continue for some years. Thus wise decommissioning plans take into account both aspects and make serious

attempts to retain the expertise for the future good of the discipline.

As the first new neutron source in Europe for more than a decade, ESS was required to define the decommissioning costs as part of the Full Lifetime Costs in order that owners and potential partners be made fully aware of their commitments. ESS decommissioning plans will be in compliance with Swedish authority requirements, defined for non-nuclear research facilities (as ESS is designated) in the relevant documents of the Swedish Radiation Safety Authority (SSM) and also align with the guidance provided by the Swedish Nuclear Fuel and Waste Management Company (SKB). In a 2008 study the cost of decommissioning ESS was estimated to be 173 M€.

In 2013 ISIS changed the basis of its decommissioning provision. ISIS benefits from being a component, albeit an important one, of a larger multifunctional national laboratory, the Rutherford Appleton Laboratory. On the assumption that the laboratory would continue its mandate when ISIS enters into a decommissioning phase, and would continue to do the same sorts of science, the new approach is to remove the highly active components (which fall within the ongoing operations costs in any case), and store the remainder until it has decayed enough to be disposable as normal waste (~20 years). The cost estimate in 2013 was 23 M£, which seems to be modest.

According to EU rules for nuclear facilities, which are automatically adopted by national governments, the decommissioning costs for ILL and FRM II are as follows.

The decommissioning of ILL has been under study since the turn of the century. In 2015 this cost was estimated to be ~246 M€ and is planned to take 6 years. A further adverse effect of decommissioning ILL will be the impact on the whole "polygone scientifique" of Grenoble and this would be not welcome at a time when a major investment in upgrading the ESRF is underway. The synergy between the two labs has been real and

the loss of it would be a collateral effect that would render damage to the ESRF and the whole site.

The total cost of decommissioning FRM II (all administrative procedures according to atomic legislation, complete decontamination, demolition of the buildings, storage of all radioactive waste, etc.) is estimated to be 269 M€, in 2014 values. Note that the storage for spent fuel is not included in these costs, since they are taken care of within the operational costs, which is the case for ILL also.

ESFRI quite correctly has been examining the "end stages of the RI lifecycle". What doubtless will be taken into account in such an examination is the trade-off in terms of cost-benefit analysis between continuing to operate and producing scientific output for a known cost, and decommissioning earlier than technically or scientifically necessary with uncertain costs.

The sunsetting of research infrastructures is far easier, strategically, politically and scientifically when there is a suite of such facilities under one umbrella. We see that today with the delicate situation that now exists in Hawaii with respect to the Thirty Metre Telescope. Bargains can be struck.

I.5 The situation that the European neutron community finds itself in today

(i) A Golden Age!

European scientists who use neutrons as a tool in their research programmes can today consider themselves to be in a golden age. The ILL is without question the world's most productive neutron source and it is likely to remain in that situation for some years. ILL benefitted from a forward-looking and innovative design, including extensive neutron guides and cold sources and it has placed Europe in the forefront of this discipline. Equally well the injection of much-needed investment since the turn of the present century has increased ILL's effectiveness considerably and maintained its leading position in the world. This has been helped by competition from sources such as ISIS, demonstrating once again the positive impact of the broad neutron park in Europe. Europe cannot claim the gold-medal position in many scientific disciplines but this is indeed one and it should not be relinquished passively. ESS has the potential to strengthen this position but only providing that it is fully instrumented and there is suitably coherent support for the wider infrastructure for neutron scattering in Europe, including ensuring that at least some of the strengths of the wide network of excellent national sources are maintained.

As a nuclear facility, the ILL has had, to its great credit, an exemplary safety record and it has benefitted from quasi-continuous upgrades to its neutron production side thanks to the demands placed upon it by safety authorities. It has also had investments in instruments and ancillary scientific support capabilities, notably the highly successful Millennium Programme. There has been no sign that this investment is diminishing. However the ILL suffers from an assumption that it will, in the foreseeable future, be shut down. There is a sword of Damocles hanging over it and this does not inspire confidence in any of its beneficiaries

i.e. the user community. There is a certain self-fulfilling aspect to such discussions which the neutron community should be watchful of. The closure of the ILL is far too often linked to the advent of the ESS. As mentioned above this linkage is not appropriate and pro-active initiatives should be taken by these self-same beneficiaries to weaken this perception.

In addition to ILL there is a network of other sources that gives structure and function to the health of neutron scattering in Europe. This enviable situation has existed for 3 or 4 decades now and has led, far more than it has in other parts of the world, to a very diverse and numerous user community. It is evident from the data that we have gathered that the bigger neutron sources in Europe contribute disproportionately to the quantifiable scientific output of neutron scattering and this fact might lead some to draw false conclusions about the value and purpose of the smaller sources. The smaller sources serve an essential function and that is to act as a nursery for new instrumental ideas and to train the next generation of neutron instrument scientists, as opposed to the users of neutron facilities who come from academia in general. Important also is the fact that having a distribution of sources helps to diminish the air of mystery surrounding the use of neutrons. Such a sensation does not exist for photon sources where every researcher on every synchrotron source instrument has learned his or her trade on the x-ray sources that are found in each and every university in Europe. To add to the perception of a golden age, Europe is now engaged in building the ESS. The instruments at ESS will be up to 50 times more intense than at any currently existing neutron source lending real weight to the perceived air of optimism.

(ii) A Golden Age?

However, the ESS will in the foreseeable future have only a limited instrument suite and it will require quite some years to reach full specification. If it should be necessary to rely on a few large sources,

the status quo of neutron scattering methodology and the scientific output will be diminished significantly. The neutron drought that so preoccupied neutron scientists 20 years ago and which was well-documented in the study by Richter and Springer [8] has not come to pass. This is because, whilst some neutron sources have indeed closed, investment in instrumentation and in certain splendid initiatives, such as the second target station on ISIS, the full instrumenting of FRM-II (MLZ), and the ILL's Millennium Programme, have maintained Europe's position up to now. It is therefore tempting, indeed it is comforting, to assume that this state of affairs will simply continue and that the present air of optimism in some quarters actually corresponds to future reality. Reducing the number of sources whilst increasing their capacity and impact will ensure that all will be well. But this is a false view. Springer and Richter were not wrong in their conclusions but rather they had heralded the neutron drought a decade or two too early by not factoring in the improvement of instrumentation that has taken place as a response. Their warning has had the very beneficial effect of provoking that much needed investment, but it has not stopped the closure of sources. After this ~20 year period of grace it is now much more certain that the majority of neutron sources in Europe will close within a decade. This is borne out by our survey, and the neutron community therefore faces the very real prospect of having very few operational neutron sources in Europe by 2030. Should that occur then, without a replacement of those sources that are closing, a significant reduction of neutron availability in Europe and a concomitant loss of expertise and scientific output will occur.

(iii) Future initiatives

It is worth repeating that neutron scattering started as a parasitic use of research reactors built for the development of nuclear technologies, materials testing under irradiation, isotope production etc. This parasitic situation was mirrored in the case of synchrotron radiation, which also

emerged as a spin-off use of HEP accelerators. Nowadays, which has been the tendency in recent decades, single-purpose sources are built – both x-ray and neutron - specifically for materials science applications. To provide the necessary base load for neutrons, beside those very few large state-of-the-art sources being commissioned and built today, new, intermediate-power spallation sources or the extension of life of reactor-based facilities are therefore necessary. Life extensions for existing facilities are particularly cost-effective since the capital investment has already been made and the instrumentation and staff with expertise exist on site.

So this solution alone is not the answer, since it will only defer the inevitable problem. At some point, the necessary replacement of closing sources themselves must be faced up to. New medium power neutron sources must be built both to satisfy the demand and to maintain a solid foundation that will allow new ideas in instrumentation and science to be generated, by trial and error often, and as a nursery for the training of instrument scientists and instrument builders as well as entry-level researchers.

I.6 The changing dynamics of neutron use

As for all scientific disciplines, changes in best practices and methodology evolve over time as instrumental capability changes. These changes are often incremental but on occasions step changes occur. We foresee such a step change in the near future for the producers and users of neutron sources caused by the reduction in the number of sources and the dependence upon a few world-class sources. In such a scenario there is little opportunity for users to engage in instrumentation matters. This has far-reaching consequences since the neutron community is becoming very distinctly bimodal – the producers and the consumers. In high-energy physics and in astronomy this polarisation is not as complete as it is in fine analysis infrastructures where the synergies strengthen the whole community. This evolution is not necessarily a bad thing, but it does require to be recognised and be acted upon in order to optimise the scientific output of today's facilities and to be better adapted to a different future landscape. The need to try to change the relationship between facilities and the diverse user communities in academia and industry to exploit their potential more fully is therefore both important and urgent.

(i) The Front-Line Stakeholders – the Neutron Community

Today there are two distinct communities that together make up the neutron community. These are the providers of neutrons and the users of neutrons and there are well-defined differences between the two groups. It is therefore worth exploring this because it has a bearing on the expectations for the provision of neutron facilities and indeed on the dynamics of the interaction between the two different communities and hence on the level of success of individual experiments and the scientific output, which extends also to planning for future sources.

Also, as we look to the future, this "two cultures" community influences greatly the planning and provision for new facilities. In the early days of neutron scattering, carried out exclusively at atomic energy establishments, those who lobbied for sources, those who took responsibility for constructing them, those who designed and built the instruments and those who used the instruments and did the science were one and the same "single-peaked" community. Today the neutron community is "double-peaked." This situation does not yet apply to high energy physics or astronomy where the communities are much more integrated and broadly-speaking pursue the same ends. Accordingly those communities have ambitious, interleaved, successive proposals for future facilities ready and waiting, even whilst the world-leading facilities they are currently working on are either unbuilt or are not yet at specification. Thus no group of people is working on a successor to ESS, there is no infrastructure to do so and there is no appetite to do so. Source directors, managers and funders are fully focused upon operating their own facility and fighting for funds. Researchers are equally fully focused upon their research programme. There are no margins to devote to an activity so distant in implementation and so apparently irrelevant to today's demands. It seems to be too early, ridiculously so, to think about a next generation world-leading neutron source, but we must underscore that ESS has already taken 27 years to get this far and it will take another 13 years to achieve full specification with a complete 22 instrument suite. Starting today it will take a minimum of 40 years, and probably longer, to get a successor to ESS. This takes us to ~2060. On current planning and costing figures, ESS is scheduled to close down in 2065. There is a lot to learn from the astronomers and the high energy physicists, and the long-term future of neutron science depends upon it.

The following are, of course, rather general differences and there is significant overlap between the two groups, but nevertheless significant distinctions still remain.

- Providers tend to be physicists and engineers by training, whereas the user community covers an increasingly wide range of scientific disciplines ranging from pharmacology to geology and a rich range of disciplines in between.
- Providers are, by culture, predominantly national/international laboratory scientists who have evolved within the rather formal, hierarchical framework of such laboratories. Users on the other hand are from academic institutions where the culture is very different. Diversity and independence is therefore more evident in the user population than it is in the provider population.
- Providers tend to constitute a youthful and enthusiastic team at the outset of a big facility, but often a large proportion of them age in synchrony with the source itself. This is evidenced in data from the ILL where the average age of staff was rising by 1 year per year elapsed in the first years of this century. The academic population is ever-changing and flexible, particularly at the younger end of the age spectrum.
- Some provider scientists make the transition from national/international laboratory status to academia at the mid- to advanced career stage; fewer make the reverse transition with the notable exception of direct appointments to directorial positions from academia. This exchange process could be encouraged to mutual benefit.
- Providers have a significantly longer time horizon than users have in achieving their goals, by a factor of five at least. To contribute to the eventual realisation of a large neutron source, dedication over 30 years is not unusual and to build and commission a new instrument takes 10 years before the first research paper is produced. To successfully prosecute elements of an ongoing academic research project however takes 3 to 5 years. This time-scale is partly defined by grant-giving bodies, by the duration of a doctoral student's thesis

work, and the need to publish prolifically in order to progress in one's career.

- Providers operate from their home base and "know the ropes" whereas users are, in the main, short-term visitors or, less frequently, longer-term guests. This can create impediments against entry-level users though most facilities work hard to minimise such barriers.

A successful neutron source (and indeed any large central research laboratory whose function is to serve primarily visiting researchers) recognises openly the above differences between these two groups and makes conscious efforts to harness and harmonise them in order to generate the best science in terms of quantity and quality. The consequences of not doing so can create divergent goals and poorer science will inevitably result and indeed a less than optimum leverage of scarce research financing will be the outcome. There is a case to be made for exploring how to lower these barriers further, for example by joint appointments and exchanges at all levels of an organisation, in order to achieve better mutual understanding and to strengthen scientific collaborations and hence output.

(ii) Industrial potential: underexploited and underserved?

There is a special class of user, the industrial user, which would benefit from a radical rethink of industrial access. Industrial researchers in general have very well-defined goals and their need is often not to publish in academic journals and present results at conferences but to obtain information that will benefit the industrial effectiveness of their specific company by solving a manufacturing problem or by increasing competitiveness in a tight commercial environment. Many industrially and technologically important experiments fall into the category where the main issue is to gain access to measuring facilities within a reasonable timescale. Academic researchers would also benefit from more immediate access to beamtime but they are mainly engaged

in ongoing continuous research programmes where they have adapted to the flow of the proposal round culture such that quasi-continuous interleaved access can be achieved.

Industrial users are very different from academic users. They are often thought to be conservative preferring to rely upon traditional experimental techniques, well-established in industrial research culture. However many industrial users are more innovative and open minded than many academics – and in general scientists in industry are at least as creative and open to change as university researchers. Neutron source operators and funders must ask whether we are "missing a trick" in failing to harness the innovation of industry in neutron scattering. In photon science, industry has driven much of the innovations in key areas in recent years – e.g. robotics, high throughout and streamlined data processing. What industry seeks is "values, numbers, and metrology" that can allow processes and products to be engineered. Industry can use innovative results as far as they are not qualitative. Physicists are less interested in absolute metrology as they look at phenomena. Here there is a barrier that extends of course to the "access to data". Only calibrated data that could fit into some sort of "certification" will be used by industry.

Industrial users are endowed with a strong economic mindset and therefore need special motivation and treatment (e.g. free pilot experiments) to convince them of the potential benefits of neutron techniques, which are expensive and long-term, and we emphasise that industry looks for timely results to specific problems. To serve this important technological use it is once again essential to have a sufficient number of instruments where industrial investigations can be carried out. Academic scientists thrive by publishing and communicating their findings, whereas there is a strong culture of confidentiality engendered by industry that contrasts starkly with the openness essential for academic research to flourish. Nowadays the concept of "open

innovation" is replacing the older proprietary research scheme. As far as basic understanding of things to be applied is concerned, the openness is less of a problem today. Only the last stage, development or packaging of products to market is secret. Nevertheless the scientific essentials addressed by industry and academia, despite coming from different perspectives, have in many cases a very strong overlap.

How do we address this polarisation of cultures? A strategic effort has to be applied so that the barrier to increasing the exploitation of neutron laboratories for industrial or commercial ends can be overcome. True industrial use of neutron sources (and indeed synchrotron sources) is hard to determine. Industrial activity that veers towards basic research and is of longer term than the "problem-solving" type of access described above, is almost always carried out through industry-financed research contracts with university groups who "know the ropes". In this situation both the industrial sponsor and the sponsored academic group are often reluctant to reveal the mutual support that they receive. The perceived wisdom is that such access via research contracts is at a ~25% level. This figure far exceeds the 1-2% of beam-time that is sold to industry and which is the only quantifiable indicator that sources have access to. The 25% figure is not quantifiable although it is much more important to know it, especially when it comes to political support for the funding for current sources and indeed capital investment for future sources. This needs to be addressed urgently.

