

Future access to neutron sources

A strategy for the UK

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The CCLRC Chief Executive's Office
CCLRC
Rutherford Appleton Laboratory
Chilton
Didcot
OX11 0QX

Telephone: +44 (0)1235 445000
Facsimile: +44 (0)1235 445147
E-mail: enquiries@cclrc.ac.uk

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Appendices – issued separately

The Consultation Process
The Science Case
The Technology 'Roadmap'
Complementarity of Neutrons and Other Probes of Matter
The UK Neutron Community

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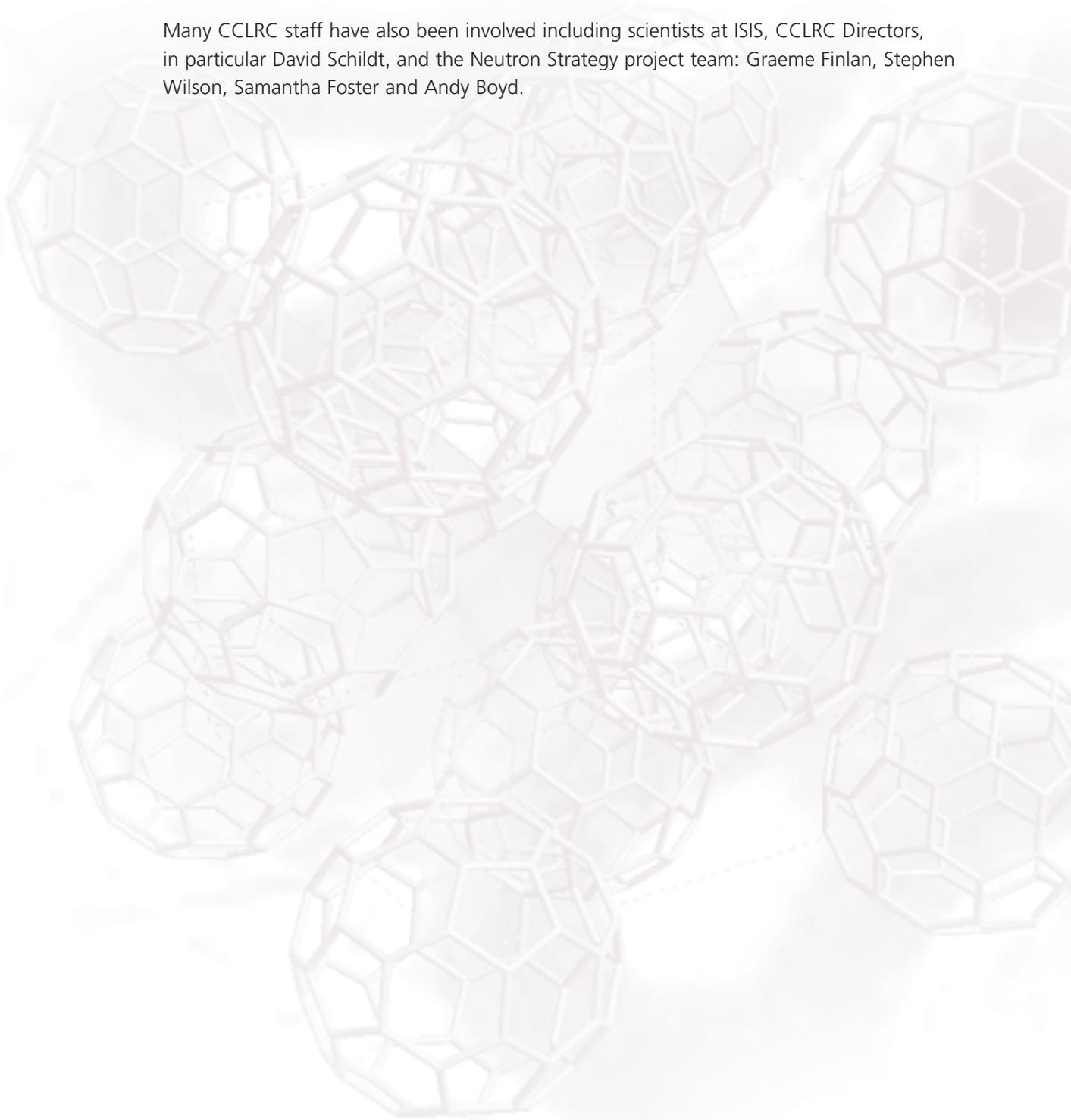
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Acknowledgments

This report has been compiled after considerable input from many sources. These include the UK neutron community, international scientists, members of the Technology Panel, the Science Case Editorial Board, the Complementary technique experts, the CCLRC International Scientific Advisory Committee and the CCLRC Council.

There have been numerous discussions with European colleagues who represented member state views including Alan Larsson (ESS-S) from Sweden and Peter Tindemanns (ESS-I).

Many CCLRC staff have also been involved including scientists at ISIS, CCLRC Directors, in particular David Schildt, and the Neutron Strategy project team: Graeme Finlan, Stephen Wilson, Samantha Foster and Andy Boyd.



Executive Summary

Extensive consultation with the community, stakeholders and international experts was undertaken during 2005 and these are the key conclusions:

- **UK scientists will continue to require access to the best possible neutron facilities for the foreseeable future;**
- **there should be enhanced investment in ILL and ISIS, jointly with international partners, that will sustain the international competitiveness of these world-leading facilities for the next ten to fifteen years;**
- **the UK research community will require access to a next generation facility that is competitive with other similar projects underway in the USA and Japan, within fifteen years;**
- **the UK is a highly credible country that could host a European next generation neutron source;**
- **the UK is well-placed and should take the initiative in organising discussions on a European plan for future spallation neutron facilities above 1 megawatt power levels;**
- **the UK has the potential to build a megawatt-class spallation neutron source through the upgrade of ISIS, but should defer further planning for this option until the outcome of the wider discussions on European plans is known and**
- **the UK should, with immediate effect, join international projects addressing key technology developments associated with the next generation of neutron sources.**

The basis for reaching these conclusions are given in the following report.

1 Background

1. Neutrons play a definitive role in our understanding of the material world around us. They can show where atoms are and what atoms do. They allow scientists to look inside the structure of matter, from the vibrations of individual hydrogen atoms to the folding of proteins, from the high temperature and pressure needed to probe the properties of the Earth's interior to the low temperature and high magnetic field needed to unlock the secrets of superconductivity.
2. Society requires more and more complex and sophisticated materials that are lighter, stronger and smarter and that can help provide solutions to major sociological and technological problems of the 21st Century, including energy, healthcare and the environment.
3. This demand for increasingly complex materials with specialised properties and functions depends on a variety of techniques to unravel and optimise their properties. Neutron scattering has and will continue to play a vital role in the portfolio of analysis techniques delivering inputs into areas as varied as: energy, nano-technology, materials processing, drug design, biotechnology, 'green' technology and information technology. A key driver for future development is the need to observe processes and reactions in real time and link these observations with increasingly sophisticated computer simulations.
4. The UK currently has access to the world's most powerful reactor- and accelerator-based neutron sources – the Institut Laue Langevin (ILL) in Grenoble and ISIS, the spallation neutron source at the CCLRC Rutherford Appleton Laboratory. Throughout their existence both facilities have consistently delivered world-leading scientific outputs. Together, they provide a baseline for facilities that ensures the UK research community is able to pursue world class experiments using neutrons for the next decade at least. With France and Germany, the UK has agreed to a ten-year extension to the intergovernmental convention for ILL (until the end of 2013) and supports the ILL 'Millennium Programme' of capital investment in enhanced experimental instrumentation and support facilities to maintain the ILL at its world-leading status. The confidence in ISIS for the immediate future has been demonstrated by the recent funding of a Second Target Station (TS-2), which will allow unique instrumentation for a new range of structural and dynamical studies of matter – especially related to engineering and biological systems.

The UK currently has access to the world's most powerful reactor- and accelerator-based neutron sources

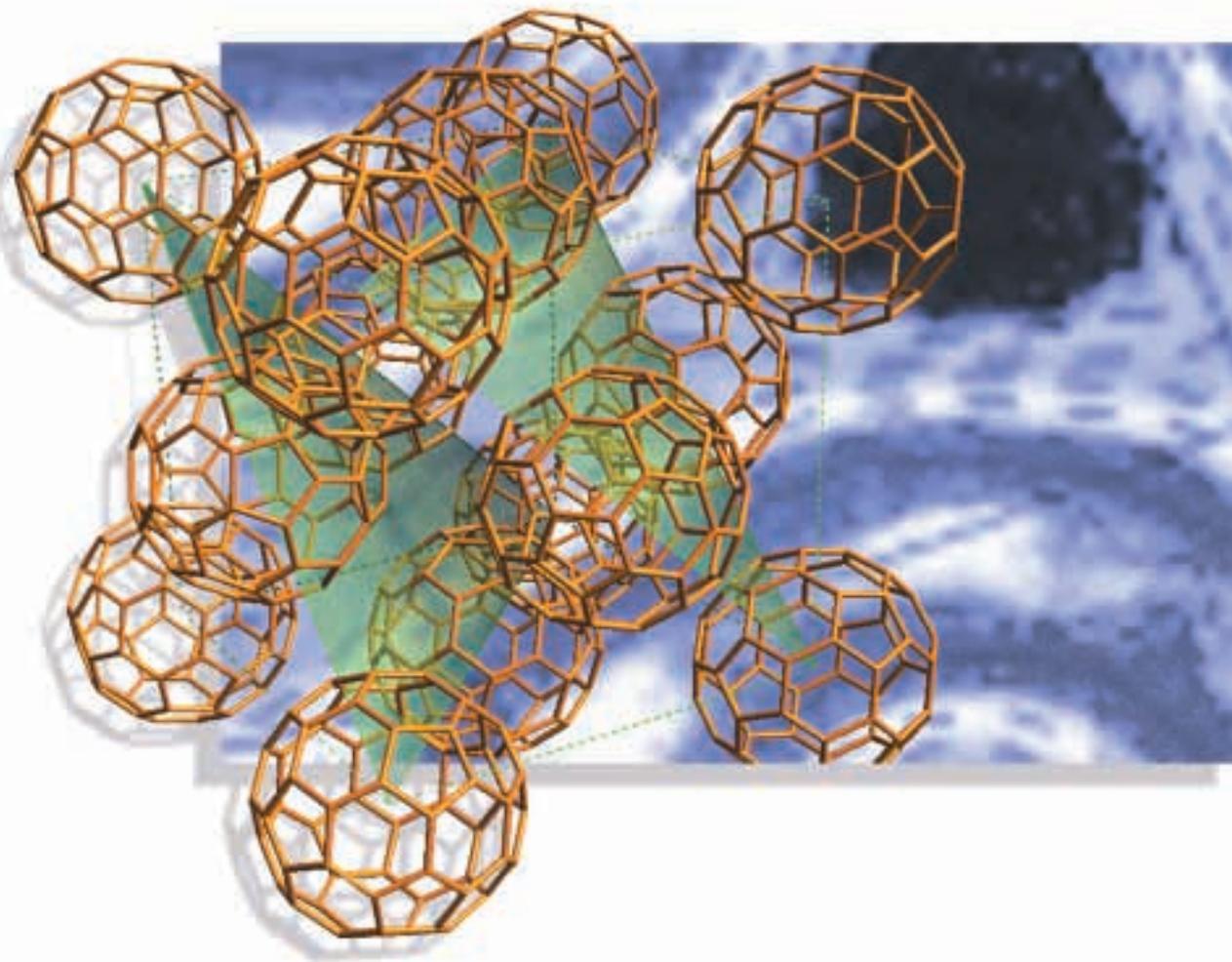
5. This review has examined four principal themes:
 - the scientific requirements for access to improved and/or next generation neutron sources;
 - the technology options for the future production of neutrons;
 - the potential for partnership and collaboration; and
 - the timeline for decision making.

