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Neutron Sources for America's Future

Report of the Basic Energy Sciences
Advisory Committee
Panel on Neutron Sources

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1 Executive Summary

Neutrons are a unique and increasingly essential tool in broad areas of the physical, chemical, and biological sciences, as well as in materials technology and nuclear medicine. Over the past decade, neutron probes have made invaluable contributions to the understanding and development of many classes of new materials ranging from high-T_c superconductors to fullerenes. The most rapidly developing area is the use of cold neutrons in the science of polymers and complex fluids — materials with enormous industrial importance and applications. The many awards given in recent years for achievements in neutron scattering research attest to the growing importance of neutrons in U.S. science and technology. Isotopes produced by neutron capture are widely used by U.S. industry. Medical uses of such isotopes for diagnosis and therapy exceed 10 million applications per year. A recent notable example has been successful cancer therapy by using ^{252}Cf. Other essential uses of neutrons for technological purposes include radiation damage studies for fission and fusion reactors, depth profiling of near-surface impurities, and residual stress measurements in metals and ceramics, as well as composite materials.

Over the last 20 years, the United States has fallen alarmingly behind the European scientific community in the availability of up-to-date neutron sources andinstrumentation. The major research reactors of the U.S. Department of Energy (DOE), HFBR and HFIR, were built more than 25 years ago and have an uncertain remaining lifetime of a decade or so, with an especially precarious status for HFIR. The earliest completion date of new sources is about 2000. A rapid decision and funding process is essential to assure that the nation retains a world-class position in the above-mentioned areas, which are of great importance to its economic strength and to its people's health. The new neutron sources recommended below will require about $2.2 billion in construction funds (1992 dollars) over a period of approximately 10 years. Construction will provide substantial new employment opportunities, with many in high-technology areas. These sources will serve the country for about 30 years after completion. Operating costs will be substantially offset by the closure of existing facilities. The new sources will be of great value to the missions of a number of DOE organizations in addition to Basic Energy Sciences — the Office of Nuclear Energy, the Office of Fusion Energy, the Office of Health and Environmental Research, and the Office of Defense Programs. Furthermore, advanced neutron sources are also increasingly important to the Department of Commerce and the Department of Defense, as well as to the National Institutes of Health.

The Panel that prepared this report had substantial representation from universities, industry, and government laboratories and included both neutron specialists and generalists. All four DOE laboratories with interests in constructing future sources were represented by nonvoting members. The Panel visited and heard presentations at each of these laboratories. It sponsored a Review of Neutron Sources and Applications, with the participation of 70 national and international experts. The Proceedings are a companion to this report. The Panel had three meetings in addition to the laboratory visits and also participated in the Review.

At its first meeting on July 31, 1992, the Panel discussed the written charge of June 1, 1992 (see below) with Dr. Will Happer, Director, Office of Energy Research. Dr. Happer made clear that he would also like an assessment of the importance of neutrons for the nation's science, technology, health, and economy, as well as recommendations for both short-term and long-term funding and construction strategies. These assessments and recommendations are presented in our report.

After reviewing different alternatives for capability and cost-effectiveness, the Panel concluded that the nation has a critical need for a complementary pair of sources: a new reactor, the Advanced Neutron Source (ANS), which will be the world's leading neutron source; and a l-MW pulsed spallation source (PSS), more powerful than any existing PSS and providing crucial additional capabilities, particularly at higher neutron energies. The ANS is the Panel's highest priority for rapid construction. In the Panel's view, any plan that does not include a new, full-performance, high-flux reactor is unsatisfactory because of a number of essential functions that can be best or only performed by such a reactor.

Recommendation 1: Complete the design and construction of the ANS according to the schedule proposed by the project.

Recommendation 2: Immediately authorize the development of competitive proposals for the cost effective design and construction of a l-MW pulsed spallation source. Evaluation of these proposals should be done as soon as possible, leading to a construction timetable that does not interfere with rapid completion of the ANS.