We recommend that the whole question of industrial use of large facilities for the fine analysis of matter be addressed in a fresh, open-minded manner, looking for radically new approaches.

(iii) Innovation

Related to industrial activity, but different from it, is the whole question of innovation. It is important to make the point that large research campuses hosting both synchrotrons and neutron sources, as well as electron microscopes, material science and nanoscience laboratories, biological partnerships etc. are innovation engines. We believe this has been understated in the past and certainly underexploited. These campuses (Grenoble, Harwell, DESY/XFEL, Villigen, Berlin, Saclay, Lund in perspective…) do represent open innovation hubs that have a high value since the potential is broad and provide opportunities for coordinated activities (such as the sharing of ancillary facilities and the sharing of competences) that represent a suitable instrument for both fundamental science and innovation-oriented technology development.

Innovation activities stemming from neutron sources or synchrotron radiation sources need to be thoroughly addressed by defining measurable performance indicators and benchmarking with other scientific domains and infrastructures. The facility staff and users must be aware and trained to exploit the innovation potential of their research work, with the professional help of dedicated innovation exploitation units or networks.

I.7 The current status of neutron sources and instrumentation in Europe

(i) Data from the European Sources

In order to obtain up-to-date statistics concerning individual source operations, the Neutron Landscape Group asked each neutron facility head in Europe to complete a detailed questionnaire. We provided guidance to the sources on definitions (e.g. what constitutes a "day for science") and, apart from a few clarifying queries, **we have accepted the responses as presented to us**. The data summarised below therefore represents the direct responses from the sources themselves. We have made no attempt to normalise the responses nor to add our judgement in order to adjust their numbers. We are well aware that there are inconsistencies but we have taken the view that the uncertainties in the data and the inconsistencies are of the same order. We are more interested in the overall global scenario than in details. Some sources chose not to answer some questions or to modify the questions that were asked. We have made no attempt to insist upon rigidity in this respect. A fusion of the responses is given in the *Tables IA, B* and *C* below. The data was collected during the summer of 2014 and has not been adjusted for recent developments at ILL, BER-II or LLB which have in the interim already signalled a fall in beam days. To counteract this, operational funding for ISIS has improved somewhat. This means that on balance the baseline presented below actually overestimates the number of instrument days currently available for research with neutrons.

Table I.A Source Information

Facility	Power MW	First neutrons achieved	Full source specification reached	Major refits	Top 3 risks	Foreseen closure	Replacement value
ILL	57	1971	1973	1993/5 Vessel 2002/6 Reactor & Instruments 2013/4 Reactor	Availability of fuel. Increasing fuel cycle cost. Safety regulations cost.	No. Earliest 2030.	2000 M€
ISIS	0.2	1984	1994	2nd harmonic (+50% power) 2nd Target station & 11 instruments	Staff retention - salaries below market values. Rising electricity costs. Uncertainties of user community (related to source availability in Europe).	No. Continuous re-lifting and renewal of accelerator.	800 M€
LLB	14	1981	1981	None	Decrease of resources (finance & staff). Nuclear acceptance. Reactor major failure or fuel supply disruption.	Yes by 2020. Technically 2031.	400-500 M€
FRM-II (MLZ)	20	2004	2004	New guide hall	Changing Regulatory requirements. Lack of qualified manpower. Budgetary issues.	No. Beyond 2044.	600 M€
BER-II	10	1973	1974	1985 to 1991, from 5 to 10 MW. Be reflector, cold source + guides.	None, due to defined shutdown date of December 2019.	Yes. Definitive shutdown at end of 2019.	85 M€ (acquisition cost) Nearer 400 M€ today
SINQ	1	1996	1998	None; continuous upgrades.	Key accelerator component failure. Heavy water tank leak.	No.	500-1000 M€
Kjeller	2	1967	1973	1973 Cold moderator. 2001 Reactor top, control room.	Running costs. Licence renewal uncertainties (2019). Major reactor fault.	No. Technically 20 years lifetime.	~110 M€
Rez	10	1957	1957	1988-9 Power increase from 2 MW to 10 MW.	Neutron provision dependent upon reactor owner. Operational cost increases. CANAM (parent organisation) funding. Political risks small.	No. 2022.	4 M€ (excluding the reactor)
BNC	10	1959	1959	1967 Power from 2.5 MW to 5 MW. 1992 Full refit & power to 10 MW. 2001 Cold source + supermirror guides.	Funding for fuel beyond 2017. Ageing components and availability. International isolation.	No. Operations >2023 only possible after major refit.	120 M€ + 40 M€

Table I.A Source Information (continuing from previous page)

Facility	Power MW	First neutrons achieved	Full source specification reached	Major refits	Top 3 risks	Foreseen closure	Replacement value
Demokritus	5	1961	1964	1974 power increase 1 MW to 5 MW.	Insufficient funding. Termination of spent fuel agreement (USA).	No. Feasible to 2030.	Estimated 50 M€
Delft	2	1963	-	Power from 100 kW to 2 MW. 2000 New guide hall. 2018 Cold source project.	Increase in operational costs, mainly due to ageing of the installation. Limited funding possibilities for the development of novel instruments. Increasing safety demands. Increasing cost of fuel. Political aspects of nuclear power.	No. Lifespan defined as 50 years.	Estimated 250 M€
Sacavem	1	1961	-	1991 HEU to LEU.	-	Yes by 2016.	Estimated 100 M€
Vienna	0.25	1962	1966	2012 new source.	Spent fuel agreement.	No. Licence to 2025.	Estimated 50 M€

Table I.B Instrumentation and Instrument-Days

Facility	Operating costs	Fully scheduled instruments	Restricted access instruments	Operating days for science	Instrument days for science	Scheduled experiments	Upgrades foreseen, needed or desirable
ILL	95 M€	30	10	200	8000	~800	Refit in 2027 ~30 M€. Instrument development ~55 M€
ISIS	62 M€	21	10 4 under construct.	120 - (150)	3720	~400 Estimated	TS-1 upgrade Accelerator sustainability ~7 M€. ISIS-II 2025 (750–1500 M€) +2 M€ on source +3 M€ on instruments
LLB	30 M€	21	-	180	3780	420	Adaption to LEU fuel (few M€)
FRM-II (MLZ)	55 M€	25	+4 by 2018	240	6000	~400 Estimated	UCN source. 2nd Guide hall. Transition to LEU.
BER-II	22 M€	14	0	~180	2520	~170	None foreseen.
SINQ	30 M€	13	-	180-190	2405	~450	Continuous upgrades.
Kjeller	~7.5 M€	2	1	~250	750	~65	Cold moderator-II (~3 M€). Continuous operations Upgrade cooling system
Rez	0.6 M€ neutron provision only	8	-	205	1640	80 Estimated	Control system upgrade. Possible reactor upgrade.
BNC	5 M€	15	-	150	2250	-	2014-2015 Cold Source upgrade 2023 Major refit 80 M€.
Demokritus	2 M€	2	0	200	400	2	Renew primary cooling system. Radiation protection ~a few M€.
Delft	4.7 M€	4	3 under construct.	200	800	10 for neutron scattering	Replacement of ageing hardware - few M€. 2018 Cold source - part of the 30 M€ Oyster programme.
Sacavem		3	-	0	0	0	None foreseen.
Vienna	0.25 M€	0	4	175 7-hour days	204		

Table I.C The User Communities

Facility	Distinct Users	External Users	Internal Users	Industrial Users	Referred papers p.a.	Commissioned & paid directly by industry	Commissioned by industry via university group	Of immediate value for industry
ILL	~1400	71%	28%	1%	~600	1%	Estimated 25%	Estimated 5%
ISIS	~1400	84%	15%	1%	~450	No answer	~15%	~15%
LLB	450	70%	20%	10%	185	0.5%	9%	0%
FRM-II (MLZ)	~1000	65%	32%	3%	215	3%	Unknown	10%
BER-II	~250	75%	24%	1%	~105	<1%	Estimated ~5%	0%
SINQ	400-500	70%	27 - 28%	~2-3%	120-140	2%	Unknown	<2%
Kjeller	~40	80%	15%	<5%	~35	0%	<5%	0%
Rez	80	85%	12%	3%	19	0%	0%	3%
BNC	250-280	60%	25%	15%	80-100	10%	No answer	10%
Demokritus	4	0%	100%	0%	5	0%	0%	0%
Delft	50	40%	50%	10%	5	0%	0%	10%
Sacavem	"Very few"	0%	100%	0%	"Very few"	0%	0%	0%
Vienna	-	0%	95%	5%	8 - 10	5%	0%	0%

(ii) Pertinent Headline Facts derived from the Data

From the data above we can extract a **number of headline facts**

- Europe has **13 operational neutron sources**
- These sources operate for **2280 days for science** in total
- **8 sources** began to operate before 1980; 3 began to operate after 1980 (see *Figure 5*)
- There are **183 operational instruments**
- These instruments provide **32469 instrument days for science**
- The total number of distinct users is **5469** (source duplication unaccounted for).
- The integrated output is **1848 scientific papers p.a.**
- **Industry pays for ~400 beam days p.a.** (1.2%) at the top 6 sources in total.

- The **capital replacement value** of all sources is estimated to be **5.7 B€**
- **Operational costs** integrated over all sources are **314 M€ p.a.**
- The average ratio of **operations costs p.a. to capital invested is 5.9%.**

The data in the tables also allows us to extract the **following global averages**:

- Average cost to operate a source for one day ~ 138 k€
- No. of papers generated per source day ~ 0.81 papers
- One published paper costs (excluding users costs) ~ 170 k€
- No. of operational hours to produce one paper ~ 30 hours
- Cost to operate one instrument for one day ~ 9.7 k€
- No. of instrument days to generate one paper ~ 17.6 days
- No. of papers published from one instrument p.a. ~ 10.1 papers

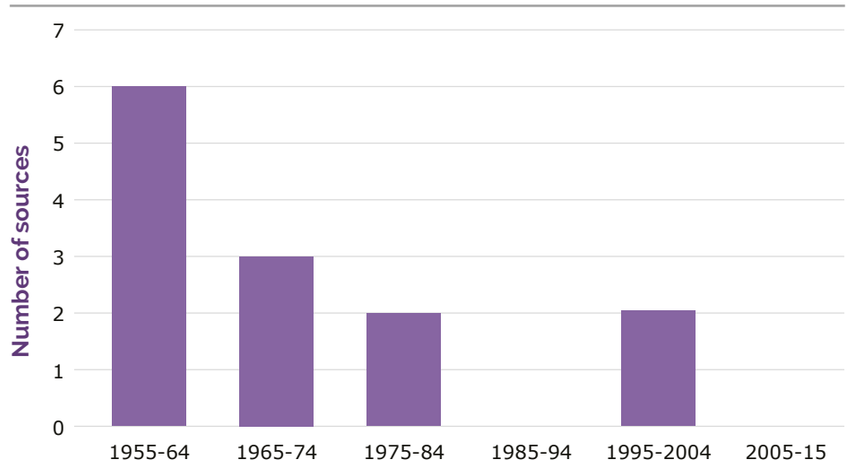


Figure 5. Start date of operarting neutron sources

The date of first neutrons generated by currently operating neutron sources. Note that almost half of the sources are more than 50 years old.

(iii) Operating Costs of facilities

We have examined the data for the 6 highest performing sources and have found an average operational cost of ~11.1 k€/instrument-day for a medium to high flux facility (see *Table ID*).

Table I.D Operational costs of the top tier neutron sources & budgeted values for ESS

Facility	Instrument days	Operational cost $M€_{2014}$	Cost per instrument-day $k€_{2014}$	Replacement value $M€_{2014}$	Operation cost/ Replacement value
ILL	8000	95	11.9	2000	4.75%
ISIS	3720	62	16.7	800	7.75%
FRM-II	6000	55	9.2	600	9.2%
LLB*	3780	30	7.9	450	6.7%
SINQ	2405	30	12.5	750	4%
BER-II*	2520	22	8.7	400 est.	5.5%
Total	26425	294	11.1	5000	5.9%
ESS_{2028}	3960	140	35.3	1847	7.6%

[to be closed down in 2019]*

This agrees with the broader data provided from all sources. Note that the operational cost per instrument-day for ISIS is abnormally high because of its restricted operational regime. Equally the operational cost per instrument-day for LLB is abnormally low, which may be associated to the fact that the Orphée reactor and LLB are separate organisations. Note that both LLB and BER-II are scheduled for closure at the end of 2019. The cost per instrument day for ESS is high, partly because the number of instruments is lower than a source of its power could sustain.

Interestingly there does not appear to be a significant difference between the figures for spallation sources and those for reactor facilities. This is explained by the fact that annual costs are heavily influenced by staff numbers and that the cost of the fuel cycle of a reactor source (increasing on every future scenario) is balanced by electricity costs for a spallation source (also a resource that is becoming more costly). Of course the statistics are rather low to be able to extract statistically

significant differences in the two kinds of source. Instead they provide a guideline that indicates equality.

What is very marked, as mentioned in the headlines above, is the surprisingly low proportion of annual operating costs to installed capital costs of **all** facilities. This ratio averages less than 6% whereas the rule of thumb for large scientific infrastructures is frequently stated as being 10%. This strongly indicates a sustained lack of investment over the years. The origin of this low value may also partially lie in the use of "replacement value" as a metric rather than "amortised value" given that most of the sources are 40 to 50 years old. However we can see that the operational costs for ESS at 7.6%, where amortisation is not an issue, is still well below the 10% that "perceived wisdom" accepts. Informally, we understand that despite this low ratio there is downward pressure on the current estimated operational costs of ESS.

II.
Future Scenarios to 2030

II.1 Perspectives until 2030

The leading position of Europe and of European sources is illustrated quite clearly in *Figure 6*. Of the papers published in high impact journals world-wide, 70% of all papers result from data taken on major European sources. Equally well reactor sources around the world still supply the lion's share (~68% of high impact journal papers) of the publications from the global neutron community. This serves to emphasise the slow pace of change that occurs in neutron provision and how it translates to journal papers even though ~5 B€ has been committed in building three MW-class spallation sources over the past decade compared to far less investment on reactor sources. It is important that this time constant - decades not years - is kept in mind by decision-makers. Long-term strategic planning is required.

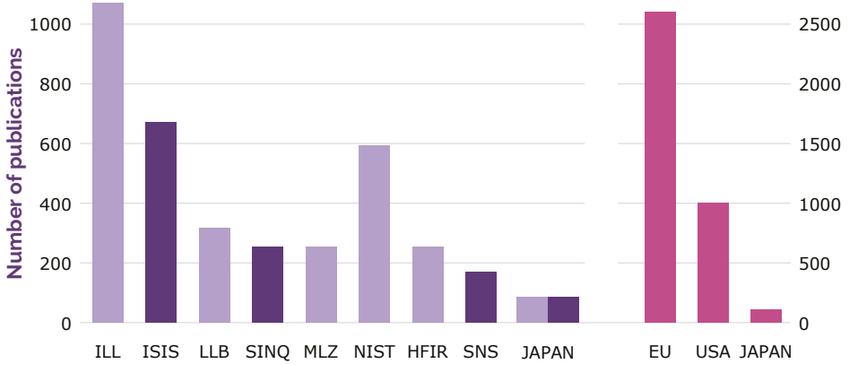


Figure 6. Publication output of major neutron sources

The number of publications of major sources in Europe and the rest of the world, integrated from 2008 to 2014. Light violet columns are reactor sources and dark violet columns are spallation sources. On the right, fuchsia columns show the data consolidated into the three regions of the world identified by OECD in 1999 as requiring a MW-class spallation source. Note the different scales.