6. Throughout the exercise the CCLRC has sought to be open and transparent in the conduct of the review. Details of how the review process was conducted and the names of advisors to the review are set out in the Consultation Process appendix.

“The consultation was a model of how a consultation should be carried out in terms of its transparency”

Consultation Steering Group’s letter of approval

7. The conclusions and recommendations presented here in the report are those of the Council of the CCLRC and were confirmed at their meeting in December 2005.



The low-temperature crystal structure of C₆₀ superimposed on a section of a map showing the distribution of molecular orientations at room temperature, revealed by neutron powder diffraction.

2 Conclusions

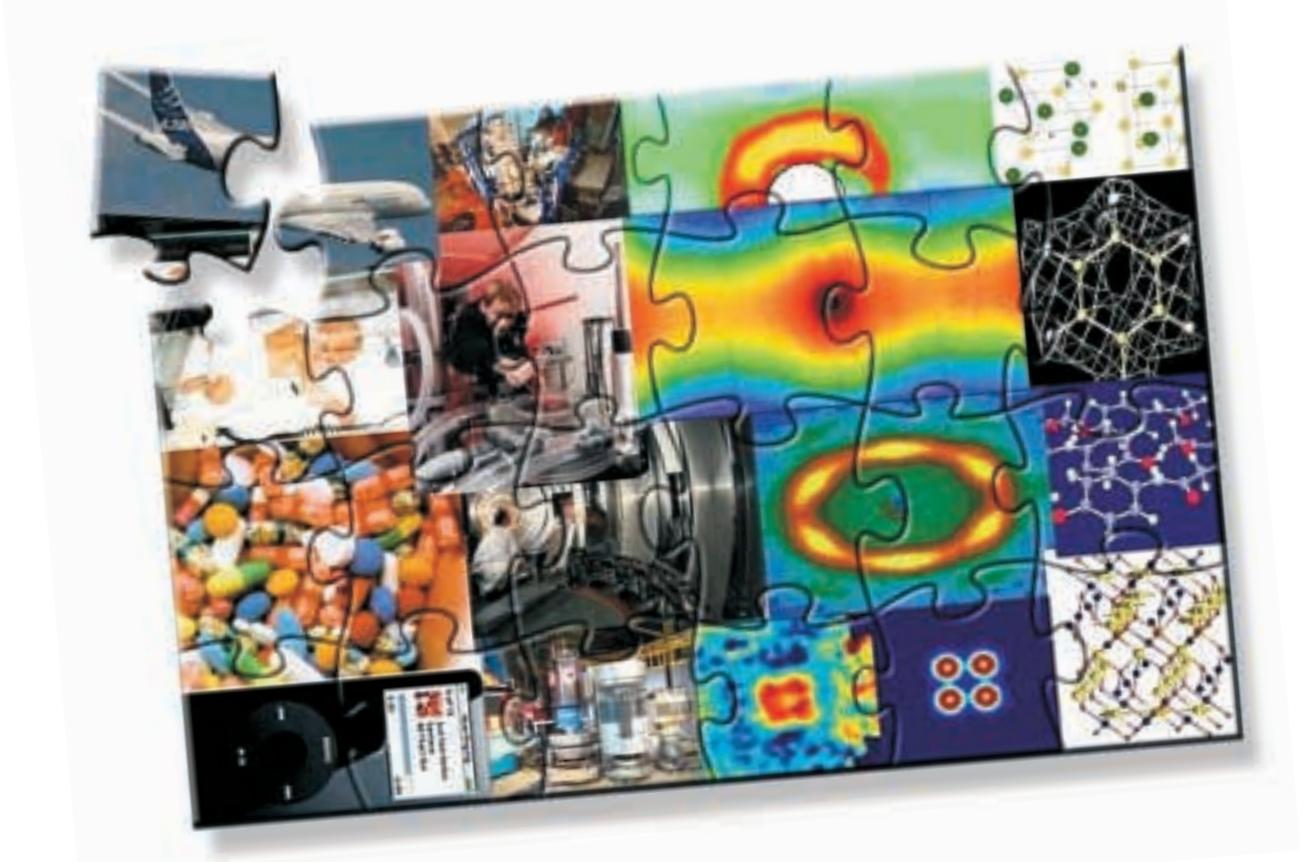
2.1 Science Case

Key conclusion:

- (i) **The UK science case requires access to the best possible neutron scattering facilities.**

8. The Technology Panel concluded that *“the UK science case requires access to the best possible neutron scattering facilities”* to remain competitive with the best in the world. The Technology Panel said: *“UK scientists occupy a major position in the exploitation of both facilities, with commensurate benefit to UK science and technology”*. The CCLRC’s International Scientific Advisory Council (ISAC) endorsed the views of the Technology Panel and described the UK science case as *“excellent”*.
9. The broad range of applications for neutrons makes them an essential tool in the discovery, understanding and applications of science in areas which are vital to the UK science and technology base. The UK has established a position of international leadership in the development of neutron-based techniques and, through facilities at ISIS and ILL, provides a unique platform to enable major contributions in areas crucial to society, such as in energy, health, transport and bioscience.

The UK has established a position of international leadership in the development of neutron-based techniques



10. While it is important to maximise the impact of the existing capabilities, it is essential to look forward to new opportunities and challenges. Chiefly, a next generation machine will allow increasingly complex systems to be analysed in real environments in real time. It is clear that increased power of neutron sources, together with ongoing advances in instrumentation, will continue to broaden the range of problems in science that can be tackled, thereby increasing the number of opportunities for breakthroughs that can be made. For example, higher power sources will enable experiments of higher resolution in both space and time, smaller sample sizes, and faster collection of data. Biological samples are often available only in small quantities, and stable for only a limited time, and samples such as crack tips are inherently small. Many spectroscopic techniques measure the small fraction of neutrons which undergo a change in energy and the accuracy of measurement improves with higher power. The study of liquid-liquid interfaces requires neutrons to pass through a liquid layer at a shallow angle – higher intensity sources enhance neutron reflection. Extreme sample environments, such as pulsed magnetic fields, higher pressures, ultra-low temperatures and very high temperatures are also facilitated by increased source capability.

A next generation machine will allow increasingly complex systems to be analysed in real environments in real time

11. Higher specification sources can operate either in a short pulse mode (SPSS), similar to the existing ISIS or with longer pulse durations (LPSS) where the technical requirements associated with increasing the power are less severe but would require instrument development. However, while there is no single source which is best for all types of studies or disciplines it is important that UK scientists have access to, and can influence the development of, a hierarchy of complementary sources with a range of powers and pulse durations.
12. The future development of neutron sources will require international coordination and cooperation and they will be developed either in a single location or in several. Given the international lead which has been built up over the past 20 years, it is appropriate that the UK should exploit this expertise and be able to host new developments while maintaining and enhancing its existing experimental base.

2.2 Technology Options

13. The conclusions on the technology options principally address three aspects:
- better utilisation of existing facilities at the Institut Laue Langevin and the ISIS spallation neutron source;
 - the potential for further upgrade of the existing sources; and
 - the development of the next generation of neutron sources.

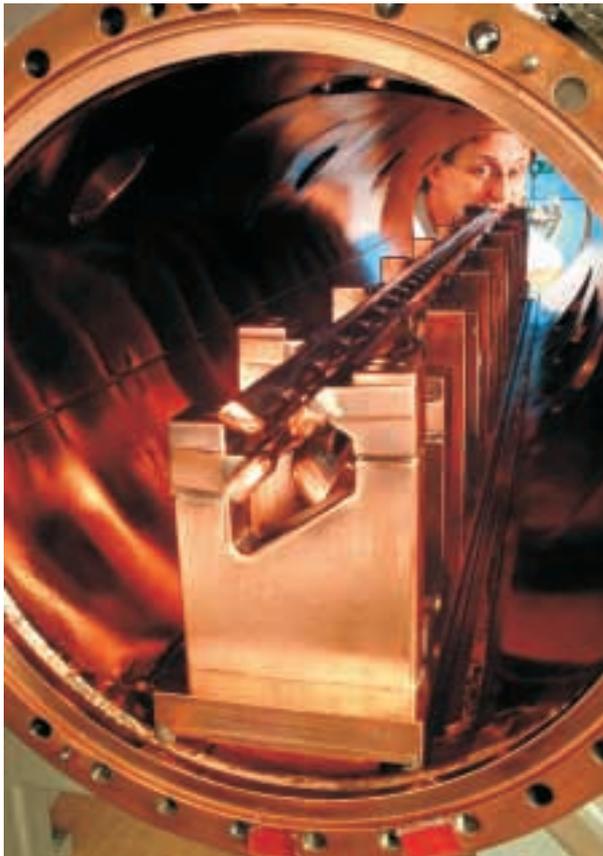
2.2.1 Better utilisation of existing facilities at ILL and ISIS

Key conclusions:

- (ii) Both ILL and ISIS will remain internationally competitive well into the next decade – provided investment in instrumentation and experimental infrastructure is sustained.
- (iii) From a UK perspective, planning the future for ILL and ISIS will require coordination within Europe and the UK should plan for the necessary agreements to be reached with other European partners within the next three years.

14. The Technology Panel said that: *“the key foundations for the success”* at ISIS and ILL *“have been similar:*

A component of a linear accelerator (linac)



- *dedication to innovative instrumentation, with strong efforts in detector development... extensive neutron guide systems;*
- *development of a broadly-based user community, primarily within the UK but also internationally;*
- *continued investment in the development and improvement of instrumentation... and facilities; and*
- *...development of specialised sources... with two cold sources and one hot source (at ILL)... and through target moderator design, culminating in ISIS TS-2”*

15. The Technology Panel said: *“Although both facilities (ILL and ISIS) have been very successful, neither is operating at an optimal level, defined as the point where increased output is no longer at least linearly related to added cost (a more economically correct measure would include return on fixed investment)”*. In examining future trends in neutron-based research the Technology Panel said: *“ISIS and ILL, with upgraded facilities and instrumentation including full development of ISIS TS-2 will meet these needs well into the next decade. Competition from the [USA spallation neutron source] SNS (and [the Japanese spallation neutron source] JSNS, somewhat better suited) in the long neutron wavelength region is at least a decade off”*.
16. Sustaining the competitiveness of the ILL and ISIS facilities for as long as possible will require improved coordination and commitment within the UK and elsewhere in Europe. The planning should address the next 10 to 15 years for both facilities. As set out later in this report, within three years the CCLRC would expect that agreement could be reached within Europe on a ‘policy and plan’ for future neutron scattering facilities. Further, within three years it is anticipated that both the new USA spallation neutron source (SNS) and the new Japanese spallation neutron source (JSNS) will have become operational, having successfully addressed the outstanding technical challenges. At that point they will begin to make scientific gains on the current world-lead held by the ILL and ISIS.
17. The CCLRC will continue discussions with the other Research Councils, who are the primary sponsors of UK researchers using the ILL and ISIS facilities. The ‘strategic partnership agreements’ with the relevant other Research Councils provide a framework for jointly addressing medium to longer term science strategies – and the impact these have on the requirements for meeting the capacity and capability needs of the UK research community at the neutron scattering facilities.

The Institut Laue Langevin

Key conclusions:

- (iv) **A first priority for the UK should be to continue to develop the quality of the existing suite of 25 public instruments at the ILL. Any plan to increase the number of public instruments would need to take account of an assessment of all ILL operation and investment costs.**
- (v) **The CCLRC should work to agree with the other international partners a future for the ILL that will exploit the unique set of capabilities that it can deliver during the next 10 to 15 years.**

18. The ILL has proved consistently successful in delivering internationally leading neutron scattering facilities for almost 30 years. The UK partnership in the ILL has reaped considerable benefits for UK science and represents an outstanding return on the intellectual and financial investment. Demand for experimental time at the ILL from the UK research community (and internationally) remains high and of high quality.