These new sources must be firmly dedicated to neutron science and technology as their principal mission. Predictability and reliability are of the essence.

It is important to recognize that most of the modem applications of neutrons are intensity limited, and thus place a premium value on the neutron fluxes available. Consequently, most fundamental breakthroughs in both scientific and technological applications of neutron sources over the last 40 years have been directly associated with increases in the intensity and quality of the available neutron fluxes.

The ANS is at a highly advanced stage of design, with a fully developed Conceptual Design Report, so that its construction cost estimate of $1,500 million (FY 1992) can be regarded as reliable if the proposed schedule is followed. Different concepts for a 1-MW pulsed spallation source are at a preliminary state of design by three DOE laboratories — Argonne National Laboratory, Brookhaven National Laboratory, and Los Alamos National Laboratory — and will require modest extrapolation of existing technologies. A preliminary cost estimate by two laboratories of approximately $500 million (FY1992) for construction (if some existing facilities are used) was considered reasonable by the Spallation Sources Group of the Neutron Review. However, on the basis of recent cost escalations beyond such preliminary estimates for other major facility construction, the Panel believes that this cost will increase considerably with more refined estimates. Each of the interested laboratories should be given the opportunity to develop a proposal of sufficient detail to allow for meaningful comparisons in choosing a design and site.

Input from the neutron community should be sought and given great weight by DOE. All cost estimates could be affected by unanticipated changes in regulation.

The recommended pair of sources would complement European facilities, which consist of a less powerful reactor in France, at the Institut Laue-Langevin (ILL), and a more powerful (5-MW) European Spallation Source in the planning stages.

The recommended construction program requires special appropriation and should not be carried out at the expense of individual investigators. While neutron sources for research are by their nature large facilities, they are used primarily to conduct thousands of small science experiments each year.

Recommendation 3: Enhance operation and instrumentation of existing sources.

These enhancements are highly cost-effective and clearly needed to prevent further erosion over the next decade and to prepare for the new sources. Detailed recommendations involving additional operating budgets of approximately $4 million and instrumentation of about $25 million are presented. The new instrumentation will be transferred to the ANS and PSS.

Recommendation 4: Devise a strategy for sustained R&D of neutron instrumentation.

The effectiveness of neutron sources is critically dependent on appropriately up-to-date instrumentation. As a model in this area, the United States should use the outstanding example of the ILL reactor in France, which is supported by smaller European “feeder” sources.

Recommendation 5: Effective management by DOE of the proposed facilities is essential.

In the opinion of the Panel, the present highly complex DOE management structure and regulatory process lead to substantial avoidable costs and delays, especially for reactors. In the Panel’s view, appropriate steps to improve management and regulatory procedures will lead to major cost savings and increased effectiveness in both construction and operation without sacrifice of safety.

In summary, failure to move ahead quickly with construction of the ANS and development of a complementary l-MW PSS would have serious, long-lasting consequences for the nation’s competitiveness in cutting-edge science, technology, industry, and medicine, The construction of these facilities represents a cost-effective and productive investment in the nation’s future.

Charges to the BESAC Neutron Panel

From the letter by W. Happer to L. Silver, 6/1/92 (Appendix 1):

1. Review the strengths and weaknesses of reactor and spallation sources of neutrons for:

   - Production of isotopes,
   - Neutron scattering,
   - Neutron irradiation effects, and
   - Other neutron research.

   Where do they complement or duplicate each other?

2. Taking into consideration their strengths, weaknesses, cost, readiness, and other appropriate factors, discuss the design goals for:

   - A reactor only,
   - A spallation neutron source only, and
   - A combination of the two.

   Recognizing that the design for a new reactor is underway and that similar data do not exist for a spallation neutron source, extrapolate from existing facilities or studies.

3. From the available information, discuss the proper timing for:

   - A reactor only,
   - A spallation neutron source only, and
   - A combination of the two.