In the following histograms of instrument beam-days (*Figures 7 to 10*), derived from the above data tables, we can visualise the situation that would occur according to the data provided by the individual source Directors.

We present three different scenarios:

(i) the baseline scenario, corresponding to the data in Tables I A to D;

(ii) a scenario where the baseline is adapted to take account of the identified risks, so-called pessimistic;

(iii) a scenario where the baseline is augmented by additional measures taken to counteract the drop in provision of beam-days, so-called optimistic.

We note that since this data was collected there are indications that some of the risks stated are already being realised, examples being the recent limited funding situation of LLB and the additional cost of the fuel cycle for reactor sources such as ILL, that raise the spectre of reduced operations at lower power and therefore higher unit costs. Two major decisions – the closure of both LLB and BER-II in 2019 – have already since been taken.

The use of instrument-days as a yardstick – We will again quantify the combination of capacity and capability in terms of instrument days. In our view this is the best overall measure to gauge the size of the user community that can be sustained by a given set of neutron sources.

During its lifetime, a facility will continually develop and adapt to the ongoing evolution of scientific needs, technological developments and societal expectations. Experience from currently operating neutron sources shows that today many of the topics once considered to be a key part of their science cases are no longer pursued, that research programmes are being carried out on topics that were never considered in the original science cases for the source, and that topics proposed

as a central plank of the original science cases are often neither fruitful nor achievable. Science cases must therefore come with a government health warning and they should not be treated as the be-all-and-end-all of the justification for a given facility proposal. They are but one input. With a precision, speed or sensitivity exceeding the original specifications by orders of magnitude or in environments (*in vivo*, *in operando*, real time, extreme temperatures, pressure or fields) that were not originally conceivable, the scientific output of an instrument suite that has developed over decades delivers more and more science. Equally the user community itself builds up and is consolidated and the staff becomes more and more experienced. Sustained development over decades at any source pays dividends and it must not be assumed that new sources today will need less time to build up capacity and therefore scientific impact. There is little doubt however that whatever instrument availability is provided, there will be a large oversubscription. Demand will exceed supply significantly.

During the last 40-50 years the number of publications from a given type of instrument has increased, slowly but surely, whilst at the same time the performance of the instruments has often increased by one or more orders of magnitude. Increased performance in terms of intensity or resolution tends to attract more difficult and penetrating scientific questions and does not simply encourage more of the same. There is a distinct increase in quality, which is the main purpose of a facility like ESS. We have also assumed that users will carry out their research at a facility best suited to, and most cost effective for, the given experiment (flux, instrumentation, ancillary equipment etc. etc.) and that the instrumentation is state of the art. Using an instrument day as a measure therefore reflects the current state of instrumentation and also the current complexity of the topic that we plan to investigate in one day. In short using instrument-days as a yardstick is a measure of the user community that can be sustained at any given point in time. There are many other indicators that can be used but our approach has been that,

while the use of instrument-days is by no means perfect, it avoids the subjective interpretations that the development of an algorithm would entail and is therefore quantitative and verifiable.

(i) The Baseline Scenario

The Baseline Scenario, illustrated in *Figure 7*, describes the situation as communicated by the facility Directors as of mid-2014.

In this scenario ILL will operate for the duration of the current Convention, which runs until 2023, at full specification.

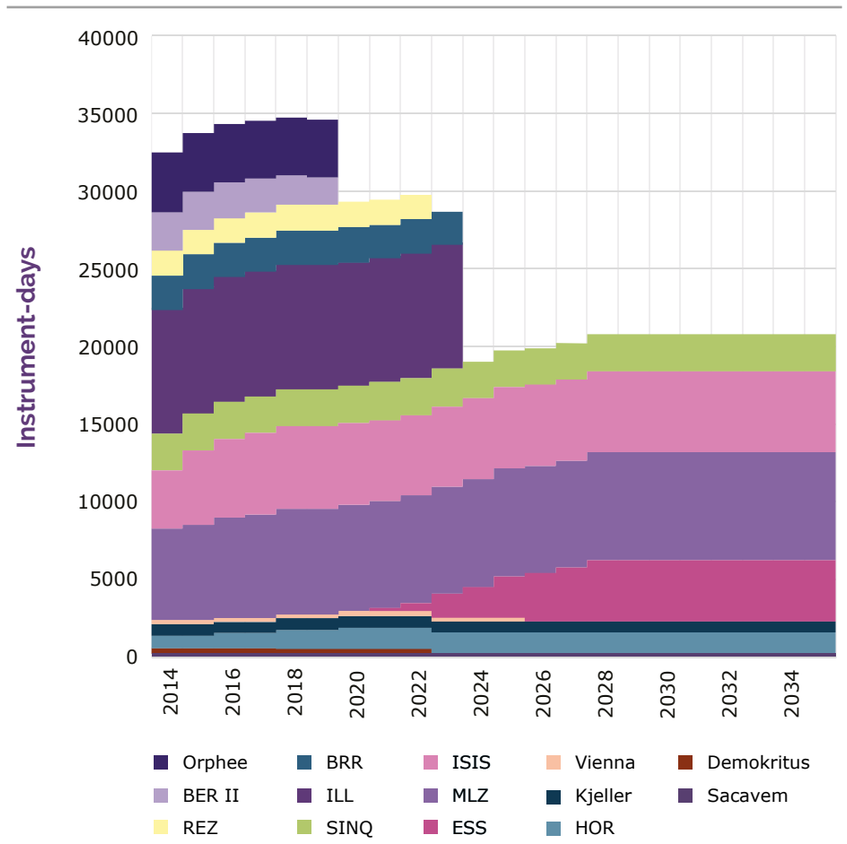


Figure 7. Baseline Scenario

The predicted delivery of instrument beam-days in the Baseline Scenario: ILL operates at full output until 2023, ESS with 22 instruments beyond 2028.

ESS is assumed to be operational at full 5 MW specification and to have 22 fully furnished instruments by 2028 according to its published schedule as shown in *Figure 8*. The drop in instrument beam-days occurring in 2020 is due to the closure of the Berlin and Saclay reactors. These decisions must, regrettably, be seen as firm. Indeed there is a risk that LLB will close earlier or, alternatively, be obliged to pursue limited operations until 2020. A second drop occurs at 2023-2024 in this scenario when Budapest, Rez and ILL all come to the end of their licenses, but note that extensions to the lifetime of these facilities, especially ILL, depend only upon financial and political considerations rather than technical or scientific reasons. Note also the slow rise to full specification of ESS from 2020 to 2028, in terms of accelerator power, target capacity and the implementation of a full suite of instruments. We point out what is obvious but what is often overlooked and that is whilst the closure of a facility results in an instantaneous drop in beam-days, the rise to full specification of a new source will be very gradual. Experience with ISIS, SNS and J-PARC indicates that a decade is not an

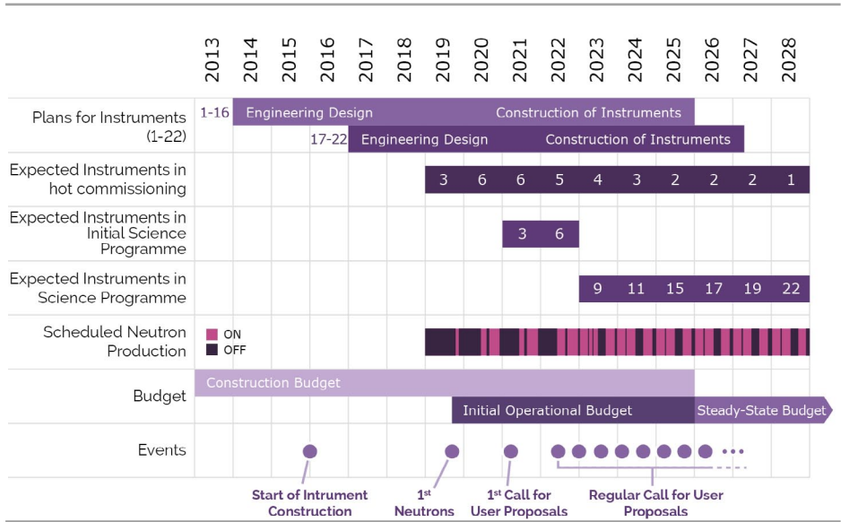


Figure 8. ESS schedule

The published schedule of instrument construction for ESS. Adapted from [9].

excessive length of time to reach full output. In this scenario, beam-days will fall to 60% of current levels in the mid 2020s and thereafter will increase only slowly, never regaining the levels of today.

This point is illustrated in *Figure 9* with data from the ISIS spallation source showing its slow but sure rise to full source specification during its commissioning years. This data of course does not show the parallel slow rise in the number of instruments, there were only ~4 instruments operational, but not complete, on "Day One" and the rise thereafter was at a rate of 1.1 instruments per year, which was nevertheless impressive. A full instrument suite of say 22 instruments, as at ESS, would require ~16 years to achieve at this pace. Whilst these figures are perhaps surprising, experience on all sources including SNS and JPARC shows that this is typical. SNS is now operating steadily at only 1 MW compared to its design power of 1.4 MW, having achieved first neutrons in April 2006, and it has a full suite of instruments. J-PARC equally has a full suite of instruments and is operating at only 400 kW, compared to

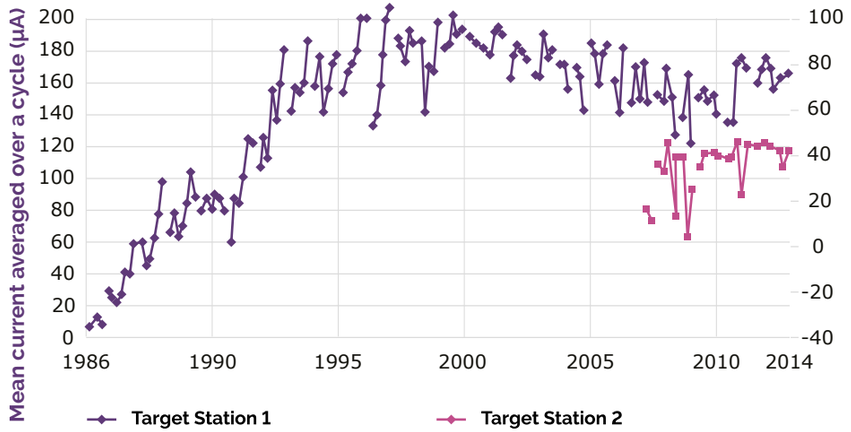


Figure 9. ISIS full source specification

The rise to full specification of the ISIS spallation source took ten years following the generation of first neutrons in December 1984. The start of the second target station is shown in fuchsia. Note the different scales.
Adapted from image courtesy of ISIS: Robert McGreevy.

its design specification of 1 MW. It produced first neutrons in ~January 2009. Nevertheless, these are laudable achievements.

(ii) The Degraded Baseline Scenario – Pessimistic

Whilst considering a pessimistic scenario at all may appear to be a bleak approach, it should be recognised that many would refer to this scenario as being the realistic outcome. Even during the writing of this report we have experienced the unwelcome decisions to close LLB and BER-II which will remove ~5500 instrument beam-days annually from the neutron supply at the end of 2019. Furthermore, the cost of powering the portfolio of neutron sources either in terms of fuel or electricity is rising unpredictably meaning that operating costs are likely to rise also. Every step of the fuel element cycle of reactor sources is becoming more and more costly as nuclear regulations become ever tighter. Electricity costs, a major budget line in the operation of accelerator sources, are also rising. Funding limitations leading to early shut down or reduced operation of facilities, or even lower power operations, coupled to technical problems, were all mentioned by the facility Directors as the most important risks to the delivery of instrument days as predicted in the Baseline Scenario above. Such a scenario would see a greater call on operational budgets to produce the neutrons as opposed to utilise them.

The members of the Neutron Landscape Group are concerned about such eventualities and highlight these potential threats. If even only a few of the postulated risks become reality then the scenario will worsen significantly as shown in *Figure 10* – the Degraded Baseline Scenario. On the other hand it is advisable for facility Directors to take seriously their generating costs and to engage actively in order to reduce these costs by innovative energy management strategies. It is easier to do this on accelerator sources than reactor sources and to implement such strategies in new facilities than old facilities.

This pessimistic scenario results in a dramatic, almost linear, fall in

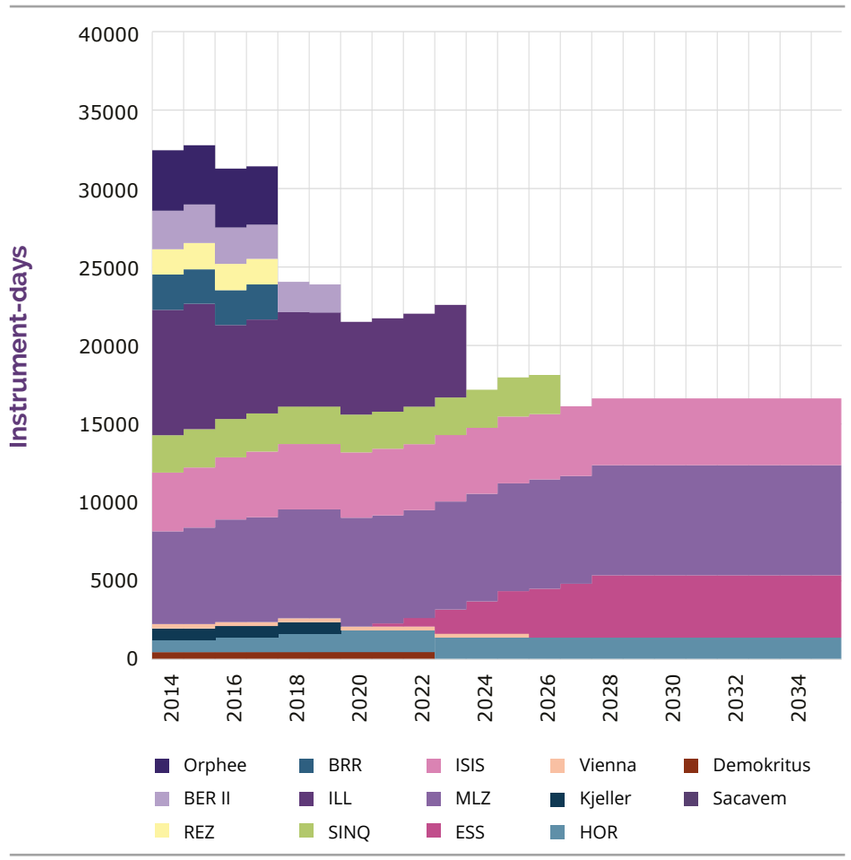


Figure 10. Degraded Baseline Scenario

The predicted delivery of instrument beam-days in the Degraded Baseline Scenario: ILL operates at reduced output until 2023, ESS with 22 instruments beyond 2028. Earlier closure and/or reduced operations for a number of medium power sources.

beam-days from 2016 until 2028 when ESS is assumed to reach full specification. At that point the drop in supply will level off but, for the following decade, it will remain flat.