19. The CCLRC notes the Technology Panel's recommendations that the current facilities at the ILL should be 'fully' supported and accepts the qualification of ISAC that they should be 'appropriately' supported. There does need to be tensioning, within the CCLRC forward planning, of the opportunity costs associated with support of all facilities. The CCLRC believes that the position adopted by the UK in the past six years, in respect of enhanced support for investment at the ILL in instruments and infrastructure, indicates the

The UK partnership in the ILL has reaped considerable benefits for UK science and represents an outstanding return on the intellectual and financial investment.

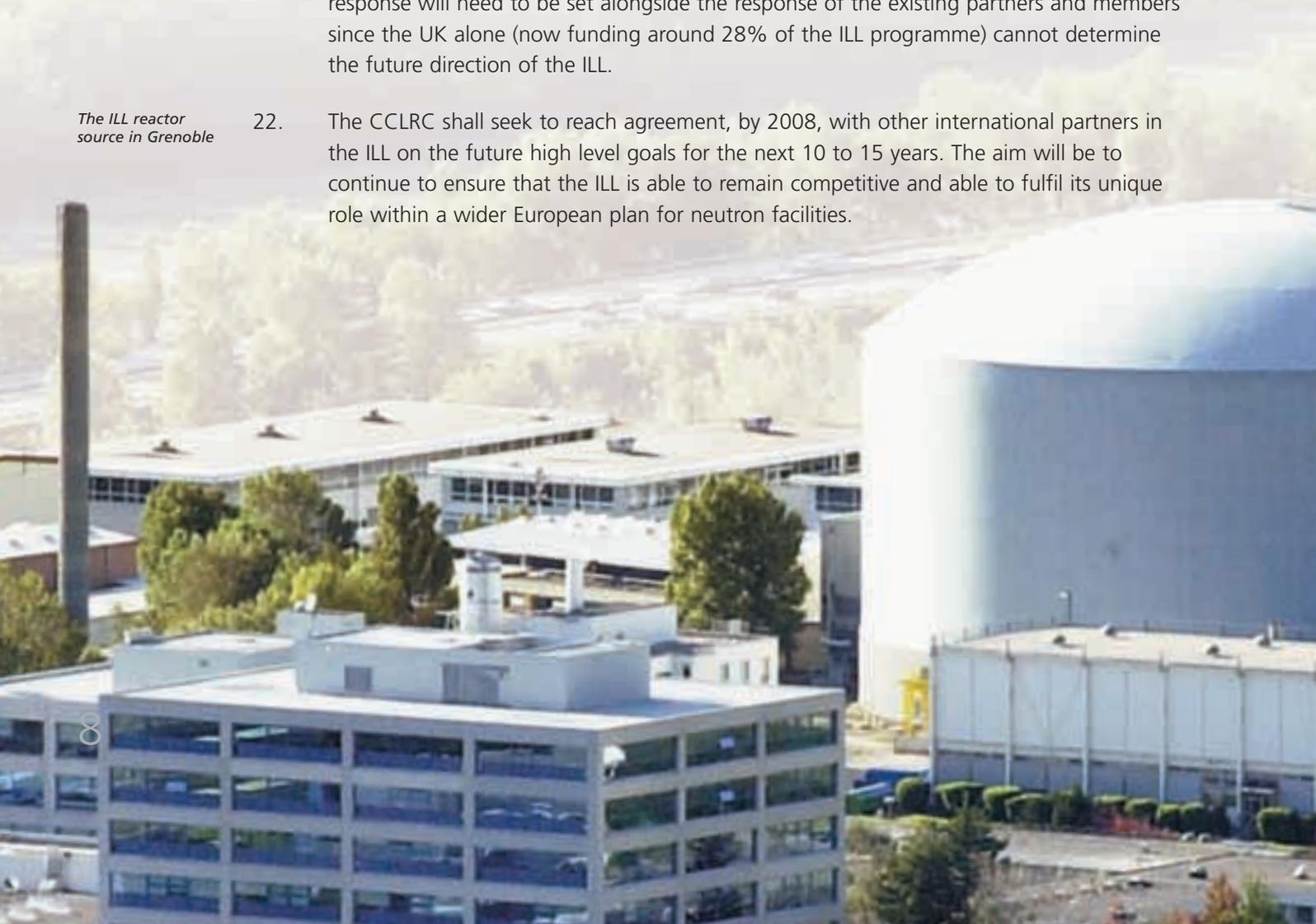
high priority the UK attaches to the ILL. The UK plans have been well received and are now matched by additional investment from France and Germany.

20. However, the extent to which the number of experimental facilities at ILL should be increased beyond current levels – as further recommended by the Technology Panel – is a matter for European discussion. In recent years the UK has placed greater emphasis on the need to maintain the number of public instruments at the ILL at 25 and to focus resources on upgrading the quality of the instruments to match scientific developments rather than on increasing their number. Investment in additional instrumentation needs also to be tensioned against other investment requirements in, for example, the reactor.

21. The current UK contribution to ILL is some £12M a year. The Technology Panel estimated the *additional* UK requirement for investment in ILL (including the cost to the UK of the number of public instruments being increased from 25 to 30) to be of the order of £4M a year. This was based on figures for a budget provided by the ILL management. Any UK response will need to be set alongside the response of the existing partners and members since the UK alone (now funding around 28% of the ILL programme) cannot determine the future direction of the ILL.

The ILL reactor source in Grenoble

22. The CCLRC shall seek to reach agreement, by 2008, with other international partners in the ILL on the future high level goals for the next 10 to 15 years. The aim will be to continue to ensure that the ILL is able to remain competitive and able to fulfil its unique role within a wider European plan for neutron facilities.



The ISIS Spallation Neutron Source

Key conclusions:

- (vi) **ISIS operations should be increased from 140 days a year to 220 days a year within the next three years.**
- (vii) **With the onset of the second target station, increased levels of international participation in the design, build and operation of instruments at ISIS should be very actively sought.**

23. As a direct result of leadership shown by the UK in the 1970s, investment in the ISIS spallation source has produced a facility which has held a world-leading position for 20 years. The technical and scientific achievements at ISIS have provided both an incentive and a foundation for the new construction projects now underway in the USA and Japan to build megawatt-class spallation sources.

24. With the onset of a second target station at ISIS we accept the view of the Technology Panel that: *“ISIS is certainly poised to provide world quality research capabilities over the next two decades. While the new US and Japanese sources will have more beam power, they will have steep learning curves, and will require substantial time to be fully instrumented. Neither of the two sources presently has funding for a second target station optimised for long wavelengths, so that ISIS will provide the UK with a competitive advantage in this area... appropriate investment now will ensure that the UK remains at the forefront for the next decade and beyond”.*

The technical and scientific achievements at ISIS have provided both an incentive and a foundation for the new construction projects now underway in the USA and Japan to build megawatt-class spallation sources.



Aerial photo of ISIS, showing the construction of the second target station

25. There is an immediate and timely opportunity to address the international future of ISIS – within a wider plan for neutron scattering facilities in Europe. Realising the continuing competitive advantage of ISIS will require increased investment in instruments. An enhanced level of international participation could, if successfully achieved, allow the instrumentation of ISIS to be completed in a timely and effective manner. This would have direct benefit to the UK research community and to the international users of ISIS.
26. Demand for access to ISIS from scientists from across the world remains strong. Further opening up ISIS to international access now could help strengthen international investment in the future programme beyond the present 10% level. It could also better position the UK when consideration is given to the question of the future host country for a next generation facility.
27. Widening international access is strongly recommended by ISAC. While this action would further strengthen the international climate at ISIS it will not, by itself, address the resource plan requirements. Widening international access needs also to be accompanied by widening international participation in the design, build and operation of instruments on ISIS.
28. One way in which this could be developed is through an international call for ‘expressions of interest’ in the design, build and operation of instruments at ISIS (for both target stations) to be issued within the next one to two years. The intention should be to design a variety of means for wider international participation and investment that will create a ‘win-win’ position for all parties – sustain the international competitiveness of ISIS, offer new opportunities for international scientists at ISIS and enhance the capacity and capability of instrumentation at ISIS for the UK research community. The aim should be to build an enhanced set of international partnerships and collaborations to sustain the competitive advantage of ISIS over the next 10 to 15 years.
29. The UK should set out clearly the operational levels it aspires to achieve for ISIS. This should be higher than the present 140 days operation a year and, within the next three years, should get as close to an optimal 220 days as resources permit. Increasing operational levels is important not only in terms of realising the return on the UK investments already made but also for meeting the high quality demand from the UK research community. It is important, too, to demonstrate that the widening of international access will not be at the expense of high quality access by the UK research community.
30. Current funding for ISIS (all sources) is of the order of £27M a year (UK contribution £24M). The Technology Panel estimate the total additional requirement for the ISIS budget to be £23M a year, based on figures provided by the ISIS management. This would allow the facility to be operated for 220 days a year and provide for a timely refreshment of instrumentation to sustain competitiveness.

2.2.2 The upgrade potential of the existing facilities

Key conclusion:

(viii) There is potential for upgrading the source power of ISIS to 1MW and possibly beyond but the UK should not proceed further with this at present. The position should be reviewed in three years, in the light of progress with the European discussions on a next generation neutron source.

31. The Technology Panel reported that design studies on a ‘next generation reactor’ have indicated that an order of magnitude improvement over the best existing reactor sources might be achieved – but there is no reliable cost estimate and substantial research and development would be required. Other potential reactor developments (such as the pebble bed reactor), while technically feasible, are considered by the Technology Panel to have too high a regulatory risk to be recommended as an option for a research reactor.

The potential for an upgrade of ISIS to 1MW beam power and beyond (from the present planned 0.24MW)

32. The future for the development of neutron sources therefore lies with the development of spallation neutron sources – since a new reactor source is probably unrealistic. Currently, ISIS is the most powerful spallation neutron source in the world. The Technology Panel has highlighted the potential for an upgrade of ISIS to 1MW beam power and beyond (from the present planned 0.24MW). They have commented that the upgrade path “*provides an opportunity to maintain the UK at the forefront of neutron research over the next several decades*”.

provides an opportunity to maintain the UK at the forefront of neutron research over the next several decades

33. The Technology Panel recommended that: “*the detailed conceptual design for an upgrade to ISIS of 1MW beam power should be initiated immediately*”. ISAC supported this recommendation, which it regarded as consistent with the recommendation for better utilisation of ISIS assets. For a 1MW upgrade a detailed costing exercise is required. For source powers beyond 1MW technical studies would also be required. The 1MW design study – estimated to cost £750k and to take two years – was felt by the Technology Panel to be something of an ‘insurance option’ in the event that “*no large European source is foreseen, and with the agreement of the UK neutron scattering community, this upgrade could allow the UK to remain competitive for many years*”.
34. ISAC concluded that the 1MW power upgrade study need not be started immediately and that a longer timescale might be contemplated. Additionally, ISAC took the view that the study might also be usefully extended to explore the potential for development of ISIS beyond 1MW – that is to explore the potential for the UK to build an SNS-class machine through the further development of ISIS.

35. The cost of the upgrade to 1MW – estimated by the Technology Panel on advice from the ISIS team to be £350M – reaches levels that equate to the cost of a potential UK host contribution to a next generation facility. If the ISIS 1MW upgrade option were taken up by the UK on its own this would effectively constrain any UK contribution to a more ambitious European next generation facility – should it subsequently be agreed – for twenty years. This scenario could also threaten the ability of the UK to adequately instrument an upgraded ISIS facility.
36. **It is not evident therefore that the option of upgrading ISIS is worthwhile pursuing for the UK.** Rather, it would appear more appropriate that UK efforts be directed to reaching European agreement on the development of a next generation neutron facility independent of an ISIS upgrade option. However, it is important – in terms of scientific competitiveness – that the European discussions on planning for the next generation of neutron facilities are able to make timely progress. The CCLRC proposes to

CCLRC proposes to review its position on the ISIS upgrade in three years time in the light of progress being achieved with planning for a next-generation neutron source at the European level.

review its position on the ISIS upgrade in three years time in the light of progress being achieved with planning for a next-generation neutron source at the European level.