4. Discuss the major uncertainties in the analysis where additional information would permit more definitive conclusions.

Expansion of charge to the Panel (meeting with Dr. W. Happer, 7/31/92):

1. Assess the importance of neutrons for the nation's science, technology, health, and economy.

2. Develop recommendations for both short-term and long-term strategies for DOE neutron sources.

2 Preface

Neutrons have become an increasingly indispensable tool in broad areas of the physical, chemical, and biological sciences, as well as in materials technology and medicine. However, no major new neutron source has been built in the United States for over 25 years, and the country has fallen increasingly behind Europe in the availability of up-to-date sources and instrumentation. Dr. W. Happer, Director, Office of Energy Research of DOE, in a letter dated June 1, 1992, and addressed to Professor L. Silver, Chair of the Basic Energy Sciences Advisory Committee (BESAC) (Appendix 1), requested the formation of a panel to report on key issues concerning possible new sources, emphasizing especially the comparison of reactors and PSSs. The duly constituted panel had an orientation meeting with Dr. Happer on July 31, 1992, where he expanded the charge to include (1) an assessment of the importance of neutrons for the nation's science, technology, health, and economy and (2) recommendations for both short-term and long-term strategies for neutron sources. This report is the Panel's response.[†]

The composition of the BESAC Panel on Neutron Sources is listed below. The DOE laboratories with neutron sources — Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Los Alamos National Laboratory (LANL), and Oak Ridge National Laboratory (ORNL) — were represented by nonvoting members, whose names are marked by an asterisk. Professor Frauenfelder joined LANL after the formation of the panel. As evidenced by the member list, a wide range of backgrounds and expertise was represented, Appointment letters to the Chair and to the members of the Panel are reproduced in Appendix 2.

Professor Walter Kohn, Chair (Condensed Matter Theory)
Department of Physics, University of California (Santa Barbara)
Former Director, NSF Institute of Theoretical Physics

Dr. David L. Price,* Vice Chair (Glasses and Liquids)
Materials Science Division, Argonne National Laboratory
Former Director, IPNS (Intense Pulsed Neutron Source)

Dr. John J. Rush, Vice Chair (Molecular Solids)
Materials Science and Engineering Laboratory,
National Institute of Standards and Technology
Leader, Neutron Condensed Matter Science

Dr. John Axe* (Neutron and X-ray Scattering)
Physics Department, Brookhaven National Laboratory
Associate Director for Basic Energy Science

[†] A preliminary letter-report submitted to Dr. Happer on September 15, 1992, can be found in Appendix 3.

Professor Robert Birgeneau (Neutron and Synchrotron Research)
Physics Department, Massachusetts Institute of Technology
Dean of Science

Dr. William Brinkman (Condensed Matter Theory)
AT&T Bell Laboratories
Executive Director, Physics Division

Dr. Paul Fleury (Lasers, Spectroscopy)
Sandia National Laboratories
Vice President for Research and Exploratory Technology

Professor Hans Frauenfelder* (Biophysics)
University of Illinois (Emeritus), Los Alamos National Laboratory
Chair, American Institute of Physics

Dr. John Hayter* (Complex Fluids)
Oak Ridge National Laboratory
Scientific Director, Advanced Neutron Source

Dr. Anthony Kossiakoff (Protein Structure)
Genentech, Inc.
Director, Protein Engineering

Dr. Roger Pynn* (Neutron Science)
Los Alamos National Laboratory
Director, LANSCE (Los Alamos Neutron Scattering Center)

Dr. Thomas Russell (Polymers and Thin Films)
IBM Research Laboratories, San Jose
Senior Scientist

Dr. Sunil Sinha (Neutron and X-ray Science)
Exxon Research and Engineering Company
Head, Condensed Matter Group

Professor Julia Weertman (High Temperature Fatigue)
Northwestern University
Chair, Department of Materials Science and Engineering Materials