The level of beam-days will fall by more than a factor of two over 12 years in this scenario, to 50% of current levels. The twin threats of descoping the ESS specification from 5 MW to a lower power - of even

2 MW – coincident with a reduction of power of the ILL from 58 MW – possibly to 40 MW - have both been raised by owners. Such threats are not unrealistic, particularly in the case of ESS, where the focus is upon delivery on time and within budget and therefore specification can often be the only parameter remaining to achieve a balance. The instrument portfolio, funded from the capital budget, has already been reduced from 22 to 16.

If the Baseline Scenario could be described as serious, scenario (ii) would change the neutron landscape beyond recognition. There would be only three sources operational after 2028.

(iii) The Enhanced Baseline Scenario – Optimistic

We present an optimistic scenario in *Figure 11* that assumes that certain mitigating actions - aimed at softening the effects seen in scenarios (i) and (ii) - will be implemented. These mitigating actions are that:

- ILL does not reduce the number of reactor cycles that it operates; it continues to run at full power; and its international Convention is extended until 2030 and beyond;
- ESS is sufficiently resourced to build and operate 35 instruments rather than 22 and the technical specification is not descoped, nor the schedule stretched;
- ISIS long-term funding should be assured so it is able to operate within scientific demands and technical limits rather than financial limits;
- The moderate flux facilities operate to full capacity, without any further unnecessarily early shutdowns.

In such an optimistic scenario even if all these measures were taken then a substantial drop in beam-days will still occur upon the closure of ILL, which here is placed somewhat arbitrarily in 2030. However, compared to scenarios (i) and (ii), the damage would be lessened. Beam-days

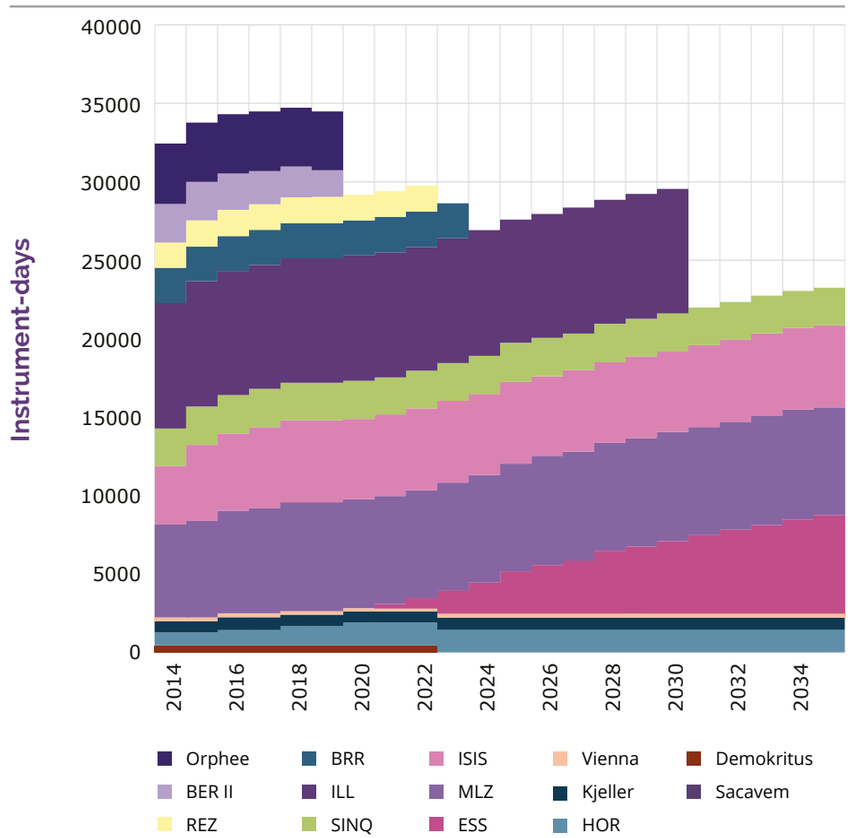
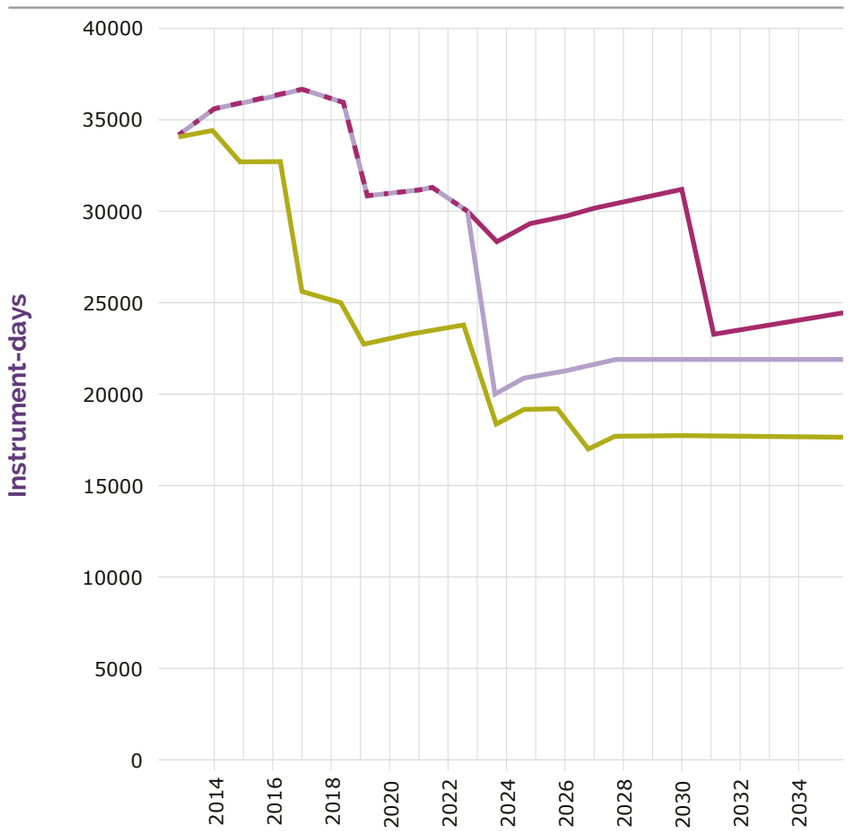


Figure 11. Enhanced Baseline Scenario

The predicted delivery of instrument beam-days in the Enhanced Baseline Scenario: ILL operates until 2030, ESS with 35 instruments beyond 2035.

would nevertheless still fall to 67% of today's level by 2031 but would rise modestly thereafter.

We should bear in mind that from 2030 onwards, even in this optimistic scenario and with ILL still operating, there would be only four neutron sources operational in Europe.



Enhanced Baseline
ILL operates until 2030, ESS with 35 instruments beyond 2035

Baseline
ILL operates at full output until 2023, ESS with 22 instruments beyond 2028

Degraded Baseline
ILL operates at reduced output until 2023, ESS with 22 instruments beyond 2028. Earlier closure and/or reduced operations, for a number of medium power

Figure 12. Integrated scenarios

Neutron provision in Europe over the period from 2015 to 2035 from data provided by the sources themselves. To quantify access capacity, the number of "Instrument-days" foreseen by the facilities is used for three different scenarios that might obtain, projecting forward from the current status of the neutron sources.

(iv) Integrated Scenarios - an Overview

The overall situation with each of these three scenarios can be more directly appreciated in *Figure 12*. Viewing the scenario until 2035 we get a more complete picture of the evolution of neutron instrument days for the next 20 years. The black line is the baseline (i), as communicated by the sources (summer 2014 – the actual status today is in fact lower than the black curve) and the green line is the optimistic scenario (iii) with ILL operating until 2030. The loss of ILL is very evident as the abrupt vertical drop, whether it should occur in 2023 or 2030 or beyond. For completeness sake we include as the red line, the pessimistic scenario (ii), which would ensue if the most likely risks to planned operations mentioned by the source Directors should all be realised. Some of these risks, such as the closure of LLB and BER-II, have already come to pass.

II.2 Perspectives beyond 2030 to 2050 - major upgrades and possible new sources

Our analysis shows that there is a clear and increasing science demand for answering fundamental questions in materials research with a clarity and quality that neutron methods can provide. However the research reach with neutrons is challenged by the changes that will unquestionably take place even within the next decade, related to the closing down of many of the sources currently in operation.

These closures are very far from being matched by a rise either in the currently planned provision of instrument-days in surviving sources or in replacement sources, of which ESS is the sole example. The prospect of a drastic reduction of measuring capacity, with the associated risk of a significantly lower output of scientific excellence, requires countering actions. To lay down a strategy that Europe might wish to consider, we have expanded our analysis beyond 2030.

If we were to push the optimism factor to its limit and assume that ILL will still be operational beyond 2030 and also include the above mitigating factors, a more reasonable picture begins to emerge. For that to happen however a proper coherent and coordinated management of neutron facilities in Europe would require to be brought in at a high level, rather than the "every man for himself" situation that exists today. For such a situation to occur then it would be essential also for the user community to make its voice heard loudly, clearly and persistently. Our perception is that the user community as a whole does not fully appreciate the precarious situation that it is in and we urge action by them. We should be aware that although these measures will reduce somewhat the depth of any dip in neutron beam-days, the loss of ILL will still be very significant whenever it occurs (in 2030 in this model).

It is abundantly clear that, even with ESS operational according to its

published schedule, the number of neutron beam-days will fall to a level such that the current science programme (and hence the current user community) could not be sustained. Available days will continue to fall steadily to ~50% of today's value by 2030. In fact the data point to the fact that half of the user community's needs could not be satisfied unless there are substantial mitigating initiatives. The question has to be posed then, whether a critical mass would any longer exist and, if that proves not to be the case, we can foresee that neutron techniques will once again attain a status as an arcane and very specialised pursuit as obtained in the 1960s, only accessible to the few. In such a situation the message to the user community would be that neutron beam science was becoming a minority pursuit and many researchers would choose to transfer their research programmes to other techniques, compensating for limitations of accessibility to neutron instruments. Once the user community does begin to disperse it will take considerable time to rebuild the competence and recover from such a set-back, should that even be possible at that point.

(i) What expectations can reasonably be placed upon the ESS?

The ESS bears the weight of high expectations from both the user community and the funding bodies. Nevertheless the schedule for building instruments remains as it was in the ESS Technical Design Report (TDR) issued in April 2013 except that now only 16 instruments, as opposed to the original 22 as foreseen in the TDR, are within the capital envelope. The provenance for the financing of the remaining 6 instruments - proposed to be taken from the annual operating budget - has therefore still to be secured. Assuming that this is agreed, which cannot be taken for granted, it is nevertheless a significant challenge to have the ESS accelerator and target station fully operational at 5 MW with 22 instruments by 2028 as indicated by the official schedule in *Figure 8*. Furthermore it is not yet demonstrated that the scientific reach of the instrumentation suite as currently planned for ESS can cover the

whole measuring landscape of ILL, which operates 40 instruments as well as an additional number of special beamlines. This full capacity use leads to a high productivity in terms of scientific output to cost ratio. In short this means that the ESS, on the advertised time scales and with its limited instrument suite, cannot fully replace ILL scientifically. ESS will without doubt open up new avenues of scientific investigation, but the absence of complete instrumental overlap between the two sources should be recognised.

The conclusion therefore points towards a conscious and deliberate decoupling of the future of ILL from that of ESS. The currently assumed coupling of the destinies of the two sources is the backbone of the accepted wisdom that presupposes that a decision on the closure of ILL (which must necessarily be taken some years ahead of the event) can be made in anticipation of a predictable rise to full specification of ESS. Our findings indicate that such thinking is deceptive, and to assume that this path will be followed without significant damage to the scientific output using neutrons in Europe would be an error.

The first 16 instruments are still within the capital budget of ESS. The mistake has thankfully not been made to conclude the capital construction phase when first neutrons are delivered, a strategy that has damaged the transition to operations on other sources. Full specification in terms of instrument-days for science should thus occur towards 2030 on a technically limited schedule. A technically limited schedule assumes that full funding will be forthcoming year on year and no unforeseen delays will arise. Such a schedule therefore represents the best possible scenario.

A number of uncertainties surrounding ESS therefore still needs to be clarified, including:

- What are the realistic margins of uncertainty in the ESS's attainment of full specification? The best possible scenario is known, but what is the most likely scenario and what might precipitate a worst possible scenario and what might that be?
- What binding commitments are there to ensure that the funding for the remaining 6 instruments will be forthcoming, and over what realistic timescale?
- What level of support exists today for a second wave of instruments beyond the 22 that would bring the instrument suite stepwise up towards 40 instruments and thereby on a par with ILL? It should be stressed that ILL instruments cannot be transferred to ESS, unlike the transfer of Jülich instruments to FRM-II. The two types of instrument are incompatible.
- To what extent is the annual operational budget of ESS secure, and hence the number of operational days assured? The annual operational cost of ESS at ~140M€ p.a. is almost 50% higher than that of ILL and yet only 7.6% of the capital investment cost.

A reliable answer to these questions is essential for a proper analysis of future trends in neutron instrument provision to be made and for informed decisions on the future of ILL to be reached.

In this analysis we repeat that we have not attempted to assign a value to a beam day on a particular facility and have instead chosen to maintain a "one day is one day" approach. Of course this approach can be criticised since it assumes that a day on an instrument at the Delft reactor will give an equal scientific output to a day on an instrument at ILL, which is clearly not the case. Our case for continuing with this approach is two-fold: a credible algorithm for assigning value is necessarily subjective and prone to error; and it is not simply the immediate scientific output that has value but rather the whole of the activities of what one day on a less strong source will give. On this latter point we indicate: the value of instrument development; the training given to a young instrument builder; the opportunity to develop new methodologies; the ability

to carry out first experiments on novel scientific ideas; the open door opportunity provided to new users of neutrons. Nevertheless the numbers must be viewed conscious of this methodology. We do not believe that our approach biases the conclusions significantly.

(ii) The future of the Institut Laue Langevin

The question has recently arisen, in feedback from the PSE to our interim report, as to **the cost of operating ILL beyond its current international convention** to, say, 2033 or beyond. Broadly speaking we understand that ILL, from an engineering point of view, is perfectly sound to continue operating to at least 2033 given its continuous process of external review by the French Autorité de Sûreté Nucléaire, ASN, through its "Groupe Permanente" mechanism and consequent amelioration of the reactor and ancillary facilities. This entails programmed component renewal, such as replacement beam tubes for example, and upgrades in all areas, including building stability. In the past these costs, with some difficulty it should be said, have been factored in to the annual budget of the institute and additional capital has been provided. The ILL was significantly strengthened during the reactor refit programme in the early 2000s and once again in response to the stress test demands consequent to the Fukushima accident. There will in the course of events be further demands from the nuclear safety authorities, but in general the NLG believes that the major cost in operating ILL for a further ten-year period would not greatly exceed its annual operating costs. This would represent good value for money.