2.2.3 Towards a next generation neutron facility in Europe

37. In a 20 year forward look at neutron scattering facilities in OECD (Organisation for Economic Co-operation and Development) countries and Russia, the OECD MegaScience Forum in 1998 predicted that many of the existing national neutron sources will have closed or be reaching the limits of their projected lifespan. The European Neutron Scattering Association equates this to a 30% reduction in European neutron scattering capacity over the same period. The 1998 OECD Ministerial Conference endorsed the recommendation of the MegaScience Forum that an entirely new megawatt spallation neutron source should be constructed in each of the Asian, North American and European regions. The US and Japan have been persuaded by the scientific case underlying the opportunities afforded by a megawatt class spallation source and our own views are consistent with this.

Aerial photo of SNS site at Oak Ridge, currently under construction



Courtesy of Oak Ridge National Laboratory

38. **At Oak Ridge, Tennessee, USA, the SNS project under construction** is a single purpose facility for a full-energy linac (1GeV) plus storage ring with a flowing liquid mercury target for neutron scattering applications, operating at 60Hz pulsing frequency and 1.4MW proton power on target. The layout provides for a second target station optimised for long wavelength neutrons. The design allows for substantial accelerator power upgrades to ~ 4MW total power, with target upgrades. Current plans are that the SNS will have first neutrons in 2006 and 14 instruments by 2012. The plans for the project anticipate that full power should be reached by the end of 2009.

The recommendation of the MegaScience Forum that an entirely new megawatt spallation neutron source should be constructed in each of the Asian, North American and European regions.

39. **JSNS is the neutron facility currently under construction at Tokai-mura in Japan**, which is embedded within the multipurpose proton accelerator complex, J-PARC. A 180MeV linac feeds a 3GeV rapid cycling synchrotron, which drives the neutron source at a pulsing frequency of 25Hz with 1MW proton power on target. J-PARC also includes a 50GeV synchrotron fed from the 3GeV ring, used for particle physics and as a neutrino source. The linac has the provision to drive a sub-critical reactor assembly. Current plans are that the JSNS will have first neutrons in 2007 and will have a full range of instruments around 2012.
40. There is currently no commitment within Europe to the construction of a megawatt class next generation neutron facility. In 2001 the design parameters for a **European Spallation Source project** were concluded by a team drawn from a group of laboratories from across Europe and beyond. The design incorporates a 1.3GeV, 10MW proton accelerator feeding a long pulse target station at 16.67Hz and a short pulse target station, via a proton accumulator ring, operating at 50Hz. The design plans are for both the long and short pulse target stations to operate at a power level of 5MW. The cost of the ESS design is estimated to be £1Bn at 2002 prices.
41. There are, effectively, only two 'nucleations' of activity within Europe at present in terms of planning for a Next Generation Neutron Facility (NGNF) within Europe: (i) the Scandinavian European Spallation Source (ESS-S) plans for a long pulse spallation source at Lund in Sweden and (ii) the ESS-I project for a step-wise implementation of the European Spallation Source project – beginning with a LPSS – that is being promoted by a number of potential site hosts in Sweden (Lund), Germany (site reference) and the UK (at Burn in Yorkshire advocated by the regional development agency 'Yorkshire Forward', together with the White Rose University Consortium). It remains to be seen what other potential bids might emerge should planning for the future start within Europe at government levels.

The nature and scope of the planning required

Key conclusion:

(ix) **The UK should take the initiative in organising discussion within Europe on the policy, technical and scientific planning required for development of a European strategy for the next generation of neutron scattering facilities.**

42. The Technology Panel has made a set of recommendations on the need for access by UK researchers to a next generation neutron facility. Such a new facility would extend the scientific capability of the neutron facilities that the community has access to – creating a new high level tier of capability.
43. While there are some current declared interests in Europe in hosting a next generation neutron facility there is as yet no arrangement in place for developing a structured approach to this issue – including within the context of the emerging ‘European Research Area’ considerations of large scale research infrastructures.
44. It is the conclusion of the CCLRC that planning for future neutron scattering facilities needs to be conducted at appropriate European levels. This view is supported by ISAC. There are a complex set of issues to be addressed. These involve scientific and technical issues, policy issues, financial issues and issues concerned with timing, prioritisation and hosting. There is currently no suitable forum in existence within Europe where the full range of these issues can be discussed and through which the essential work plans might be coordinated.
45. The CCLRC considers that the initial step should be for the UK to take the initiative in organising discussion on what the scope of the necessary European planning should be,

as a prerequisite for establishing study groups with defined technical and scientific remits. The UK’s scientific and technical expertise in spallation neutron sources makes it credible that it should take such a lead.

It is the conclusion of the CCLRC that planning for the future for neutron scattering facilities needs to be conducted at appropriate European levels.

46. From discussions with ISAC and elsewhere in Europe, the CCLRC concludes that a first step would be to convene a group of nominated representatives from a small number of countries within Europe with significant interest in neutron scattering facilities. The process should be started as soon as possible in 2006. The group should be invited to draw up a **‘prospectus for action’** for wider consideration in Europe – including a timeline for decision making. The aim should be to complete the prospectus within one year and subsequently to reach agreement on a **‘policy and plan for Europe’**, with a wider set of interested countries, within the following two years.
47. The CCLRC would propose that the UK invite Germany, France, Spain, Sweden and Hungary to form an initial group to begin these discussions.

The preferred technical options

Key conclusion:

- (x) **The UK should take a lead in establishing study groups to review the options for a megawatt-class next generation neutron facility in Europe.**

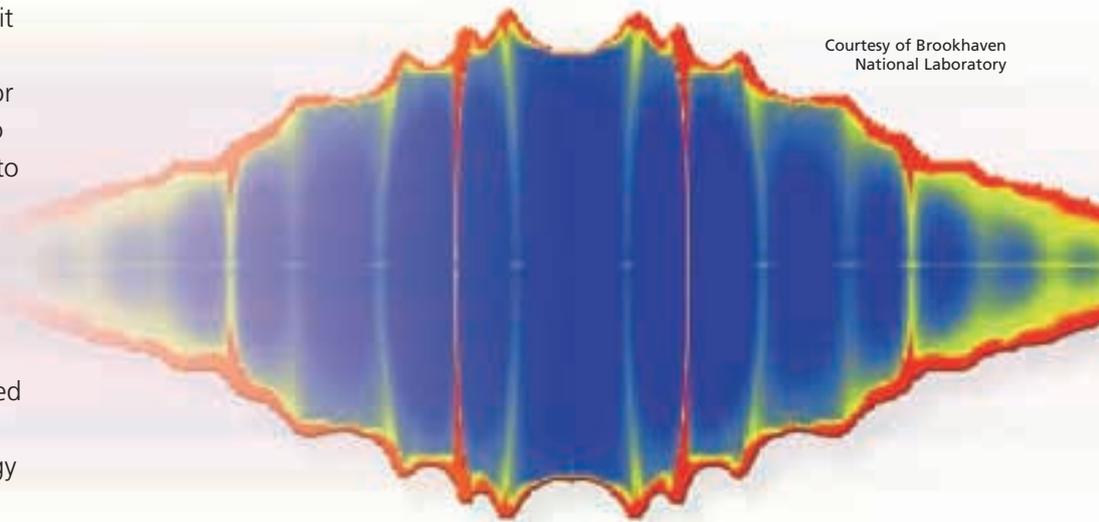
48. Of the various technology options available at this time – and having particular regard to the requirements of the UK science case – the Technology Panel considered: “... an LPSS with a beam power of 5MW and possibly higher, and a 5MW SPSS appear the most promising”.

49. The Technology Panel concluded that, in terms of technology development needs, the UK should also take a lead in establishing appropriate technology study groups. The Panel estimate that such studies would take five years, should be undertaken with European collaboration and would cost the UK £750k (to organise the study groups, excluding technical studies and associated research and development costs).

50. ISAC considered that it was not immediately obvious why the UK or Europe might want to plan from the outset to ‘leap ahead’ of the existing USA SNS and JSNS technical goals. There remain considerable uncertainties associated with being able to achieve the Technology Panel’s goals for both the LPSS and, even

more so, for the SPSS. It was the view of ISAC that the build of an SNS-class facility in Europe could also represent an effective response to the competition – and even with this option there are significant technical challenges outstanding (such as the need for substantial target technology development) that remain to be addressed. ISAC concluded, therefore, that a European technology study should examine the ‘best achievable’ power, which could include the possibility of a sub-5MW (SNS-class) source.

51. Having an SPSS on one site (possibly with two target stations) and an LPSS on another (with the possibility to upgrade the power and to add an extra target station) would seem to be a scenario that would enable Europe to maintain the necessary capacity, with significantly increased capability, the broadest range of instrumentation and the better prospects for upgrade. A step-wise approach to building this scenario could assist Europe in more readily defining a starting point for planning the next generation of neutron sources.



Courtesy of Brookhaven National Laboratory

Cavitation simulation in the Mercury target

52. The cost of a next generation neutron facility – currently estimated at £1Bn – would be difficult for the UK to contemplate funding on its own. The construction costs alone would equate to ten years exclusive commitment of the current Office of Science and Technology (OST) Large Facility Capital Fund. The annual operating costs – estimated at up to £100M a year would represent almost three times the present level of spend by the CCLRC on neutron facility operations. This would almost certainly necessitate UK withdrawal from the ILL and the closure of ISIS. The CCLRC does not advocate this approach.
53. The CCLRC concludes that the UK should take a lead in Europe in establishing technical study groups to review the options for more powerful next generation neutron facilities – that take account of the progress achieved at the facilities under construction in the USA and Japan.

2.2.4 The potential of the UK as a host for a next generation neutron facility

54. The CCLRC concludes that the UK would be a highly credible host country for a European next generation neutron source. This is for a number of reasons, including:
 - the legacy of technical expertise in the UK in the design, build and operation of neutron scattering facilities that have occupied world-leading technical capability positions for more than 20 years;
 - the leadership shown by the UK in underpinning technology development;
 - the breadth, depth and intensity of the high quality science and engineering research undertaken by the UK research community using neutron scattering facilities;
 - the preparedness of the UK to invest significant resources from the Science Budget over the past 30 years to sustain the competitiveness of the world-leading facilities at ILL and ISIS;
 - the ability of the UK to successfully sustain international partnerships in the development and exploitation of neutron scattering facilities.

The UK would be a highly credible host country for a European next generation neutron source

2.2.5 The timeline for decision making

55. The Technology Panel concluded that *“in view of the length of time between the conception and commissioning of major neutron facilities – 12 years in the case of the SNS and likely to increase as sources become larger and more powerful – it is necessary to start planning now to ensure that the next generation facilities will be available when needed”*. The CCLRC agrees with the Technology Panel that *“action must be taken as soon as possible to ensure continuity in the access of UK scientists and technologists to world-class facilities”*.
56. Present assumptions are that it will take three years to agree a plan for neutron scattering facilities within Europe and a further two years to build a partnership structure and agree the host country or countries – depending on the options agreed.

57. This period could be coterminous with the five year period of technical study recommended by the Technology Panel for an SPSS – after which construction could commence. According to the Technology Panel it would be feasible, from a technology perspective, to plan to commence construction of an LPSS on a shorter timescale – though the CCLRC would expect that it will take some equivalent time to resolve the planning/hosting issues within Europe. Construction of a next generation neutron source is estimated to take seven years.

“...it is necessary to start planning now to ensure that the next generation facilities will be available when needed”

58. On this timetable first neutrons at a European next generation source would be available in 2018. A further five to ten years would be required to build up the source power and an initial suite of instruments to, say, twenty overall on each of an LPSS and the SPSS.
59. The proposed timeline for the construction of a next generation neutron source by 2018 takes account of the CCLRC’s assessment of the likely response time of other potential European partners. The timeline is also predicated on current estimates for the period during which the competitive advantage of both the ILL and, for the UK, ISIS could be sustained against developments in the USA and Japan.
60. The attached diagram illustrates the proposed ‘timeline for decision making’ drawing on the conclusions reached above. It also positions the current plans for the SNS.