Institutional Breakdown:
- 4 industry
- 3 universities
- 7 government laboratories (5 nonvoting)

Neutron Experts/Generalists:
- 10 experts (4 nonvoting)
- 4 generalists (1 nonvoting)

The Panel visited each of the four DOE laboratories with neutron facilities for about four hours of intensive presentations by the laboratories' staff. The presentations were followed by discussions, as well as tours of the facilities and meetings with representative members:

BNL:	July 30, 1992
ORNL:	August 18, 1992
LANL:	August 19, 1992
ANL:	September 9, 1992

In addition, Panel members met to discuss the issues contained in its charge and to prepare a preliminary letter report, dated September 15, 1992, and the present final report, dated December 1992, as follows:

National Institute of Standards and Technology:	July 31, 1992
Oak Brook, Illinois:	September 10-12,1992
Santa Barbara, California:	October 28-31, 1992

In conjunction with the Panel's meeting in Oak Brook, the Panel, under the leadership of Vice Chairs D.L. Price and J.J. Rush, organized a broad Review of Neutron Sources and Applications during the period of September 8-10, 1992, in which Panel members participated. Chairs of the Review Subpanels presented their findings and suggestions to the Panel on September 10, 1992. The Proceedings, entitled "Review of Neutron Sources and Applications, Oak Brook, IL, September 8-10, 1992," form a companion to this report.

The review of Neutron Sources and Applications engaged the talents of 70 national and international experts on neutron research, sources, and instrumentation. Separate working groups were assembled (1) to review the current status of advanced research reactors and spallation sources and (2) to provide an update on scientific, technological, and medical applications, including neutron scattering research in a number of disciplines, isotope production, materials irradiation, and other important uses of major neutron sources such as materials analysis and fundamental neutron physics. The groups stressed the growing importance and vitality of neutron research, including the explosive growth at research reactors of applications of cold neutrons in the study of polymers and complex fluids, the key role ofneutrons in the study of new materials, the maturation of spallation sources in time-of-flight (TOF) applications, and the development of exciting new techniques such as materials analysis and neutron reflectometry. The growing lag in source and instrumentation capabilities of the United States was also stressed.

On September 24, 1992, the Chair made a presentation based on the Panel's preliminary letter-recommendation of September 15, 1992 (Appendix 3), to the Secretary of Energy Advisory Board Task Force on Energy Research Priorities in Fairfax, Virginia. On November 4, 1992, the Chair and Vice Chairs gave a preliminary account of the conclusions of the Panel's Santa Barbara meeting to Dr. W. Happer, Professor L. Silver, and members of the Basic Energy Sciences (BES) staff in Washington, D.C.

This report and the accompanying Proceedings of the Review of Neutron Sources and Applications aim to provide a technical basis for the urgent policy decisions concerning major new neutron sources.[†] The costs of such sources are very substantial. However, strong future U.S. capabilities in neutron science and technology are vital to the nation's economy, as well as for important health applications.

Respectfully submitted,

W. Kohn
D. L. Price J. J. Rush

W. Kohn, Chair
D.L. Price, J.J. Rush, Vice Chairs

Acknowledgment

The Chair and Vice Chairs wish to express their appreciation to the Scientific Secretaries, Drs. William Kamitakahara and Ross Erwin, and to the editorial and secretarial staffs involved in the generation of this report, including Linda Clutter, Florence Henning, Dorene Iverson, Suzanne Maroney, Judy Robson, Barbara Salbego, and Judy Spillman.

[†] The Panel explicitly omitted from its considerations the institutional needs of the several DOE laboratories.

3 Scientific, Technological, and Medical Importance of Neutrons

3.1 Introduction

Over the past 40 years, research-based neutron sources have been crucial to advances in fundamental science, technology, and medicine. Neutrons provide critical information that is impossible to acquire by any other means. For many purposes they provide a necessary complement to x rays, and the parallel development of both neutron sources and x-ray synchrotron sources is essential.