One of the reasons for the excellent reliability of ILL is the very fact that it is overseen in a very focussed manner by the French, European and International nuclear authorities. This requires component reliability standards to be followed and a renewal programme of such components, strict reporting practices and redundancy of components and systems. A further concern expressed by the PSE is the fuel cycle of reactor sources, which also represents an increasing cost and a

technical risk. ILL, like FRM-II (MLZ), uses highly enriched uranium (HEU) as its fuel, which is a strategic material and subject to stringent controls. Today, as we understand it, ILL operates under a long-standing signed agreement with the USA authorities to collaborate in studying the feasibility of operating the reactor using low enriched uranium (LEU) fuel. LEU means <20% in the U235 fissile isotope. A European consortium LEONIDAS (Low Enriched Option Network Initiative for the Development of a European Appropriate Solution) was set up to pursue this goal. In 2013, the LEONIDAS consortium was expanded to include FRM-II and was renamed HERACLES (Highly enriched European Reactors Action for their Conversion in a Low Enriched Solution). Calculations indicate that conversion is possible without a significant loss of neutron flux levels, hence maintaining instrument capability and scientific output, and without extensive modifications to the reactor itself. The limiting step in achieving this however is that there is not yet a sufficiently satisfactory LEU fuel, tried and tested to nuclear standards, that is available. Until such times any estimate of when a conversion from HEU to LEU might happen and the associated costs of conversion is only educated guesswork, and therefore a most probable working hypothesis would be that ILL will continue to operate using HEU supplied by the USA, as part of the signed agreement, for the foreseeable future. The recent report (2016) from the US Academies of Sciences, Engineering, and Medicine [10], indicates that little progress in developing this fuel has been made.

It is estimated that the budget of ILL has had to be increased by 5 M€ per year to account for the additional compliance work related to the fuel cycle new ESPN regulations following Fukushima. Further compliance issues are foreseen to increase this budget by a further 5 M€ p.a. until 2033. However it is considered that, unless even more stringent standards are imposed, the mooted change of the reactor vessel will not be needed. Operating in the decade from 2023 to 2033 at 5 M€ over and above the current 95 M€ p.a. would therefore cost an additional 50 M€.

What is clear from the analysis that the NLG has conducted is that the ILL will continue to represent excellent value for money, and all the evidence is that this situation might well continue even over the next two decades.

(iii) The global situation: the potential output of neutron sources and instrumentation world-wide

The international situation shows overall growth largely due to the advances at SNS and J-PARC which still have the character of new sources, despite having operated for a decade and are yet to attain full specification. The Bragg Institute in Australia (OPAL) is also on an upward growth curve and there are facilities in India and Indonesia where expertise and capacity is high. Plans have been laid down at government level for twin reactor facilities in Argentina and Brazil based upon 2nd generation versions of the OPAL reactor which itself was built and commissioned by Argentina. South Africa is closely following this situation since it is likely that their Safari reactor will close in the near future. China is building the Chinese Spallation Neutron Source in Dongguan due for first neutrons to be delivered in 2017 and India have plans for two new reactor sources at Visakhapatnam on the Bay of Bengal. This could result in 5 new reactor facilities and 1 new spallation source being built in the southern hemisphere by 2030. Set against this was the announcement in February 2015 that the Canadian government had definitively decided to shut down the NRU reactor. Today, the "Government direction remains to close Canada's source of neutrons, the NRU reactor, at the end of March 2018. Regular production of one isotope, Mo-99, will stop in October 2016, while all others will continue in production. After October 2016, the NRU is expected to continue operating at full power for its science missions." Chalk River has been a centre for neutron scattering and instrumentation development for decades and was the home of Nobel Prize winner Bert Brockhouse.

Nevertheless even with this increasing growth curve globally and taking

the most optimistic scenario, the number of beam days for neutron science in the rest of the world, slightly below 30000, falls just short of what is delivered in Europe today. By 2030 however the rest of the world will have overtaken Europe, purely as a consequence of the fall in the Baseline Scenario in Europe shown above rather than the possible bringing on line of currently planned facilities.

The future landscape in **Europe** will result, in essence, of one world leading facility together with two or three world class sources. The trend observed at global level is more sanguine. The facilities for neutron scattering are however predominantly dimensioned to serve national and regional use rather than international use. In the US, for example, the foreseen evolution is represented by a major refit and a twenty years extension of the two reactors HFIR and NIST together with the currently world-leading spallation facility SNS (in terms of power), potentially equipped with a second target station by 2030. The provision of instrument days at the three main big facilities in the US (SNS, NIST & HIFAR) will, assuming that these measures proceed, be of the order of 20000 instrument days. The US also has a tradition of small university-based sources and facilities like MURR at Missouri and the LENS development project at Indiana provide training grounds and stepping stones to the bigger sources.

A similar situation describes the future scenario in **Japan**, where a second target station at J-PARC is being considered. It is not foreseen that the second target station will be functional before 2035. The JRR-3M reactor facility, on the same site as J-PARC, is still not operational following its serious damage by the east-Japan earthquake. It is well-instrumented and has been adventurous in its instrument portfolio and has consistently had a high-quality scientific output. It is now going through stress-testing and aims at a possible restart in 2017. Japan also has a tradition of small university-based accelerator and reactor sources and that continues to a certain extent, for example the KURR reactor and the KURRI linear accelerator at Kyoto University.

Table II.A

A summary of the outlook for neutron facilities in the different major regions of the world, as communicated by facility Directors or garnered from published reports or the internet.

Region	Instr. days	Longer term trend
Europe	32000	Decreasing on a 10 year timescale, prior to rising again on a 20 year timescale, but not regaining current supply levels. The neutron community in Europe far exceeds that in other regions of the world. Equally European science benefits from researchers from other regions carrying out research at European facilities. At ILL non-partner access has been capped at 10%.
USA	12000	Stable (although IPNS & LANSCE have ceased operations). NIST has 26 operational instruments, SNS has 20 and HFIR has 12. Potential to increase capacity if SNS gets a 2nd target station (planned but unfunded). HFIR is now >50 years old and its future lifetime must be limited. NIST goes from strength to strength.
Canada	~1000	The NRX reactor at AECL Chalk River has been closed down after >50 years of innovative work including the triple axis work that brought Brockhouse the Nobel Prize. The 135 MW NRU reactor with its 6 beamlines is scheduled to close in March 2018. The case for a replacement facility, either a reactor or a spallation source, was made in 2015 but continually stalls.
Argentina, Brazil & South Africa	~1000	An Argentinian company built the OPAL reactor in Australia. Argentina is now building a Mark-II version of this design which would have a similar capacity to OPAL. Brazil signed a cooperation agreement to build a twin, but our understanding is that this has stalled and the project has been put on hold. South Africa has expressed interest in replacing its ageing Safari reactor with a similar Mark-II OPAL reactor.
India	~3000	The 100 MW Dhruva medium flux reactor is operational at Trombay near Mumbai. It is furnished with 13 instruments. A user programme has opened up. Plans have been made for two new reactors at Visakhapatnam - a 125 MW high-flux Dhruva-type reactor and an Hanaro-type reactor using HEU (2019 completion date is now delayed). Plans exist also for a spallation source at Indore close to the Indian synchrotron source.
Japan	3500	Stable or potentially increasing. 9000 instrument days were planned for 2014, but only 3000 were delivered by J-PARC in 2015. J-PARC has 18 instruments with 3 under construction and operated for 171 days over the past 12 months. It is steadily working towards full capacity and full specification. Long term J-PARC, currently the sole neutron source in Japan, could be furnished with a 2nd target station, which has still not been approved. The earliest date to start construction would be 2017. The instrumentation at the JRR3 reactor on the Tokai site was damaged by the "Fukushima" earthquake. The reactor is undergoing stress tests and could be operational again in 2017. Japan also operates the 5MW Kyoto university research reactor where, in particular, techniques development is carried out.
China	2500	Positive growth from a low level. A 100 kW ISIS-type spallation source (CSNS), upgradeable to 500 kW, is under construction in Dongguan. User operation is foreseen for March 2018. A new guide hall and cold source for CARR in Beijing is in construction. The potential depends upon the level of instrumentation for CSNS.
Korea	~1600	30 MW Hanaro reactor operates for 198 days per year currently at 26 MW with 8 instruments. The reactor was first operational in 1995 and is relatively new.
Indonesia	~500	The 30 MW SIWABESSY reactor in Serpong has been operational since 1987. It has 6 instruments for neutron scattering and operates for 87 days a year.
Australia	1750	The OPAL reactor at ANSTO near Sydney is relatively new. The potential exists to double the output within the next decade – with a further doubling possible in instrument days by 2030 with a new guide hall (planned but unfunded).
Russia	3000	IBR-2, a 2 MW pulsed reactor in Dubna is a recently upgraded facility with an international user programme on 11 instruments. It is scheduled to operate for 107 days in 2016. Many smaller facilities in Russia are not open to users. The WWR-M reactor at Gatchina has 16 instruments including a number of UCN & VCN installations for fundamental physics. The 100 MW design PIK reactor at Gatchina is not operational but it has the potential for up to 40 instruments and 200 days operation per year giving 8000 instrument days per year. The reactor was designed and built in the 1980s but has only recently been brought to criticality at a few watts power. A new guide hall is built with instruments from Geesthacht. If and when it begins to operate must be regarded as uncertain.

Russia is working on bringing the PIK reactor into full operation over the next few years and there is visible progress now after many decades of stagnation. There is political support for PIK at the highest level in Russia, and some limited political support from Europe exists. It is fair to say however that those European scientists who are aware of its existence are not greatly optimistic that it can achieve its ambition to be considered as an equal to ILL. It is felt that this could take decades to realise and will require very significant investment to renew outdated ancillary reactor facilities. Russia has a number of smaller neutron facilities mainly employed for local user communities. Russia also hosts the pulsed reactor, IBR2, at JINR in Dubna, which is now operational following a major refit. JINR is an international research organisation whose members included many countries in what is now the eastern wing of the EU. IBR2 is a truly unique facility and the source itself has been totally refurbished in recent years. It boasts an extremely high instantaneous power and is intermediate in characteristics between the short pulse sources such as SNS, J-PARC and ISIS and the long pulse ESS. In many ways it is underexploited, despite the fact that its pulse length is well-matched to the moderating times of cold neutrons, and therefore optimal in terms of neutron economy. With these facilities fully functioning, Russia would be able to sustain an increasing national user community and to attract international researchers. It would therefore become a full member of the global network of facilities. Currently Russian facilities provide only a few % of the available neutron beam-time open to global use based on peer review but there is certainly the potential for this to increase well beyond the current 3000 instrument days.

China is operating two reactor-based facilities CARR in Beijing and CMRR in Sichaun, and an ISIS-like accelerator-based facility is under construction in Dongguan in southern China. This facility, the Chinese Spallation Neutron Source, is currently specified at 100 kW with the goal of putting first beam on target in September 2017 and starting user

operations in March 2018 when there will be 3 instruments operational. A further 17 will be built in coming years. The capital equipment cost, excluding staff and buildings is estimated to be 1.67B RMB (230 M€) and there are currently 351 staff. The build up of capacity in China is primarily to meet national needs, as for the other major global regions, but it is clear that China is planning a serious expansion of its scientific infrastructure in line with infrastructure development in general. For example a 5 MW ADS nuclear waste transmutation accelerator facility is to be built in the Guangdong region as a precursor to a 40 MW production facility. There are synergies here with ESS.

The HANARO reactor in **Korea** is used for neutron beam applications, material irradiation, nuclear fuel testing, neutron activation analysis, radioisotope production, neutron transmutation doping, and the development of nuclear materials. It operates annually for 198 days with 8 instruments for neutron scattering use. Korea will host the International Conference on Neutron Scattering in 2017.

Multipurpose uses and goals have been the predominant factors for the reactor facility OPAL operating in **Australia**, as well as the facility under consideration in **Argentina**. These facilities are all based on a modern multipurpose medium flux reactor. The Australian source is a very important facility for the region and the same is expected to be the case for the new facilities in South America. The Bragg Institute, which embraces the neutron scattering activities on OPAL, has plans for a second guide hall, which has not yet been funded.

Neutron instrumentation facilities are frequently part of a multipurpose laboratory. Isotope production for medical and technological uses, irradiation for industrial needs such as silicon and for accelerated ageing studies, the generation of other particles for fundamental physics (protons, muons, positrons, and one can include here ultra-cold neutrons), as well as fronting the development and training in the use of new nuclear technologies and hospital physicists, are only a few of the

parallel uses of many sources. These alternative uses often determine the choice of technology for the source itself.

It is clear that future growth and investment opportunities in the rest of the world contrast sharply with the situation in Europe where all the eggs are in one basket – that of the ESS.

When considering the **globalisation of neutron sources**, which is surely the next step on the horizon, many factors come into play. Planning for the next generation of neutron sources that will surpass ESS, SNS and J-PARC will surely be dealt with on a global basis. It should be noted that the European Commission proposed the ESS as a potential Global Research Infrastructure in 2015 to the GSO Group of Senior Officials, initiated by the Carnegie Group of G8+5 Science Advisers on Global Research Infrastructures. For the moment the GSO exercise is only exploratory, but it indicates the direction that science strategy is moving in. Given the gestation period of large scientific facilities – 40 years and more is becoming the norm today - it is not unreasonable to start planning now for the source that will supercede ESS in half a century's time. In Europe we have benefitted immeasurably from the liberalisation of border controls and the transport of sensitive samples – radioactive, toxic or biohazardous - has become far easier today than a few decades ago, similar to the ease of international flow of scientists. Import controls on fairly standard instrumentation for instruments and individual experiments have more or less disappeared. One cannot say this beyond the inner European Community, where such things are still not simple and the bureaucratic process of the granting of visas for the increasingly cosmopolitan research community mitigates against simple solutions to globalisation. However lessons can be learned here from other communities such as particle physics and astrophysics.

II.3 Mitigating actions in Europe – full instrumentation, life extensions, new sources and enhanced functionality

Which actions are realistic in order to enhance the capability for scientists who use neutrons and to maintain the integrity of the user community, as we look to the middle of this century? Any mitigating measures that will ensure Europe-wide access to neutron facilities require actions now, in order to be effective over the period 2030-2050. In this study we have considered two major ways and one underlying way of filling the evident drop in access that will occur between the imminent shutdown of existing facilities and the slower build-up of new capacity and capability represented today only by ESS. The different scenarios are heavily dependent upon the shadow cast by the eventual shutdown of ILL.

These scenarios are:

- An increased utilisation of those sources that can be sustained beyond 2030 by the construction of more instruments, and
- Major source upgrades and the construction of new medium intensity sources, as well as
- A thorough examination of whether the operating regime of current neutron sources is fit for purpose in today's world.

These scenarios have, however, rather different strategic impacts and a quite different funding envelope.

(i) Increasing the instrument suite of already existing European facilities

Let us look at the possibility of increasing the number of instruments and extending the life of the key European neutron facilities that

are planned to operate beyond 2030. The data is based on a second questionnaire to the facilities during the autumn of 2015. In this questionnaire the facilities were asked to look at the technical feasibility of possible initiatives and to provide a very rough estimate of the cost of upgrades, potential life extension and the additional capacity this would bring. Note that the upgrades are not limited to published plans and in almost all cases the funding of such plans will need decisions and commitments at an international level, given that the access will be demanded by scientists from several countries, with or without bilateral agreements with the source owner(s).