On this timetable first neutrons at a European next generation source would be available in 2018

2.3 Other Important Issues

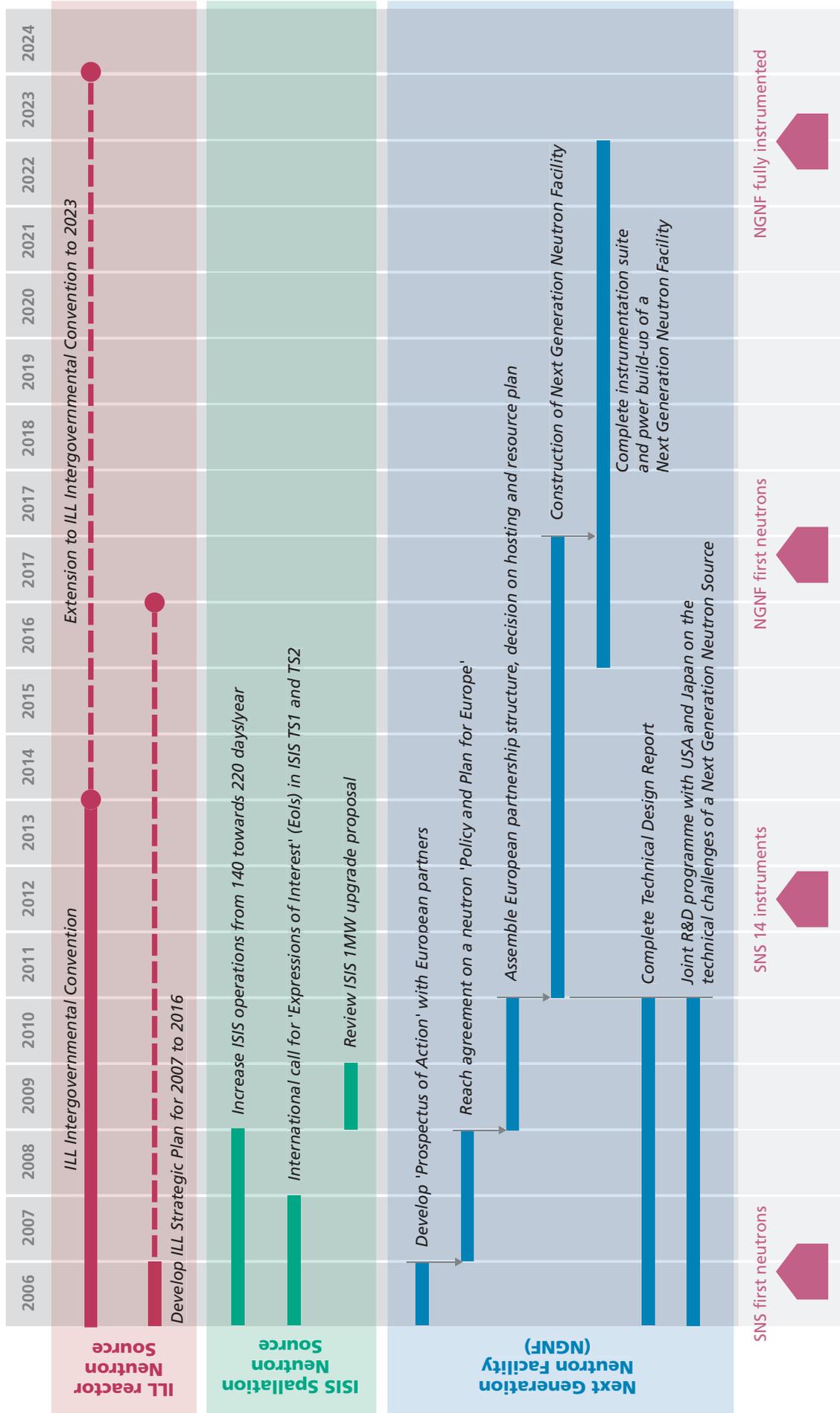
Technology Collaborations

*Proof of Principle
Proton Fixed Field
Alternating Gradient
(FFAG) synchrotron*

61. The Technology Panel has identified a series of technology needs to underpin the development of a next generation neutron source including: high-power short pulsed spallation targets; high power accelerator developments; fixed-field alternating gradient (FFAG) synchrotrons; moderator development; and, detector technology development. It has strongly recommended that the UK should plan to join existing international technology collaborations in these areas where they exist.



© KEK



62. In addition, the Technology Panel has recommended that the UK should track several other “areas of development which have their own bases of support, but are relevant to high power neutron sources and their optimisation” including: nuclear waste transmutation; particle physics applications; ultracold neutron sources for fundamental physics; and fusion technologies, notably Inertial Confinement Energy (laser fusion) development. While the latter is “still a long way from practicality, these have potential for application in a new class of research neutron sources” – though not within the timescale (up to 30 years) foreseen in the Panel’s report. The Panel recommended that the UK keep such technologies under review.
63. The CCLRC considers that there are real opportunities for achieving synergies in technology development requirements – for example those needed for a neutrino factory and a next generation neutron source. The CCLRC will discuss opportunities with other relevant Research Councils, especially the Particle Physics and Astronomy Research Council.

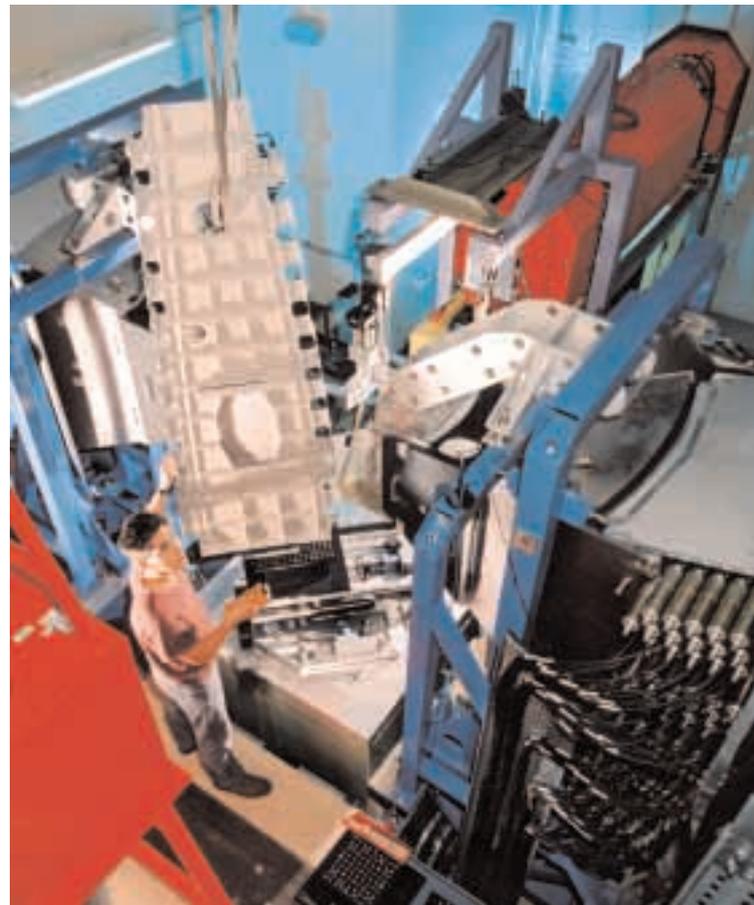
The UK should plan to join existing international technology collaborations

There are real opportunities for achieving synergies in technology development requirements

Measurement of a full-scale section of an aircraft wing on the strain scanning beam line ENGIN-X

Industrial users of neutron facilities in the UK

64. Neutron scattering is a very widely applicable analytical tool employed across the sciences – from engineering to biology, to physics, chemistry and materials science. Not surprisingly, neutron scattering science is employed within the research and development programmes of many UK industrial sectors:
- aerospace
 - automotive
 - computing
 - energy
 - mobile communications
 - personal and household care
 - paints and coatings
 - pharmaceuticals



65. The highly specialised nature of neutron scattering facilities encourages all but the largest companies to conduct their research in collaboration with an academic partner. The academic partners broker the solution of industry problems utilising the most appropriate neutron scattering techniques. This indirect use of neutron scattering science is a significant driver of the research programmes that are conducted by UK academics at ISIS and the ILL. This is an area in which the CCRLC will be developing greater insight in establishing its knowledge transfer programmes. In contrast direct, proprietary purchased, industrial research using UK beam time is limited, typically at the 1% level, although use on any specific experimental station will be higher.
66. UK companies who have used neutron scattering include; Airbus UK, AstraZeneca, BNFL R&T, BP Amoco Research, British Energy, Toshiba Research Europe, ICI, Infineum UK, Kodak, QinetiQ, Rolls Royce, Scottish Crop Research Institute, UKAEA Fusion, Unilever Research.
67. As announced earlier, the CCLRC intends to reappraise the relationships between industry and the large research facility programmes and improve the range of mechanisms for significant engagement of industry in the CCLRC large research infrastructure programmes. There are further steps we shall begin in 2006, looking at three aspects of the relationship with industry in particular:
- the prospects for collaborative early stage research and development on the technologies that will underpin the next generation of large research infrastructures – in particular accelerator based technologies and instrumentation;
 - opportunities for broadening access by industry – across all relevant sectors and size of companies – to the large research facility programmes (for neutrons, synchrotron radiation and high power lasers); and
 - the needs of industry for the technicians, scientists and engineers whose training has benefited from participation in the large research facility programmes.



Improve the range of mechanisms for significant engagement of industry in the CCLRC large research infrastructure programmes.

Studies of the socio-economic impact of large research facilities

68. Following scientific considerations, the economic benefits and return from public investment in large research facilities is a recognised consideration in the decision making process to host them. The wider socio-economic impact of large research facilities has been the subject of many reviews and wide consideration in the UK and elsewhere. While the remit for this current review does not include undertaking a socio-economic study of the impact of hosting a major international science facility, the key reports that have been undertaken since the last major UK assessment of impact conducted by the Cabinet Office, OST and Office of Public Service and Science in 1993 are detailed in the appendices. A short précis of the key findings of each of these reports is presented in the Consultation Process appendix.



Construction of the Japanese spallation neutron source

69. There is general consensus in the findings of these reports for which their key conclusions are:
- there is significant socio-economic benefit from hosting large international research facilities;
 - the rate of return is uniformly regarded as positive although its calculation is subject to assumption and quantification challenges;
 - the benefits can be categorised as:
 - **Direct** – through the design, construction and operation of the facility. Such impact, relatively easily quantified, is short to medium term in nature – at least for the 20-30 year life of a facility – and is primarily localised.
 - **Indirect** – through the creation of campuses surrounding a facility – by definition localised – clustering high technology users/exploiters of a facility's capabilities, through spin-close, spin-in and spin-out enterprises. The impact of the campus is harder to quantify and extends beyond the actual lifetime of a facility;
 - **Global** – the diffuse and very long term impact that arises from the establishment of a global hub in the knowledge economy. The impact of such a focus extends from the influence of national attitudes to and exploitation of science and innovation, and the establishment of global contact networks – to national prestige, credibility and influence.
70. It would be timely to perform a further detailed review of the benefits of hosting large international facilities following that undertaken by The Treasury in 1993. There are a number of interested bodies who should be invited to come together to develop the study and oversee its implementation – including The Treasury, the Department of Trade and Industry, the Office of Science and Technology (OST), relevant Research Councils (including CCLRC, PPARC, NERC, and ESRC) and appropriate regional authorities and others.

It would be timely to perform a further detailed review of the benefits of hosting large international facilities following that undertaken by The Treasury in 1993

3 Recommendations for Action

Recommendation 1

The UK must proactively ensure access to internationally competitive neutron scattering facilities for the foreseeable future.

Recommendation 2

Planning for the ILL should focus on sustaining and enhancing the unique scientific capabilities and ensuring that the neutron scattering instruments remain internationally competitive over the vital next 10 to 15 year period.