In the fundamental science arena, since the 1984 Seitz-Eastman report, neutrons have made invaluable contributions to new materials that have emerged and have had a singular impact in polymer science. Specifically, the following examples of key contributions can be cited:

- Structure and excitations of high-T_c superconductors,
- Polymer conformations and interactions,
- Structure and dynamics of new-generation catalysts,
- Interfacial structure of polymeric and magnetic layers,
- Spin dynamics in highly correlated metals,
- Structure and phase transformations of fullerenes (“buckyballs”), and
- Condensate fraction in superfluid helium.

These major developments in fundamental science have been paralleled by important contributions to technological advances, such as:

- Residual stress in metals and ceramics,
- Radiography of aircraft and energy production components,
- Near-surface impurities and deposits in semiconductors,
- Giant magneto-resistant multilayers,
- Cavitation and embrittlement of structural alloys,
- Adhesion of polymer laminates,

Materials irradiation for fission and fusion power programs, and

Sintering processes of ceramics.

The production of isotopes, primarily at reactors, has also made major contributions to medicine and technology. More than 50 isotopes are used for about 10 million medical treatments and diagnoses in the United States each year. The successful use of ^{252}Cf and other transuranics for the treatment of certain cancers stands as one example.

Even with the achievements noted above, the development of research neutron sources and facilities in the United States has fallen dramatically behind the rest of the world. The potential contributions of new, more powerful neutron sources in these and other areas are enormous. The remainder of this section outlines in greater detail some of the recent developments.

3.2 Scientific Importance

A nuclear reactor has three principal products: neutron beams for scattering studies, energetic neutrons and gamma rays for materials irradiation, and a wide variety of neutron-rich isotopes. Spallation sources are effective mainly for beam experiments and, in certain cases, may also be valuable in materials irradiation studies and production of certain proton-rich isotopes. A primary justification — both scientific and technological — for next-generation neutron sources is their utility in scattering experiments. The issues and opportunities in neutron scattering studies of liquid and solid matter are emphasized in this section.

Neutron Scattering

For more than 40 years, neutron scattering has played an indispensable role in studies of condensed matter, including materials as varied as copper oxide superconductors, shape memory alloys, and block copolymers. The unique utility of neutrons can be understood by noting a number of simple basic facts. The neutron is a neutral particle and therefore, can typically penetrate very deeply into material — whether liquid or solid, insulator or metal. The neutron couples directly to the nuclei of the target via purely nuclear forces; the nuclear scattering at thermal energies is isotropic in space, with a typical cross section of ~10 barns (1 barn = 10^{-24} cm^2). The neutron cross section for a nucleus has no simple relationship to the atomic number and, compared with x rays, light atoms such as hydrogen and oxygen can be readily located. In addition, the neutron has a magnetic moment that couples to the magnetic moment of unpaired electrons in the target; the associated cross section is also typically ~10 barns. Further, the neutron can be polarized so that detailed magnetic information about the target can be very effectively obtained.

At thermal energies, the wavelength of a neutron is comparable with the separation of atoms in condensed matter. Thus, thermal neutrons display pronounced interference effects when they are scattered from condensed matter systems. The interference patterns, in turn, contain target. Length scales between 1Å and 1,000Å can be readily probed, and these limits can be extended with specialized techniques. (In general, the neutron energy is in the thermal range, from 10K to 1,000K [1K ≈ 10^{-4} eV]). Cold neutron sources extend this range down to 1K. Hence, neutrons provide a very sensitive means of studying the thermal energy spectra of the structural and magnetic elementary excitations and the dynamics of the target system on length scales ranging from atomic to mesoscopic dimensions. Excitation energies between 0.1K and 1,000K are easily accessible and, again, these limits may be extended with specialized techniques. Spallation sources extend the useful energy range to above 10,000K.