The average incremental cost for the capital investment and annual operating costs for adding one further instrument to an operating source has been used to estimate the overall approximate cost of the options described below. Instruments on spallation sources tend to be physically longer than those on reactor sources and require substantially more shielding and as a consequence are more expensive. We use a figure of 6 additional staff distributed through the neutron use side in order to operate one instrument. In general one person accounts for his/her salary in consumables and purchases such as liquid helium etc.

Table II.B

Incremental cost of adding an instrument to an existing source communicated by the source Directors.

	Reactor instrument	Spallation source instrument	Additional annual operations cost per instrument
Incremental cost per instrument (M€)	7 - 9	15 - 17	2.0 – 2.4

FRM II

It is Europe's newest reactor source, and beside world-class neutron beams and a high quality diverse set of instruments, it is also a source of positrons, isotopes, neutron irradiation, neutron activation analysis etc. An additional 9 state of the art neutron instruments could be added to

the facility by an extension to the existing guide hall and by the addition of a new guide hall.

SINQ

Sited at the Paul Scherrer Institut, SINQ is a continuous spallation neutron source fed by the High Intensity Proton Accelerator HIPA at PSI. HIPA, in addition to neutrons, provides the highest intensity muon beams worldwide and is a global centre for science using muons. Adding a second experimental hall would allow the construction of 7 additional state of the art instruments. Instruments on SINQ tend to be hybrids given the continuous nature of the beam which is nevertheless generated by spallation.

ESS

The full-capacity utilisation of ESS is a crucial issue. The present plans will exploit only ~50% of the ultimate capacity of its current target station, even ignoring the possibilities provided by a second target station. This is especially pertinent to the situation that neutrons face in the next 20 years because ESS will bring in completely new capabilities with the opportunity to explore new avenues of instrumentation and research at a modern innovative facility. At ESS there is room on the present target station for an additional 13 fully optimised instruments on conventional beamlines. We refer to this below as ESS-IIa. Furthermore by using the concept of bundles of neutron guides, which have been so successfully employed at most reactor-based facilities, and pioneered by ILL 45 years ago, ESS would have the capacity to construct another 10 instruments. This we term ESS-IIb. Such initiatives would bring the instrument capacity of ESS into the ILL's league and would justify completely the investment of 1.8 B€ for its capital cost and give excellent value for money in terms of scientific output.

ILL and ISIS

They will be dealt with below.

Table II.C

The consequences of increasing the capacity of key neutron sources by adding further instruments and extending the lifetime.

Upgrades to existing facilities	ESS-IIa	ESS-IIb	FRM II	SINQ
No. of instruments	13	10	9	7
Average number of instrument-days per year	1900	1500	1600	1250
Construction period	2031 - 2037	2037 - 2042	2030 - 2034	2030 - 2036
Capital cost	208 M€	160 M€	72 M€	84 M€
Additional annual operating costs	29 M€	22 M€	20 M€	16 M€

The replies from these operating facilities reveal the fact that the capacity to build new instruments during the next 10 years is very possible although it will be challenging. These sources however have three central goals: continuing their user programme; maintaining the current instrumentation suite at state of the art levels; and designing and building instruments for ESS. This means, realistically, that constructing additional instruments at these facilities can only start to materialise beyond 2030 because of the other constraints referred to above. It is of course obvious that additional funding will be needed that in most cases must come from beyond the direct national level.

(ii) Major source upgrades and new facilities

ISIS

ISIS is, like ILL, a cornerstone of the European neutron scene. Its achievement has been in the 1990s to demonstrate firstly the viability of spallation sources to compete with the output of the best reactor sources, and then to define the way ahead for the next generation of world leading neutron sources. The accelerator system is getting old but could be replaced within the existing buildings. Replacing the existing accelerator, upgrading the original target station and adding a new target station would provide Europe with a short pulse spallation facility

of similar source quality to SNS and J-PARC. This constitutes a cost effective solution that would pay dividends far into the future. ISIS is one of four facilities worldwide that also produces muons for condensed matter and materials research.

In a first phase of renewal, upgrading ISIS with a new linac and synchrotron accelerator installed in the existing buildings and feeding into a rebuilt and fully optimised first target station and sharing 500 kW of power as well as adding seven instruments is a realistic option. This could provide ~1000 additional instrument days. In a second phase, which has already been planned, the whole facility could be rebuilt in stages to a power exceeding 1 MW. During this build process, for much of the time the current instruments would remain fully operational. The estimate for these upgrades which would furnish an additional 17 instruments and ~3000 instrument days is €755 million.

For Europe to equate to the American and Japanese short pulse neutron sources (SNS and JPARC) by far the most cost effective solution would therefore be to build a MW-class short pulse facility at ISIS, reusing existing infrastructure and facilities as well as drawing upon on-site competences. The current facility could operate until the new facility is operational with its initial suite of instruments.

ILL

Since the year 2000 the ILL has substantially updated its instrument suite with a continuous investment programme called the Millennium Programme. This has incurred a cost of around 60 M€ and provided an increase in data rate from the instruments of about a factor of 30. The ILL's Millennium Programme demonstrates beyond doubt the benefits of adding further capacity to an already functioning facility. Furthermore this modernisation programme has brought the whole instrument suite to state-of-the-art capability and has maintained ILL's position as the leading neutron source in the world. This investment

programme will continue. On the other hand to increase the capacity in terms of the number of operational instruments is probably unrealistic. Instead, the accumulation of capacity and capability of the ILL can be capitalised upon by operating it well into the current century. The design of the nuclear aspects of the ILL allowed for the replacement of all key components and this has proved to be key to its longevity. Therefore further 10 yearly extensions of the ILL's International Convention are an obvious way to maintain Europe's lead during the commissioning of the ESS, and enhance the scientific output of this facility. A rough estimate of the additional operating costs are in the region of 10 M€ per year. Therefore to extend the lifetime of the ILL by 20 years would cost an additional 200 M€.

New Sources

Currently there is little effort in Europe being devoted to replacing those reactor facilities that are being shutdown or to planning for a future beyond the ESS. All spare capacity is going into the mammoth task of bringing ESS to its operational phase and to building the instruments and the ancillary facilities necessary in order to exploit it. This contrasts greatly with the astronomy community and the high energy physics community where plans for successive projects after the European Extremely Large Telescope or the Large Hadron Collider are already well developed. Substantial TDR documents already exist for the Overwhelmingly Large Telescope OWL and for the Compact Linear Collider CLIC as well as the Future Circular Collider FCC. Both these communities benefit from larger, well-regulated administrative structures that allow a small number of scientists and engineers to develop themselves to these activities. This is not the case for neutron sources nor for synchrotron radiation sources.

Let us defer this question for the moment, and outline what possibilities might exist for new as yet undefined neutron facilities.

If the benefits of the neutron landscape that has existed in Europe for some decades are considered to be sufficiently great, given that this framework has delivered dividends in terms of Europe's lead, then new medium intensity spallation sources could be built in different places in Europe. Realistic possibilities would be the construction of three 500 kW spallation sources each having say 20 instruments and serving a particular region of Europe, though not exclusively so. Locations and hosts exist for such sources and the design of three facilities could be sufficiently differentiated so as to provide a range of instrumental and thus scientific possibilities. For example, one source could concentrate upon thermal and near epithermal neutrons whilst a second source could focus upon cold neutrons and ultracold neutrons. This latter idea was pursued enthusiastically with the AUSTRON facility which was to have been built close to Vienna and to some extent has been realised in the shape of the second target station at ISIS. A third source could be based upon the idea of a proton driver with a pulse length much closer to the moderating times of slow neutrons than either the short pulse of ISIS or the long pulse of ESS. Such a spallation source with a proton pulse of say 50 μs would have a more-nearly optimum ratio of neutron output to proton power and would still be competitive even at powers of 100 kW. Such facilities are likely to cost in the region of 600 M€ with annual operating costs of ~50-60 M€. Significant contributions to the capital costs could come from European regional funds.

Other possibilities for smaller sources might emerge from the work that is being carried out in Jülich in Germany and in Indiana in the United States. Design studies and prototyping have been pursued using accelerator drivers that do not use protons. The idea behind such sources is to optimise the coupling of target to moderator and in the optics for the beam distribution, thereby enabling a remarkable optimisation of the performance to be made and to provide relatively low cost sources (200 – 500M€). At the moment such ideas are in the proof of concept stage but more work should be devoted to understanding their practical

realisation and feasibility. In the future such neutron sources could host perhaps eight instruments and provide of the order of 1000 instrument days per year with an annual operating cost of around 25 M€ per year. Such facilities take inspiration from the second target station at ISIS which delivers high quality results from a closely coupled second target station that operates at only 36 kW, a case of "small is beautiful".

Discussions on synergies between the development of new accelerator technologies and applications may allow novel concepts for neutron production to emerge. One scenario is that it will be possible to develop a Compact Neutron Source based on non-spallation concepts. The recent developments in this field indicates that a competitive prototype CNS concept can be ready rather soon (by 2025 onwards), if the corresponding efforts and means are available.

Other more futuristic ideas for the generation of beams of slow neutrons have already been published with ideas for the use of fusion and the generation of neutron rich isotopes having been put forward. It remains for these ideas to be progressed but currently they do not appear to be practically realisable within the coming few decades.

(iii) Advanced operating regimes

The paradigm that many neutron sources work on today for the user access programme is based upon the system that was implemented at the ILL by Mössbauer in the early 1970s. It has served the community well and, indeed, has since been adopted by the synchrotron radiation sources. After 50 years it is perhaps now that this paradigm ought to be revisited. We therefore recommend that a radical examination of current operational practices should be undertaken.

Such a re-examination should first revisit the twice-yearly application round culture, checking on speed of access for both academic users and industrial users and more effective use of remote access. In addition the opportunity would present itself to really examine relationships with

industry. How can this be improved? Although less than 2% of beamtime is bought by industry, around 25% is directly or indirectly funded by industry. Efforts towards being able to reliably identify this quantity of industrial access will pay dividends in dealing with politicians and funding agencies. To be effective however requires the willingness of both sides to compromise and be more open. Related to this topic is the exploitation of innovations. Traditionally scientific facilities 25 years ago were positively dissuaded from exploiting innovations. The situation has changed but it is not clear that large facilities have reacted as nimbly as could be expected. There are best practices that can indicate a way forward, for example at EMBL where the harnessing of innovations via EMBLEM has become a visible and positive activity. Intellectual Property is a resource that is not sufficiently protected, nor yet given sufficient weight.

It is also timely to look at the relationship between the user and the facility. This relationship would benefit from being strengthened, for example by the temporary exchange of staff. One simple way to improve scientific effectiveness would be to increase the number of visiting researchers funded to attend each experiment. This would also function as a training initiative. It has become quite normal for researchers, given 3 to 4 days of beamtime, to regard being exhausted as the experiment proceeds as a badge of honour. It is clearly not efficient nor effective in utilising the beamtime. The time has come for teams of users to be more realistically manned and lessons can be learned from what is done in the astronomy and the high energy physics community. Increasing the size of teams that are funded to do experiments is a minor cost compared to the cost of delivering one beam day on an instrument, but it is resisted by governing bodies. Furthermore the use of IT technologies can be strengthened - the analysis of data as it is being taken, the comparison with predictions and, importantly, the taking of decisions on behalf of the user team is hardly employed at all today. When we look at other walks of life e.g. the piloting of aeroplanes and the move towards

driverless cars, we see that there are philosophies and best practices that would readily transfer over to neutron sources. Data quality is often too poor because of lack of intensity, but at the same time and, through tiredness, measurements are often allowed to continue far longer than is necessary for good statistical quality, and human decision-making becomes less focussed.

Open access to data is rare in the field of materials science, but we can learn from the way in which data, paid for by public money, can be made available to a far wider community of researchers than the principal investigators of a given experiment. We will deal with this in the next section, but it is sufficient to say here that significantly more science emerges from a facility when data is freely available. We recommend that this innovation be seriously examined. Even the question of the standard neutron quanta of beamtime - one day - should surely be re-examined, but this requires more support staff. At the same time the implementation of automated processes should be critically examined. For example the changing of cryostats within radiation exclusion zones does not today need to be done manually by inexperienced user groups during silent hours. Robots could do this task and many others more effectively and with less risk, also operating under radiation exposure.

Moving to source operations, in the present era of climate change it is essential that sources examine their energy use and are able, properly funded of course, to identify and then to implement such changes that will reduce these costs in the long term. The issue of long-term sustainability is putting pressure on the governing bodies of the research infrastructures to implement maximum energy efficiency. Ranging more widely, the interaction between the different sources in Europe, and indeed globally, is friendly but weak. Cooperation and coordination is surely the order of the day rather than the friendly competition that pays so well in times of plenty. Today the times of plenty are receding. Furthermore there are benefits to be gained by seriously meshing source

operating schedules and shutdowns, and for methods to be set in place where experiments are done on the most appropriate instrument, which might imply nominating a different instrument in a different Institute for a given experiment. This implies great flexibility and willingness to innovate. It also leads on to the need for a wider ownership model for the remaining neutron sources in Europe. We recognise that this is a very sensitive issue but we believe that access should be widened to all nationalities in Europe as of right, and that ownership should become less monolithic in nature. Of course this leads on to the eventual creation of an umbrella organisation where decisions are pooled and strategies are created whose goal is the greater good of the whole scientific community, rather than what is considered to be best for a particular source in isolation.

III.
A likely Short-Term (2015 to 2030) Scenario in Europe projecting forward

The overall trend that neutron facilities and their users are facing is clear. The conclusions that we derive from the data submitted by the European sources - the Baseline Scenario – indicate that neutron scattering capacity in Europe will fall in the next decade to accessibility levels approaching 50% of what the user community enjoys today. The ESS, which will come on line in the middle of the next decade, will of course be a powerful next generation flagship and will undoubtedly open up new avenues of research but it is likely to be a flagship without a fleet, since many medium flux sources will have been shut down by then. This Baseline envelope represents a projection forward from the *status quo*, as per the questionnaire returns, which assumes:

- LLB and HZB will both operate at full capacity until their closure by the end of 2019
- The fuel cycle questions which affect all reactor-based sources are solved in a reassuring, reliable and economically viable manner
- The full operation of ILL is secured until 2023, and
- ISIS operates at full capacity at ~150 days or more per year.

This is the scenario that is anticipated by facility Directors if no additional actions are taken. This would nevertheless alter the neutron landscape in Europe irrevocably for the worse.

By taking the Baseline Scenario and proposing some modest initiatives and extensions we can begin to mitigate the problem, but a severe fall in measuring capability still results. This mitigated outlook – an Enhanced Baseline Scenario - assumes two things:

- incremental life extensions to a number of sources;
- corrective actions, currently feasible, are taken which are that
  - ILL operates for the entire period considered at full power (2015 to 2030).
  - ISIS operates for a minimum of 150 days p.a.
  - Fuel supply is secured for Rez, Budapest and FRM-II (MLZ).

Regrettably, we do not see any realistic opportunity to achieve extended lifetimes for either LLB or HZB, both of which are perfectly viable facilities with unique capabilities, high scientific outputs and highly capable staff. The destiny of these two facilities was determined unilaterally and raises questions about the absence of a coherent European policy on neutron provision. Similar actions taken in the future for other sources would represent a clear risk to the whole scientific discipline in Europe. A Europe-wide approach needs to be facilitated.