Recommendation 3

The operational regime for the ISIS Spallation Source should be increased beyond the present level of 140 days a year. This should be accompanied by a significant increase in international engagement.

Recommendation 4

The UK should take the initiative, during 2006, in coordinating European efforts to deliver, within three years, proposals for a scientific, technical, financial and policy road map for neutron scattering facilities in Europe.

Recommendation 5

The UK should plan to provide access for the UK research community to a megawatt-class next generation neutron facility within the next 15 years and should look to achieve this through European collaboration in the design, build and operation of such a facility.

Recommendation 6

Plans for the study of the upgrade of ISIS to 1MW beam power and beyond be deferred until the outcome of discussions with other European countries on a European-wide strategy for future neutron scattering facilities can be assessed within the next three years.

Recommendation 7

The UK should act immediately to join international projects addressing key technology developments associated with the next generation of neutron sources (e.g. high power targets, high power accelerators, new proton accelerators and detector developments). The UK should also remain alert to possible transformational technologies applicable to neutron scattering, such as Inertial Confinement Energy (laser fusion).

Recommendation 8

A study of the socio-economic costs and benefits arising from the hosting of an international research facility in the UK should be initiated in 2006, bringing together the interests of The Treasury, the Department of Trade and Industry, the relevant Research Councils and the appropriate regional authorities and others.

Glossary of Terms

- **Accelerator based neutron sources**
Accelerator based neutron sources generate neutrons by bombarding a metal target with high energy charged particles (protons) in a process called spallation.
- **CSG** - Consultation Steering Group
Established by the CCLRC to advise on the consultation process, the CSG was led by Professor Sir John Enderby, President of the Institute of Physics, with member nominations drawn from the learned societies.
- **ENSA** - European Neutron Scattering Association, http://neutron.neutron-eu.net/n_ensa/
ENSA is a common interest body representing a significant proportion of the European academic neutron scattering community.
- **ESRC** - Economics and Social Research Council, <http://www.esrc.ac.uk>
The UK Research Council with responsibility for funding research in the social sciences.
- **ESS** - European Spallation Source
A proposed design of a next generation spallation neutron source for Europe consisting of both an SPSS and LPSS generated by the neutron community. ESS-I an organisation recently established to promote the ESS project.
- **ERA** - European Research Area
A vision for pan European organisation and co-ordination of scientific research allowing the EU to compete effectively in the global knowledge economy.
- **FFAG** - Fixed-Field Alternating Gradient synchrotron
An alternative technology for accelerating charged particles, including protons. It could provide a cheaper and more compact alternative to existing accelerator and synchrotron technologies.
- **ILL** - Institut Laue Langevin
The ILL is the world's most powerful reactor based neutron scattering source managed by France, Germany and the UK, situated in Grenoble, France.
- **ILL 'Millennium Programme'**
The 'Millennium Programme' is an accelerated but sustainable programme of instrument renewal aimed at maintaining the ILL's status as a leading generator of neutron-based science research.
- **ISAC** - International Science Advisory Committee
Comprising leading international academics with expertise covering the diverse sciences relevant to the CCLRC's facilities ISAC provides the CCLRC Council with independent scientific advice.
- **ISIS**
ISIS is the world's most powerful neutron spallation source situated at the CCLRC Rutherford Appleton Laboratory, Oxfordshire. The ISIS proton accelerator operates at 0.16MW.
- **ISIS Second Target Station (TS-2)**
Is a new neutron spallation source currently under construction at ISIS, fed by the same proton accelerator as the existing first target station. TS-2 is optimised to yield lower energy, longer wavelength neutrons that are particularly applicable to soft matter, bioscience and advanced materials experimentation.

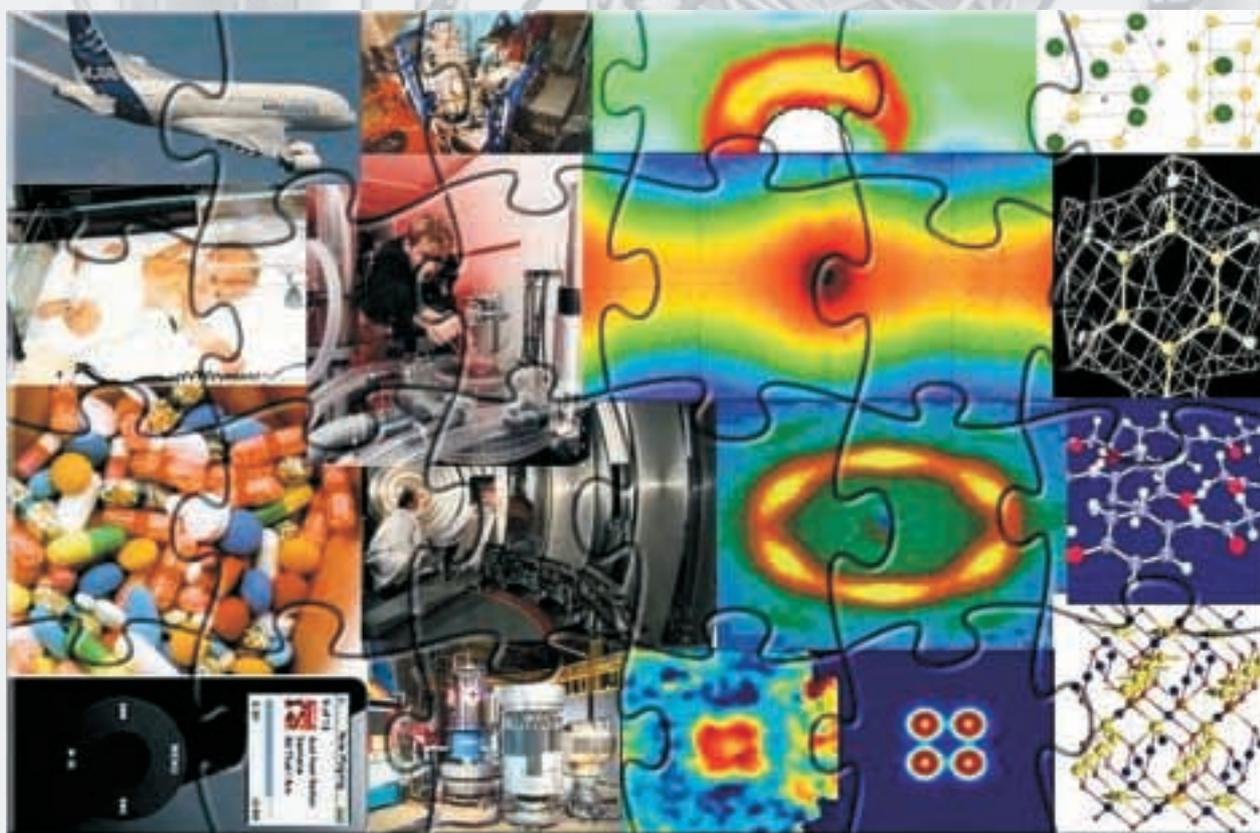
- **JSNS** - Japanese Spallation Neutron Source
Currently under construction and due for completion in 2007, JSNS is a next generation spallation neutron source, part of the Japanese Proton Accelerator Research Complex (JPARC). The JSNS plans to operate at 1MW.
- **Laser Fusion Source**
A potential future and alternative mechanism to generate an intense source of neutrons. The process is based on the confinement of a fusion fuel, deuterium, within a pellet upon which a very short laser pulse is fired igniting the fuel and generating neutrons through fusion.
- **Linac** - Linear accelerator
A technology that accelerates charged particles to very high speeds, energies, in a straight line using radio waves.
- **LPSS** - Long Pulse Spallation Source
A potential future technology, an LPSS uses longer duration proton pulses producing greater neutron yields but at the expense of resolution.
- **Moderator**
A body of material that surrounds the source of neutrons, spallation or fission. Containing light atoms, for example heavy water or methane, the moderator slows neutrons by repeated collisions to deliver the required energy distribution for neutron scattering experimentation.
- **NERC** - Natural Environment Research Council, <http://www.nerc.ac.uk>
The UK Research Council with responsibility for funding research in the environmental sciences.
- **Neutrino source**
Neutrinos are exotic particles generated in extremely large numbers, for example by the sun, that interact very weakly with matter. Interest in neutrino science stems from the belief that they may answer fundamental questions about the origin and mass of the universe, the 'dark' matter. One route to generating an intense neutrino beam, as a basis for neutrino investigation, is through proton collision with a target.
- **Nuclear waste transmutation**
A process by which the radioactive components of waste arising from, for example a nuclear reactor, is changed to non radioactive material.
- **OECD MegaScience Forum** (the MegaScience Forum)
The MegaScience forum is a group of 30 member countries, with active relationships to 70 more, sharing a commitment to democratic government and the market economy. Best known for its publications and its statistics, its work covers economic and social issues from macroeconomics, to trade, education, development and science and innovation.
- **Peer review**
The self regulating process widely employed by academic publishers and science funders, the Research Councils, through which a community, generally the established and leading scientists of the community, review the scientific output, papers, and funding proposals for that discipline.
- **PPARC** - Particle Physics and Astronomy Research Council, <http://www.pparc.ac.uk>
The UK Research Council with responsibility for funding research in the astronomy and particle physics.

- **Reactor based neutron sources**
Reactor based neutron sources generate neutrons by controlled nuclear fission of uranium, as found in a nuclear reactor.
- **SNS, the Spallation Neutron Source**
A next generation spallation neutron source under construction in the Oak Ridge National Laboratory, USA, and due for completion in 2006. The SNS plans to operate at 1MW.
- **Spin-close, spin-in, spin-out**
Terms used to describe the relationship between an academic body and private sector companies exploiting academic capability: spin-close - the location of the companies with the academic body; spin-in - the co-location of a company to exploit academic facilities and expertise; and spin-out - the creation of a company to commercialise academic intellectual property.
- **SPSS - Short Pulse Spallation Source**
The type of spallation neutron source presently in operation at for example ISIS, an SPSS produces short duration, bright neutron pulses for high resolution neutron scattering.
- **Synchrotron**
A cyclic accelerator of large radius that can accelerate charged particles, electrons and protons, to very high energy.
- **Synchrotron radiation**
The highly focussed and intense beams of X-ray, infrared and ultra-violet light employed to probe the basic structure of materials generated in a synchrotron.
- **Technology Panel**
A panel of four international neutron technologists commissioned by the CCLRC to develop a 'road map' for future neutron technologies to deliver the UK neutron science case.

Neutrons

Neutrons

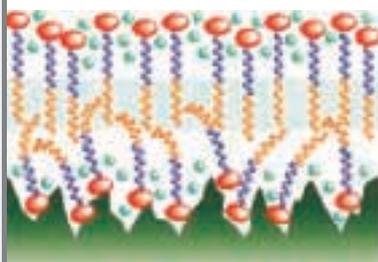
for future science and
technology



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Science in the early part of the 21st century is increasingly being driven by the need to expand and exploit a 'high value' technological economy. Society wants more and more complex and sophisticated materials that are lighter and stronger, devices that are smaller and cheaper, medicines that cure diseases quickly with minimal side effects, and everything must be energy efficient and environmentally friendly. This will require the development of, for example, new sensors and electronics, smart responsive structural materials and synthetic bio-materials. It will demand a detailed understanding of the relevant physical processes.



The increasing complexity means that scientists and engineers will need a range of complementary methods to unravel and optimise the properties of these new materials, and lead on to the next generation. Because of its unique abilities, neutron scattering will play a vital role in the portfolio of analysis techniques, in fields as varied as energy, nano-technology, materials processing, drug design, biotechnology, green technology and information technology.

Neutrons play a definitive role in our understanding of the material world around us, and have done so for the past fifty years. For example, the foundations of our atomic understanding of magnetism are mostly provided by neutron scattering. Our detailed knowledge of atomic and molecular dynamics owes much to pioneering research using inelastic neutron scattering.