The optimistic scenario that we present, with increases in operating periods for several sources and a commitment to operate ILL until 2033 and even beyond, in addition to a commitment to furnish ESS with more instruments than the 22 would, in our view, represent the only sensible way ahead if the health of the European neutron scattering community and its world-leading scientific output were to be properly nurtured. Such a path would preserve the research programmes of the European research community and, with ESS acting as the flagship source, ensure that the scientific legacy that ESS inherits would be built upon in a proper manner. A further improvement would of course result if both LLB and HZB did not close down until 2025.

In all cases above it is assumed that ISIS, FRM-II (MLZ) and PSI will all be operating for the entire period and adding additional instruments incrementally.

Were all these upgrades to be funded we estimate that ~ 9450 additional instrument-days for science would become available. This is a matter to be addressed by the funding bodies of Europe and their priorities.

Table III.A

Additional output and associated costs supplied by the five major sources referring to feasible upgrades to their facilities. The ISIS information contains significant upgrades to other equipment and is something of an outlier in this data. Looking at the other sources there is remarkable consistency.

Facility	No. of extra Instruments	Effective capital cost per instrument M€	Additional Capital cost M€	Additional Operations cost M€/year	Additional Operations cost per instrument M€/year
ESS	23	12	275	27	1.2
ISIS	17	45	755	18.5	1.1
FRM-II	9	9	80	8.4	1.0
ILL	7	17.7	124	14	2.0
SINQ	7	7.1	50	7	1.0
TOTALS	63	11.5*	529*	74.9	1.25*

[average]*

III.1 A Possible Remedial Scenario

The different options above – upgrades, extensions and new facilities can be combined in a multitude of different ways. The analysis shows that whilst new sources, and full exploitation or upgrades of existing sources will be able to deliver neutrons in the long term, the only way to avoid a big drop in coming years is to delay the closedown of the ILL. In *Figure 13* we show, as an indication, the effect of extending ILL's lifetime to 2027. Of course every year of extension beyond 2027 will fill in the gap. For the upgrade scenarios for ESS, FRMII and SINQ, the numbers to first order scale with the number of instrument days. i.e. half the money will provide half the number of instrument days. For any of these scenarios to be realistic however the discussion between funding agencies and sources needs to start now.

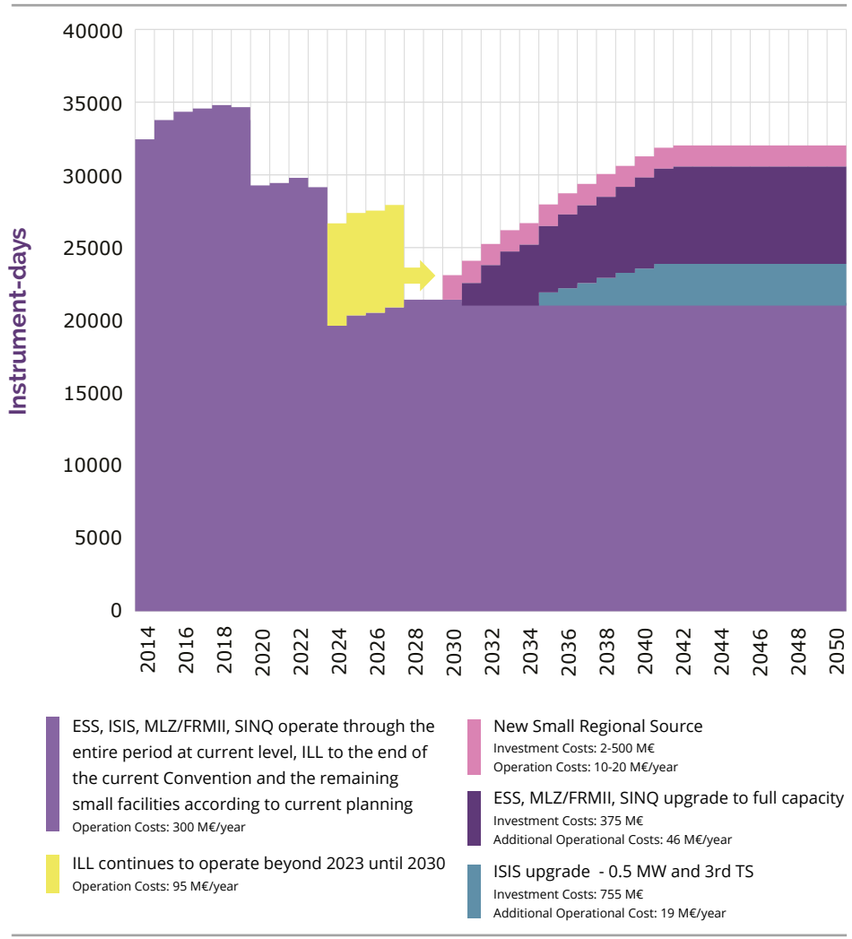


Figure 13. Possible Remedial Scenario

Instrument beam-days following the implementation of a remedial plan.

IV. Recommendations

IV.1 European funder's network organisation for neutron science

Research with neutrons in the coming years is faced with a great change. Many of the sources currently in operation will be closed-down entailing a drastic reduction of measuring capacities throughout Europe. Timely mitigation measures must be implemented, if severe drawbacks for the European Research Area are to be prevented. For this purpose, the European member states should agree on a common strategic approach and try to bring co-ordinated activities into play, so that the scientific community of neutron users can operate successfully in global top-level research with neutrons in the coming decades.

One way in which this can be achieved, is the establishment of an international organisation that serves as a forum for discussing the various national research policy positions in the simplest case but has the potential to develop and implement a pan-European long-term strategy for research with neutrons. In such a network, representatives of Ministries and funding agencies should come together as official delegates from the funders side, who provide a different perspective on the conceivable concepts presented by the scientific community, but perceived in many cases to be unrealisable without such coordination.

International collaboration at the level of scientists and facilities has evolved very well over decades, but there seems to be a lack of co-ordination on a pan-European level amongst the funders of science in strategic planning for the long-term future of neutron science in the broader landscape of the strategically needed analytical facilities.

In order to better co-ordinate the transition from today's deceptively comfortable situation with regards to available instrument beam days to the long-term prospect of probably less than half in about 15 years, it is timely to establish a European funder's network organisation for neutron science and task this body with developing a common strategy to cope with this potential challenge.

Examples from other scientific fields like Astronomy and Astroparticle Physics have shown a clear added value from setting up an international body made up by representatives from the funder's side addressing strategic issues and developing structuring activities, in which case one could envisage some science-based convergence. We fully understand that such an endeavour could be challenging but the potential benefits should be enumerated and the opportunities set against these challenges.

A lot can be learnt from benchmarking against other disciplines and embracing best practices. Open access to data, for example, so common and productive in astronomy but resisted by neutron users, is long overdue. Open access takes various forms – and also comes with obligations and costs such as the furnishing of proper metadata. As a first step, access to data should be more open, whilst recognising that making it happen will require extra resources. This open access has led to significantly more scientific output from telescopes, which is quantified by publications from the Hubble Telescope as shown in *Figure 14* where it can be seen that the scientific output has more than doubled by open access. The jealous ownership culture of data in the neutron field leads to data being underused, slowly analysed and publication delayed to the detriment of the user and the source itself, and indeed to the whole discipline. We understand that the 'neutron' and 'astronomy' models have differences that could justify a shortish embargo period for 'neutrons' and 'photons'.

Serious thought therefore needs to be given to developing an Open Access policy and mechanisms suitable for analytic methods such as neutron scattering in materials science, and identifying the resources required to make them happen.

Ministries and funding agencies of interested countries could set up

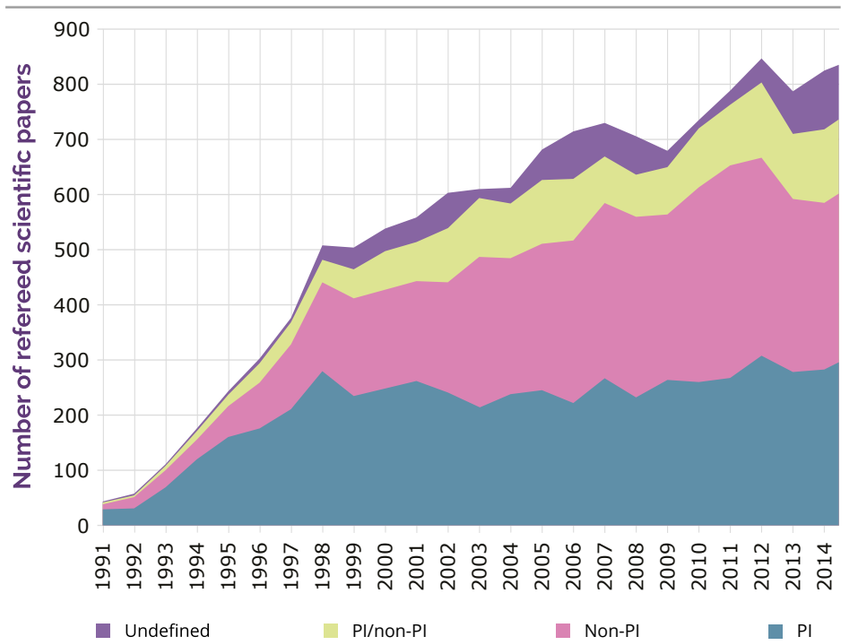


Figure 14. Hubble Space Telescope publication rate

The evolution of the number of refereed scientific papers from Hubble Space Telescope data following the opening up of access to data. Steel blue colour indicates the Principle Investigator papers (PI) and fuchsia colour refers to papers published as a result of open access (non-PI). Lime colour are papers written by PI-non-PI collaborations. The ratio of non-PI to PI papers is 1.02 meaning that scientific output has at least doubled. The urgency to publish by the PI team however, encouraged by competition, almost certainly results in many more papers being published overall than simply a factor of two.

an organisation that is mandated to develop a common European strategy for the supply of neutrons. The primary purpose of the funders' organisation would be to exchange information on the current strategic planning regarding the developments in neutron science of each member country. But furthermore, starting with the evaluation of the current situation, this organisation could create scenarios to mitigate the consequences and finally present a common long-term action plan, which provides its member states with recommendations for

implementation under the individual national science policies.

Whilst the members of the funders' network organisation would be official delegates representing Ministries and funding agencies, dedicated expert groups would be created as required in order to fulfil specific tasks as support measures for the funders' network organisation. Typically, members of these groups of experts would be scientists from the group of users and operators of sources. They bring in the necessary scientific and technical expertise needed by the policy-makers who are represented in the funders' network organisation. As an example, such a group of experts could be charged with studying at a level deeper than simply conceptual, the feasibility, both scientifically and technically, of next generations of neutron sources.

IV.2 Key actions

A number of key action points emerge, which a collective European strategy should address:

- Maintain the ILL's world-leading scientific output over an extended overlap period with the ESS by providing political and financial support. It is important to ask whether, in the very unlikely event of premature closure of ILL for safety reasons as happened to the HFR in Brookhaven, Europe should not be elaborating a Plan B?
- Develop, without delay, a growth plan for the ESS that provides for more than the 22 planned instruments, and commit secure funding in order to achieve it.
- Examine the opportunities available to invest in the broad neutron pool in Europe that serves so well scientific productivity. The network of medium sized neutron sources would be maintained by the implementation of an upgrade programme of the 4 to 5 newest current sources, ESS, ILL, ISIS, MLZ and PSI, that can be operated beyond 2030 sustaining a major technical renovation.

- Put in place studies for the development of new medium-power high-brilliance neutron installations.
- Activate the European neutron user community such that they, in partnership with the sources, act energetically and coherently to secure the future health of the discipline.
- Explore the feasibility of setting up a more coherent and coordinated strategy group at the pan-European level to oversee and sustain Europe's neutron sources at an appropriate level by taking a collective view.
- Current sources are urged to examine their operational regimes and to reinvent themselves, implementing best practices from other disciplines.
- Develop an Open Access to Data policy and identify mechanisms for neutron scattering, as part of a broader initiative for analytic methods in materials science.
- Launch a study on a next generation world-leading European neutron source that would begin to operate in the second half of the century, exploring possible global partnerships.

In Summary

The strength of the neutron community

- Almost 1900 journal papers are published each year resulting from data taken at the 13 European neutron sources. These sources generate almost 30000 instrument-days per year from ~160 operational instruments.
- The user community of such sources exceeds 6000 individual researchers.
- Europe has led the world in the use of neutrons for materials science for over 40 years.

The portfolio of neutron sources

- The installed capital value of the European neutron sources park is ~ 5.7 B€; the integrated operating costs are ~ 314 M€ per year.
- The ratio of operating costs to installed capital of current sources is, at 6%, well below levels that are considered to be sustainable for capital- and equipment-intense large organisations.
- Two-thirds of currently operating neutron sources will close in the coming ten years.

- ESS is under construction.
- No further neutron sources are planned.

The changing dynamics of neutron beam use

- Having significantly fewer sources will herald a complete change in the relationship between sources and their users that has put Europe into its world-leading role today. Instrumentation and techniques development; scientific exploitation; training of both users and source staff; inter-source collaboration will all require a changed approach. The sources that remain 10 years from now will have to adapt to this new situation and they are not funded to do that. Scientific output, both in quantity and quality, will therefore suffer.
- Competition between Europe's neutron sources has paid dividends in the past, a period of comparative comfort. That situation is changing and from now on cooperation will have to be embraced much more pragmatically than it has been up to now today, despite positive moves such as periodic source Director meetings.
- The fuel cycle for reactor sources is a significant threat both financially and politically and therefore operationally.
- Many neutron sources are operating below capacity, and some well below capacity.
- The eventual closure of ILL and the rise to full capacity of ESS represent a gross uncertainty in any attempts to predict the future availability of neutron instrument beamtime in Europe.
- When ILL closes, and especially before ESS has reached its full design specification in terms of accelerator power and instrument portfolio, Europe's leading position in the world will be abruptly lost.
- The availability of neutron measuring capability will fall significantly over coming years reaching a minimum 10 to 15 years from now at levels of 50% to 65% of today's levels, depending upon the scenario that plays out.
- Europe's loss of its leading position will not principally be because they have been overtaken by a surge in global capability, but rather because European capacity will have fallen dramatically and faster than global sources have risen. This inevitably means that neutron techniques as a whole will fall in scientific impact world-wide and the research community will contract, and especially so with respect to other techniques such as photon scattering.
- ESS is a large undertaking and, no differently from any large project, it faces uncertainties and risks in the coming decade. In order to minimise these risks sufficient secure resources have to be allocated to the project. Funding uncertainties and especially short-term variations cause increased costs and stretched delivery times. In any scenario the rise to full capacity for the ESS instrument suite will inevitably be gradual, requiring a ten year period at minimum, and again no different from the documented experience at other spallation sources.
- The very diverse user community must take a leading role in protecting its access to the neutron instrumentation that generates its scientific output. The community is composed of high quality individuals who have strong potential impact upon the funding authorities. Now is the time to use that impact. The demonstrably rich scientific case for neutrons must come principally from them rather than from the sources. There is a vehicle for this activity: ENSA, the European Neutron Scattering Association.