The UK is a leading international player in the development of neutron based techniques. Starting from the early days of research at AERE Harwell, then through its key role in both the Institut Laue Langevin and the ISIS spallation neutron source, the UK has developed an outstanding academic user base for the broad scientific exploitation of neutrons across the scientific disciplines, from solid state physics and structural chemistry, through engineering and materials science, to the investigation of soft condensed matter and biomaterials.

Neutrons can show where atoms are and what atoms do. They allow scientists to look inside the structure of matter, from the vibrations of individual hydrogen atoms to the folding of proteins, from the high temperature and pressure needed to probe the properties of the earth's interior to the low temperature and high magnetic field needed to unlock the secrets of superconductivity.

Neutrons will, for the foreseeable future, continue to make significant, unique and necessary contributions to help solve numerous scientific and technological problems, from the understanding of fundamental physics to the optimization of industrial processes. Looking back over the last century, we can see that we are not very good at predicting, even 20 years into the future, which discoveries science will make or which directions technology will take. But we can clearly see that, given their unique abilities and the breadth and depth of their applications, neutrons will certainly be needed.

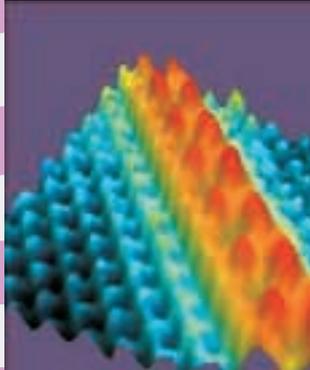
Because of their very wide range of applications, neutrons will provide underpinning scientific solutions in many of the current and future priority areas that are crucial for future technological solutions. and applications.

Drug design and pharmaceuticals



- Development of safe and efficient targeted drug delivery systems, such as in gene therapy
- Exploitation of natural antibiotics in the treatment of drug resistant pathogens
- Protein folding and mis-folding; degenerative diseases
- Understanding the associated processes at a molecular level

Nanotechnology



- Templating for the synthesis of new materials
- Nano-composites for lightweight structural materials
- Nano-fabricated magnetic clusters or molecular magnets or for quantum computers
- Atomic scale characterization of nano-particles

Sensors and smart materials



- Functionalised surfaces and interfaces
- Sensors and bio-sensors (lab-on-a-chip)
- Photoresponsive and polymer based materials for devices, displays and recording media
- Improved lubricants, adhesives and coatings
- Molecular electronics – beyond silicon

Bio-technology



- Bio-sensors (tissue based sensors)
- Synthetic bio-replacement materials with improved bio-compatibility and bio-lubrication – bio-mimetics
- Food technology

Environment and clean technology



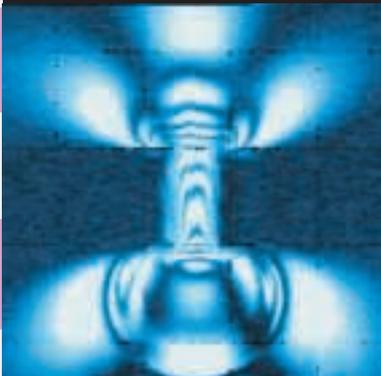
- Catalysts
- Materials for carbon sequestration
- Environmentally friendly materials, e.g. 'green' refrigerants
- Mineralogical origins of earthquakes and volcanoes
- The use of natural enzymes to break down environmental contamination
- Safe radioactive waste disposal

Energy for the future



- Hydrogen storage materials
- Fuel cell components; oxide ion conductors
- Clathrate hydrates for energy sources
- Light, high energy density batteries
- Energy efficient transport; superalloys, ceramics, fuel additives
- Next generation nuclear reactors

Materials and processing



- Processing of soft solids and complex fluids in extruders, mixers, pipe flow and micro-fluidics
- Controllable rheology for lubricants and oil extraction
- Structural integrity and safety: remediation of residual stresses in alloys, composites and welds
- Light weight, high strength alloys and composites; superconducting wires, bulk amorphous alloys
- In-situ measurements to understand materials synthesis, processing and treatments

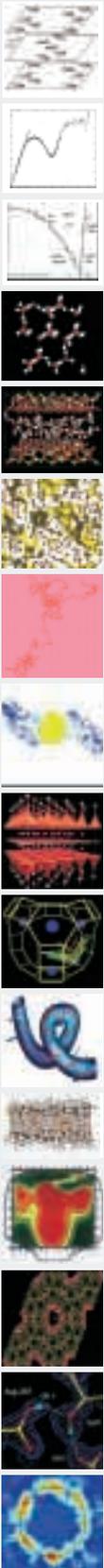
IT and quantum devices



- Giant magnetoresistance and exchange bias for spintronics and high density data storage
- Hard thin film magnets for micro-motors, -switches and -sensors
- Understanding magnetic roughness and phase diagrams – towards better electronic devices
- Understanding quantum complexity

50 years of scientific success

Neutrons



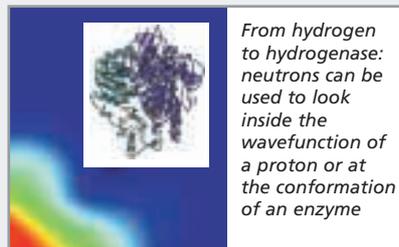
Neutrons have been making key contributions to our scientific knowledge for more than half a century. Continuous development of techniques and technologies has led to a continuous improvement in experimental capabilities, which has in turn led to a continuous broadening of the range of applications. Neutrons have been one of the first techniques of choice for detailed characterization of the atomic and magnetic structure and dynamics of many of the important new classes of materials that have been discovered or developed. They have also played a key role in validating many of the most important theories and models of the behaviour of condensed matter (and in disproving other theories).

- The first determinations of magnetic structures were made by Shull (Nobel Prize 1994) using neutron diffraction, confirming the theoretical ideas of Néel (Nobel Prize 1970). Without neutrons our microscopic understanding of magnetism would still be mainly theoretical. They remain the most important technique for determining magnetic structure and dynamics at the atomic scale.
- The development of triple axis neutron spectroscopy by Brockhouse (Nobel Prize 1994) led to the first measurement of phonons, confirming the quantum theory of solids. This provides the basis for our understanding of atomic dynamics in crystals.
- The elementary excitations in superfluid helium (^4He) - 'rotons' - were measured using time-of-flight neutron spectroscopy. Later 'tour de force' studies extended this to the 'Fermi liquid' ^3He . Such experiments provide stringent tests of our understanding of fundamental statistical physics.
- Small angle neutron scattering has been used to determine that polymer chains in the liquid state have a random coil conformation, as predicted by Flory (Nobel Prize 1974).
- Polymer reptation dynamics has been measured using neutron spin-echo spectroscopy, validating the model of de Gennes (Nobel Prize 1992).
- Bonding electron distributions have been determined using the combination of highly accurate neutron and X-ray single crystal diffraction data.
- Neutrons have made essential contributions to the understanding of phase transitions, for example in the measurement of soft modes.
- Neutron diffraction studies of ions in solution, using isotopic substitution to 'pick out' the arrangement of water around the ions, overturned textbook ideas of ionic solvation. Diffraction and reflectometry studies, using contrast variation to highlight the contributions of particular parts of complex molecules, have proved crucial to our microscopic understanding of the behaviour of soft matter systems such as polymers and surfactants.
- Neutron diffraction measurements determined the crucial importance of copper-oxygen arrangements in high temperature superconductors, discovered by Bednorz and Mueller (Nobel Prize 1987). Measurements of the magnetic dynamics have shown that magnetic interactions are crucial to understanding the mechanism of high temperature superconductivity.
- Neutrons have made significant contributions to our understanding of the structures and dynamics of fullerenes and fullerides, as discovered by Cull, Kroto and Smalley (Nobel Prize 1996).

See the world in a unique way

Length and time scales:

Neutron scattering enables us to study atomic and magnetic structure and dynamics over an enormous range of distances and times, from 10^{-11} m to 10^{-6} m and from 10^{-14} s to 10^{-6} s. While other techniques can provide information either within the same distance range or the same time range, this combination of both structural and dynamical information is unique to neutron scattering.



From hydrogen to hydrogenase: neutrons can be used to look inside the wavefunction of a proton or at the conformation of an enzyme

Sensitivity and selectivity:

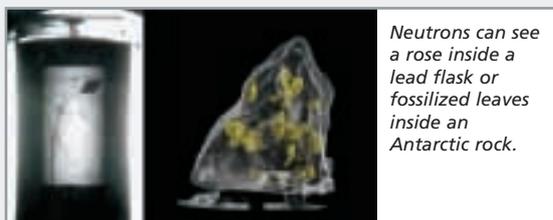
The amount that neutrons are scattered by chemical elements of similar atomic weight, or even by different isotopes of the same element (such as hydrogen and deuterium), can vary significantly. This allows us to isolate or highlight particular atoms, or groups of atoms, in mixtures or complex materials.



Replacing hydrogen by deuterium in different parts of a molecule allows neutron scattering to build up a picture of the different building blocks of the structure

Penetration:

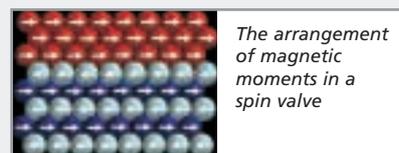
Neutrons pass easily through most materials, allowing us to study large or bulk samples, and buried interfaces, under extreme conditions such as high temperature or pressure. Neutrons are non-destructive, so delicate materials or precious objects can be studied without fear of damage. Neutron imaging techniques can be used to look inside objects as large as a car engine.



Neutrons can see a rose inside a lead flask or fossilized leaves inside an Antarctic rock.

Magnetism:

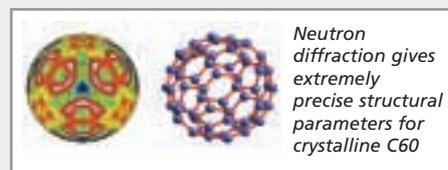
The neutron acts as a tiny magnet, but has no charge, so we can use it to study the magnetic structures and dynamics of materials at the atomic scale, which underpin the properties we use in the everyday world.



The arrangement of magnetic moments in a spin valve

Precision:

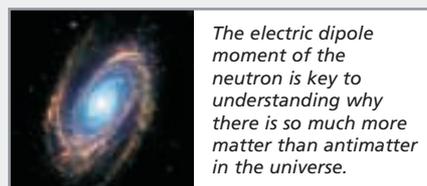
Neutrons are a very precise tool. Their interaction with atoms is weak which makes analyzing the data, and understanding it, straightforward. We can easily compare neutron scattering results with computer simulations or models.



Neutron diffraction gives extremely precise structural parameters for crystalline C60

Fundamental properties:

Studies of nuclear and particle physics using slow neutrons probe the fundamental interactions in nature, helping us to understand events from the creation of the chemical elements during the first few minutes after the big bang of the universe to supernova explosions billions of years later.



The electric dipole moment of the neutron is key to understanding why there is so much more matter than antimatter in the universe.

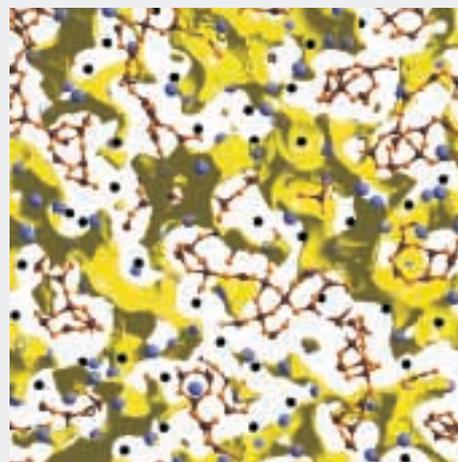
Providing pieces of the puzzle



The neutron is an indispensable tool for studying atomic structure and dynamics in condensed matter because of its particular unique properties. However, the value of neutron data can be considerably enhanced by combination with complementary data obtained by other methods, and similarly data obtained by other methods are enhanced by combination with neutron data. There is no single experimental technique that can provide us with all the

information we need to know about materials. Different techniques, based on different physical processes, provide different information. As the complexity of the materials under study increases, the approach needs to become 'problem based' rather than 'technique based'. The future trend is towards the use of multiple complementary experimental techniques, each of which gives us some pieces of the puzzle. Advanced techniques of computer simulation and modelling can be used to help put these together.

Developments in experimental techniques over the past decades have been amazing, and will continue to be so in coming decades. X-ray tubes have given way to 3rd generation synchrotrons with many orders of magnitude greater brilliance, and this trend will continue with the X-ray free electron laser. Optical lasers can now be used to investigate matter on the timescales of chemical reactions. Developments in neutron source power have been more modest, so why do an ever greater number of scientists use neutron scattering to study an ever wider range of scientific problems? On the one hand, neutrons offer unique characteristics as an experimental probe. On the other hand complementarity means that advances in the use of one probe, e.g. X-rays, produce an increased demand for information that can only be provided by another probe, e.g. neutrons. The combination of information means that the result is very much greater than the sum of the individual parts.



Structure of a glass, showing pathways for ion conduction. Such structures have been derived using computer modelling techniques directly based on the combination of complementary experimental data from neutron diffraction, X-ray diffraction, EXAFS and NMR

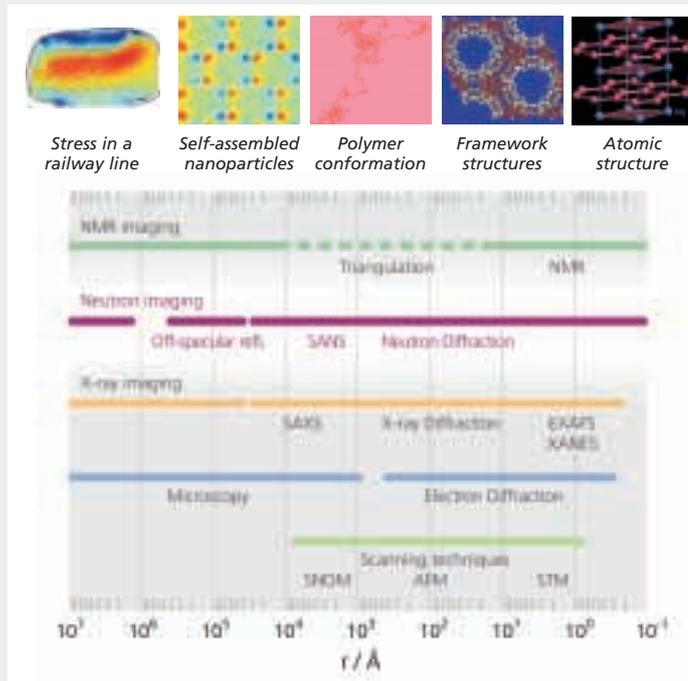
Because of the simplicity and weakness of the scattering interaction, atomistic computer simulations, models and theory can be used to straightforwardly calculate the expected neutron scattering data, and hence can be rigorously tested by experiment. This relationship is in general far more direct than with any other experimental technique. Neutrons therefore have a special role to play in the validation of both computational and theoretical techniques, and of the interaction potentials or other input parameters that may be used in them.

Filling the gaps

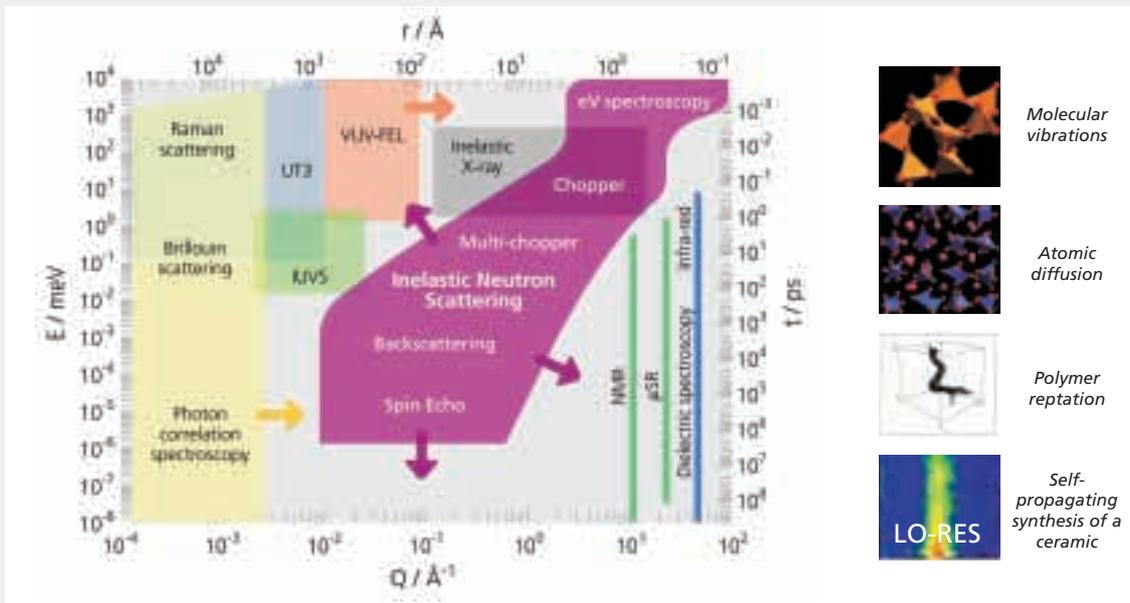
Neutrons

For structural studies there is considerable overlap in terms of the distance scales covered by different techniques, but the information obtained is nearly always complementary because of the different element specificity. Neutron scattering plays the major role in magnetic structure determination. Microscopy techniques are typically only applied to very small samples, which can be an advantage or a disadvantage depending on the application.

For dynamical studies the complementarity of inelastic neutron scattering and other experimental techniques is remarkable. The degree of overlap is small. Indeed, this is actually a disadvantage as it means that the differences in element specificity cannot be exploited as well as they can in structural studies. Instrumental and technique developments, both for neutrons and other methods, are currently tending to 'fill in the gaps', rather than providing more overlap.



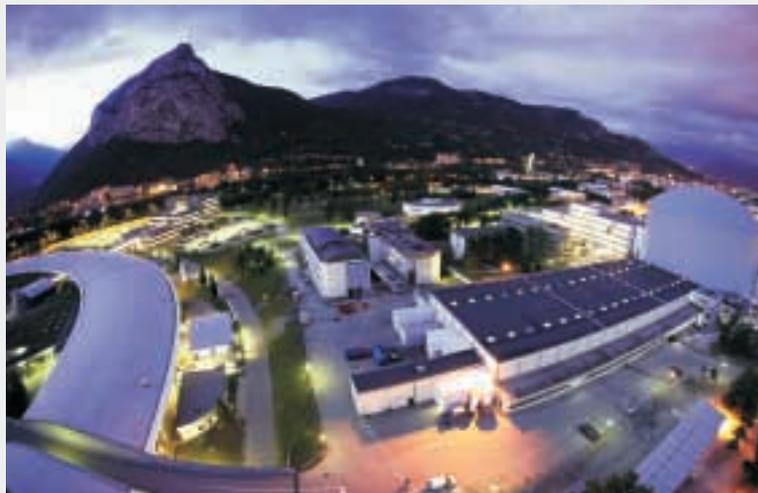
Distance scales covered by some complementary experimental techniques. These vary by a factor of 10^9 , equivalent to the size difference between a football and the earth



Areas in distance-time covered by some complementary experimental techniques. Those that only probe time dependence, but do not directly provide distance information, are indicated as bars along the time direction. The time scale only refers to equilibrium phenomena. Non-equilibrium effects, such as those studied in 'pump-probe' experiments at very short times (fs) will always remain the domain of photon based techniques. With neutron techniques 'pump-probe' experiments may be possible down to μ s, covering the longer length and time scales important in soft condensed matter and biological systems.

The future ... Neutrons

This science case gives a glimpse of what could be achieved, with the right investment at the right time. The breadth of applications of neutron scattering continues to grow, and advances in complementary techniques only increase, rather than decrease, this breadth. However, if the neutron facilities of today and tomorrow are really to realise their full potential,



they need to offer more than just neutrons, more than just the continued development of instruments, optics, detectors and techniques that has been so successful up to now. They must form a core part of a 'research super-centre' which provides a whole range of scientific capabilities, based on the 'user service' model which has been used so effectively at neutron facilities over the past 30 years. The majority of future 'users' will be experts in the particular scientific problem, not experts in using neutrons as a step towards the solution. Scientists based at neutron facilities of the future will act as the 'neutron expert' in a multidisciplinary approach to an increasingly wide variety of problems. This will require more than just neutron sources and neutron instruments. It will require a broad based scientific infrastructure located around the source, coupled with comprehensive scientific and technical support for using that infrastructure.

It is no coincidence that there has been deliberate co-location of neutron facilities with materials science or biological research centres, or with synchrotron or other facilities, at several sites around the world. There is a growing user demand for an increasingly wide variety of complementary measurement and characterization techniques to be available in conjunction with neutron experiments. The challenge will be to co-operate these facilities to achieve the maximum synergy, while maintaining the natural competition that drives scientific discovery.

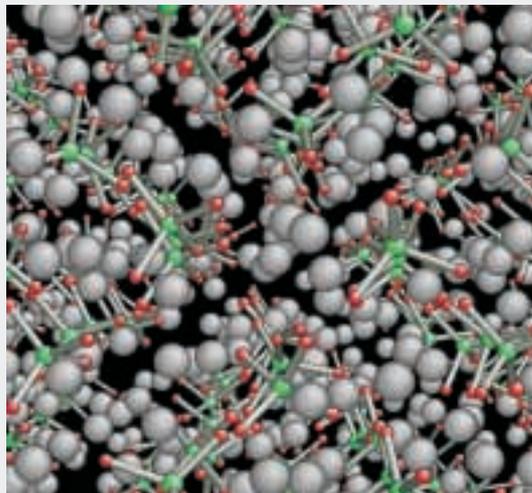


Scattering experiments need samples. In particular cases, because of the specialised nature of the synthesis and its close relationship to neutron scattering, it makes sense to co-locate the synthesis and neutron facilities and offer the combined capability to users. The most obvious case is deuteration; selective deuteration and contrast variation are absolutely central to the full exploitation of neutron scattering methods, particularly in the areas of soft matter, biology and disordered materials. The capability to synthesise selectively deuterated samples, from polymers to proteins, needs to be made available to a wide range of users, but this is by no means a trivial task. Another need is for crystal growth facilities, for example for the large crystals needed for inelastic scattering studies.



There is an ever increasing demand for a wide variety of sample conditions and treatments: temperature, pressure, magnetic field, electric field, stress, shear etc., often with more than one parameter being varied. The extreme conditions of this year become the standard conditions of next year. There are also demands for simultaneous measurements using techniques such as conductivity, magnetometry, heat capacity, X-ray diffraction and infra-red and Raman spectroscopy. Samples are synthesized and treated in-situ, sometimes under conditions relevant to industrial processes - 'bringing the laboratory to the beamline'. Experimental success depends on these services being provided with high reliability on a 24 hour basis, exactly the same as for the neutron source. This requires an increasing level of technical expertise and support.

Modern neutron instruments produce larger quantities of data, from more complex samples, at an ever faster rate. This data could either be used more qualitatively, or its analysis and interpretation could become the bottleneck in the research process. Given that one of the great strengths of neutron data is that it can be related directly and quantitatively to models and theory, it is clearly crucial that the analysis should be as quantitative as possible and make full use of all the data measured. This will require increased investment in the development of software, computing facilities and e-science. One goal is for sufficiently detailed analysis to be available on the same timescale as the experiment, so that the results can be used to guide the experiment interactively (and in some cases even automatically). This is particularly crucial as there are more and more non-expert users, from an increasingly wide range of scientific backgrounds, who no longer want to see 'data', but really want to see what neutrons can tell them - 'where the atoms are and what the atoms do'.



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