Seeking greater effectiveness

- Our analysis indicates that over recent decades there has been a lack of co-ordination on a pan-European level in the strategic planning with respect to the neutron source park throughout Europe. It is not too late to remedy this situation but it would require a continent-wide approach.
- Lessons can be learned from the practices of the High Energy Physics community and the Astrophysics community which are both highly organised in terms of European strategy, researcher involvement and consultation, with respect both to protecting current installations and preparing the scientific case for future facilities.
- Neutron sources must be strongly encouraged to increase their operational effectiveness. This includes: automation; use of robotics; sustainability of energy use and cost; data accessibility to the wider scientific community; beamline accessibility in terms of speed and diversity of methods; emphasis on techniques employing the uniqueness of the neutron (eg polarisation); and the exploitation of innovation; amongst other things.
- An increasingly close liaison between sources, universities and industry in terms of staff mobility would pay dividends.
- Industrial access, either paid for or through collaboration with university groups, needs a fresh approach. Scientifically, technologically and politically this is extremely important. Documented access of only ~1 to 2% by industry is far below the levels that could benefit from neutron techniques, and industrial access via university groups is often undocumented and therefore politically unusable. The diametrically opposed cultures of science and industry – openness as opposed to guardedness – are a barrier to progress.

Closing Statement

The European neutron user community has to face up to a serious threat to their capability to address appropriately scientific challenges which can not be accomplished by other methods.

All outlined scenarios within the next 10-15 years show a dramatic contraction in the capacity of the European sources to provide neutron beam days compared to current levels. This, inevitably, will influence the user community to a great extent. If no substantial mitigating initiatives are introduced in a timely manner, half of the user community's needs will not be satisfied and the current science programme cannot be sustained.

It is however obvious that a collective policy of wise stewardship of Europe's neutron sources has been absent. Whilst individual sources and instrumentation have been maintained and upgraded, the question of source renewal has been ignored. Decisions about operations, investments and whether to prolong lifetimes or envisage closures are in general taken by the owner or owners themselves of individual facilities. They are perfectly within their rights to do so within the current system but this may not be of overall scientific benefit. That is the situation that Europe finds itself in today with respect to neutron provision. There has been a marked lack of renewal of neutron sources as a result of this unilateralism.

A full compensation of these needs by other analytical techniques will not be possible. Neutrons are able to penetrate deeply into bulk matter, unlike a number of other probes investigating the same distance and energy scales that, in the main, are surface probes. This allows structure and dynamics to be studied deep inside samples or samples held within bulky apparatus, such as are necessary to study systems at very low temperatures, *in situ*, or *in operando*. The weak interaction with matter means that radiation damage is very low, enabling prolonged and detailed studies to be made of soft and biological materials under varying conditions.

Neutrons are particularly effective at determining the positions of light elements such as hydrogen, which is often crucial to an understanding of the function of biological molecules as well as those technologically important materials required for catalysts, hydrogen storage and transport in the development of greener materials for energy. Neutron scattering thus provides a remarkably powerful probe of the structure and dynamics of a wide range of materials at the atomic and molecular scales which is unique in many respects, and which complements other techniques based on synchrotron radiation, electron microscopy and nuclear magnetic resonance.

By using neutron scattering we are able to study materials comprising mixtures of heavy and light atoms, with different isotopic ratios, at the bulk level as well as on the surface, with clear identification of atomic location and element specificity, and in addition revealing the collective and local movements of these atoms or molecules in solid or liquid matter through coherent or incoherent studies.

“Neutrons answer the question on where atoms are and what atoms do”. This is the simple message of the value of neutrons as a probe to study matter, and in Europe today this capability is at a crossroad.

We have addressed the situation as we see it for neutron sources in

Europe in 2050. A number of guiding principles have governed our work:

- Europe will need a reactor-based source in the future, along with the spallation sources, in order to ensure the necessary instrumental and scientific complementarity.
- Europe needs to ensure and extend the life of some of its top reactor sources.
- Europe needs to plan a number of medium-flux sources in the future. The mechanism necessary to arrive at such a position forms part of this study, drawing in experience from other scientific disciplines operating and depending upon large scale facilities.
- Europe’s neutron park needs to refresh and modernise its functional models, bearing in mind the inevitable reduction in capacity in the coming two decades.
- The neutron user community has a significant role to play in assuring the health of the discipline, working as equal partners with the sources.

The goal must be a well-balanced European Landscape to serve neutron science adequately and for that to be achieved coordinated investment is urgently needed.

Final Conclusion

It is clear from the data that have been provided by the current neutron sources in Europe that the European neutron scattering community faces a 15 to 20 year period of significant change. From the current rather healthy multiple source scenario to a scenario where, by the early to mid-2030s, almost certainly only three or perhaps four sources will be operational and perhaps even fewer, is an unwelcome vision. Such a transformation will have severe consequences. The situation can be mitigated to some extent if the remedial actions outlined above materialise. This mitigation however comes at a cost, both financial and political, and neither aspect is simple to address. Action needs to be taken now.

Acknowledgements

We have benefitted from the hospitality and friendly assistance of staff at the Directorate-General for Research and Innovation of the European Commission. In particular we would like to thank Ms Imma de la Motta. We acknowledge the PSE Strategy Working Group of ESFRI, particularly its Chair Prof. Giorgio Rossi, who have supported us fully in our work, for which we thank them. The NLG expresses its thanks to Maddalena Donzelli for transforming the format of the text and the diagrams into the professional quality that we now have. We acknowledge the willingness of the neutron source Directors in Europe to provide information openly and to the Directors of sources outside Europe who have helped us in our enquiries.

Documentation

[1] ESFRI Roadmap Landscape Analysis for the PSE Analytical Facilities, 2016

[2] OECD Megascience Forum Report of the Neutron Sources Working Group. P Tindemanns Ed. OECD, 1999

[3] French Cour des Comptes, 2016

[4] ILL Associates' Strategy for Neutrons, 2013 http://www.ill.eu/fileadmin/users_files/documents/news_and_events/news/2013/20130704-Report-ILL-Associates-including-scientific-case.pdf

[5] The Science Case for ESS, 2014

[6] ENSA publicity for ECNS Zaragoza, 2015

[7] Perspectives of Neutron Research in Germany in the Light of the Coming New European Neutron Source. KFN, 2011 https://www.sni-portal.de/kfn/kfn/SP11/index-engl.php

[8] Richter, D. & Springer, T. November A twenty years forward look at neutron scattering facilities in the OECD countries and Russia, 1998

[9] ESS Update and Meeting Goals. James H. Yeck, 2014. http://slideplayer.com/slide/6581340/

[10] US National Academies of Sciences, Engineering, and Medicine. Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, 2016

Appendices

Appendix I
The Terms of Reference

PSE SWG Landscape Analysis Exercise: Neutron Landscape Subgroup (NLS)*

In the framework of the Landscape Analysis of the Research Infrastructures in the PSE domain in view of the 2016-ROADMAP the PSE SWG decided (Meeting in Rome, February 10th 2014) to proceed with a first landscape document on neutron sources.

The "time priority" is set by the ongoing negotiations for the possible quick start-up of the construction of the European Spallation Source.

The ESS could come on-line in 2023 so it is of maximum relevance to understand what is the likely scenario of available neutron sources for spectroscopy and irradiation of materials across Europe at that time and during the ramp to full operating capacity.

The document will be also an integral part of the Landscape Analysis of Analytical Research Infrastructures in view of the new ESFRI Roadmap 2016.

* The name Neutron Landscape Subgroup (NLS), adopted by the PSE SWG, was changed into Neutron Landscape Group (NLG) according to a decision taken by the Group itself. This is the denomination used throughout the entire publication.

The document shall be composed of two sections:

1. current availability of neutron sources and foreseen situation in 2023-2028
2. **strategy of neutron spectroscopy in the 2020-2050 time frame**

- In order to draw such documents it has been agreed to set up a **Neutron Landscape Group** of high profile with the participation of stakeholders (heads of institutions owners of neutron sources, ministerial representatives, science community representatives) of the field.
- **Chapter 1** the current activity of neutron spectroscopy and irradiation across Europe and in the world (accessible to European scientists and non-accessible): figures and trends. The chapter should develop on the expected scenario of European and world neutron source availability in 2023-2028 and later, i.e. at the time some of the currently active sources may be phasing out and the ESS might be ramping up. The chapter shall be limited to about 10 pages with relevant tables, graphs and references.
- **Chapter 2** shall focus on strategic analysis in the longer period and be of more flexible format; it may include recommendations about optimizing and strengthening the role of neutron science in the next 30-40 years.
- The terms of reference of the work are outlined below. The two chapters may be written in time sequence with chapter 1 being the most urgent (May 2014), whilst the full document needs to be in time-line with the ESFRI-PSE Landscape Analysis (July 2014 or earlier).

A. Mandate of the Neutron Landscape Group (NLG)

- The PSE SWG decides on the mandate of the NLG
- The activation, duration and composition of the NLG, its activity, and its specific terms of reference are decided by the PSE SWG.

A.1. NLG Chair/Coordinator

- In analogy with ESFRI's procedural guidelines, the NLG shall be chaired or co-chaired by a PSE SWG member.
- The duration of the mandate of the NLG is up to the end of 2014.
- The NLG Chair is responsible for the timely and good organisation of NLG meetings of needed and timely circulation of all relevant e-mail documents.

A.2. NLG Membership

- Nominations of potential members of the NLG have been agreed upon by the PSE SWG, establishing a potential high profile NLG with overall representativeness and equilibrium of Countries and Stakeholders.
- The PSE SWG Chair shall contact and verify the availability of the potential members.
- If the balance of the nominations is not appropriate the NLG Chair should alert the PSE Chair, who in turn will alert the PSE SWG and identify remediation actions.
- The NLG Chair may, if he/she chooses, invite other members of PSE SWG to participate as observers in order to ensure coordination and awareness.
- All NLG members shall provide a fair and impartial contribution to the group, understanding its relevance as reference document for decision processes.

B. General topics and activities

- These ToRs are common to those of the Landscape Analysis Drafting groups developing the Landscape Analysis for the ESFRI roadmap.
- The role of the NLG, under PSE SWG's coordination and supervision, is focused on the following topics:

1) availability of neutron sources in 2023-2025

- the scenario of active neutron sources for spectroscopy and irradiation of materials in 2024-2025;
- the scenario of available beamlines and general class of instrumentation;
- the expected pressure of academic and industrial users;
- the expected pressure of innovation programmes;

2) strategy of neutron spectroscopy in the 2020-2050 time frame

- the potential of science and technology developments requiring neutrons;
- the potential of material science, biology, medical science programmes integrating neutron spectroscopy or neutron irradiation as key methods;
- the innovation and energy research developments;
- the role of neutron science and technology in Europe and in the world;
- the industrial use and industrial application of results;
- the foreseeable needs of upgrades or more new sources in Europe (including regional/national sources) and in the world;
- the size of the user neutron community.

C. Method of work

- The method of work includes:
  1. Meetings and/or exchange of questionnaires/documents;
  2. Drafting of chapters 1 and 2;
  3. Presentation to PSE SWG of drafts and final documents.
- NLG may seek independent scientific, technical or socio-economic advice making use, as necessary, of existing bodies and/or specific experts. When appropriate the
- NLG shall propose to the PSE SWG the organization of a dedicated Agenda to deepen the discussion.
- The NLG shall avoid to become or to be perceived as the expression of any specific lobby-group supporting or opposing a specific proposal.
- Background material includes the previous ad-hoc Expert Working Group on Analytical Research Infrastructure of May 2010, national roadmaps and international roadmaps, MoUs, conference presentations and proceedings, project CDRs and TDRs at global level.
- Members shall respect the confidentiality of discussions to facilitate and nurture open discussions and the outcome of meetings should be treated in a confidential manner.

D. Deliverables

- A report on **current availability of neutron sources and expected scenario in in 2023-2028 (ch. 1)** and a proposal for a **strategy of neutron spectroscopy in Europe in the 2020-2050 time frame (ch. 2).**

- Delivery of **chapter 1** and an outline of the whole document is expected within 3 months (May 2014), whilst the full document could be delivered within 5 months (July 2014).
- Only ESFRI is responsible for the final acceptance of the SWG report which will be published on the ESFRI web site.

E. Resources and time scale

- The NLG does not have any budget: participation of experts (travel & subsistence) must be borne by the members or their Ministry/ host-organisation. In case of meetings taking place in Brussels, the EC may offer logistic support (e.g. meeting room, video-conference facilities) subject to availability and advance notice.
- The ESFRI Secretariat (with the support of the above-mentioned EC official) will provide, if needed, access to a web-based facility reserved to the NLG members, who can use it to share documents and information in a confidential way.

Appendix II
Membership of the Neutron Landscape Group

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Previous Director-General of ESS and former Director of ILL, having learned his trade in neutron instrumentation and sources at Birmingham University, Ispra, Harwell, & ISIS

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Deputy Director for Large Scale Facilities at PSI, having learnt his trade in neutron instrumentation and sources at Risø, Harwell, FZ-Jülich

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Science policy activities related to large scale research infrastructures for many years on behalf of BMBF in international settings: OECD, ESFRI and European Commission

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Head of Neutron and Positron Methods in Materials section, TU Delft. Previously deputy Director of the Berlin Neutron Scattering Centre and acting head of the Neutron Instruments and Methods department HMI (now HZB-Berlin)

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Head of the Department of Physics and Earth Science, University of Perugia. Professor of Experimental Physics. Vice-Chair of ESS Council and former member of ILL Steering Committee and ESRF SAC. MIUR Delegate in FP7 Programme Committee Research Infrastructures.
Past experience in neutron instrumentation and spectroscopy at ISIS, LLB and ILL

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Past President of ENSA (European Neutron Scattering Association), Scientific Director & CEO, of HMI/HZB Berlin, Professor of Physics University of Mainz and TU Berlin. Trained in techniques and use of neutron scattering at University of Tübingen, FZ Karslruhe (FZK), ILL and BNL

Appendix III
e-mail from John Womersley (ESFRI Chair) to the Heads of Neutron Laboratories in Europe regarding the Neutron Landscape Group

Dear Colleagues,

The European Strategy Forum for Research Infrastructures (ESFRI) brings together representatives of Ministers of the 28 Member States, 9 Associated States, and the European Commission. It supports a coherent and strategy-led approach to policy making on Research Infrastructures. ESFRI is mandated by the Council of Ministers to to develop a European Roadmap and prioritise research infrastructures. ESFRI's Physical Science and Engineering (PSE) Strategic Working group has started the process of working towards a new Roadmap for 2016. The first part of this work includes a thorough landscape analysis of existing Research Infrastructures (in the PSE area) and a strategy outlook of the field in the next 2-3 decades.

A specific aspect concerns the availability of neutron sources for spectroscopy and materials irradiation as the landscape will be strongly impacted by new sources coming online and perhaps other sources being reduced or discontinued in the next decade 2020-2030. This is a very specific aspect of the landscape and ESFRI decided to set up a specific expert group with the mandate to analyse this area as well as to suggest possible strategies for the field in the longer run, also taking into account the synergies with complementary X-ray sources. The Neutron landscape working group will seek advice from all the key players in the field at European and international level. ESFRI's aim is for the Landscape Analysis to be as complete and balanced as possible, so that it can serve as a useful reference.

The first phase of the landscape analysis will be a data-gathering exercise

on the availability of neutron scattering facilities. The working group is chaired by Colin Carlile and co-chaired by Caterina Petrillo, and they will be in touch to follow up with more details of how you can provide input to their work.

Thanks very much for your help and support!

Best regards

John Womersley
5th April 2014

Appendix IV
The Heads of European Neutron Labs

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Photo credits: C. Carlile - Science Village Scandinavia; C. Petrillo - Roger Eriksson, ESS.

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