Other structural and spectroscopic probes of liquids and solids exist — most notably photons, electrons, positrons, and muons. The majority of experiments are undoubtedly carried out with photons. Each of these probes yields valuable information, albeit almost always complementary to that gained with neutron scattering techniques. For example, light scattering provides very precise values for the energies of Raman-active phonons at $q = 0$ in crystals, whereas neutrons measure the energies of all phonons at all wave vectors, albeit with less precision. Low-energy electrons and positrons both are able to provide detailed information about surface structures and excitations but are of limited value for studies of bulk materials. (As discussed later, as a by-product, a next-generation reactor source could produce a revolution in positron science by yielding much more intense sources.) Both muons and radio frequency photons (NMR) are able to give precise information about *local* magnetic and crystallographic structures. (A next-generation spallation source would provide an abundant source of muons.)

In the last decade, revolutionary advances have occurred in the application of x rays because of the development of dedicated synchrotron sources. Atomic positions in crystals can now be measured with a resolution of 5 x 10^{-5} Å. Further, the high fluxes of x rays available from synchrotron sources have made magnetic x-ray scattering research feasible. It has evolved, however, that x-ray studies most often complement neutron scattering measurements and the techniques usually are synergistic. For example, in chemical and biological systems, x rays are used to obtain the overall structure, while neutrons are able to locate the H atoms. In magnetic systems, x rays can be used to study the development of long-range order with unprecedented precision, while neutrons can provide unique information on static and dynamic spin fluctuations. Again, for most samples, the penetration depth of x rays ranges from microns to a millimeter, whereas neutron samples typically range in size from 1 mm to 2 cm. This synergism is perhaps best illustrated by noting that recent APS Buckley and ACA Warren prizes (Table 3.1) have been awarded to groups who carried out combined neutron and x-ray studies of novel materials.

Traditionally, neutron scattering was used primarily by condensed matter physicists and, to a lesser extent, physical chemists. A remarkable growth in the use of neutrons as probes of polymers and complex fluids has occurred in the last decade. Studies of biological molecules and assemblages are still in their infancy, but the initial results are impressive. A next-generation source could produce great advances in neutron studies of systems of importance in biology. Neutrons also are now used in a wide variety of very important materials science applications. The great and growing impact of neutrons in a number of disciplines is illustrated by the many prizes

TABLE 3.1 Major Scientific Awards for, or Strongly Influenced by, Neutron Scattering Research

Year	Name	Award	Research Area
1957	Clifford Shull (MIT)	APS Buckley Prize	Neutron diffraction, magnetic structure
1963	Bertram Brockhouse (AECL)	APS Buckley Prize	Phonons, magnons
1973	John Axe, Gen Shirane (BNL)	ACA Warren Diffraction Award	Soft modes, phase transitions
1973	Gen Shirane (BNL)	APS Buckley Prize	Phonons, soft modes
1974	Paul Flory (Cal Tech)	Nobel Prize, Chemistry	Polymer structure
1978	Henri Benoit (Strasbourg)	APS High Polymer Prize	Neutrons, polymer structure
1982	Edwards (Cambridge) and Pierre de Gennes (Col. Paris)	APS High Polymer Prize	Reptation theory
1984*	Charles Han (NIST)	APS Dillon Medal	Polymer structure and dynamics
1986*	Muthu Kumar (U. Mass.)	APS Dillon Medal	Theory of polymer structure
1987*	Robert Birgeneau (MIT)	APS Buckley Prize	Magnetism
1988*	Robert Birgeneau (MIT), Paul Horn (IBM)	ACA Warren Diffraction Award	Low-dimensional systems
1988*	Jean Guenet (Saclay)	APS Dillon Medal	Gel formation
1989*	Frank Bates (AT&T)	APS Dillon Medal	Block copolymers
1990*	Pierre de Gennes (Col. Paris)	Nobel Prize	Theory of polymers, liquid crystals
1990*	James Jorgensen (ANL)	ACA Warren Diffraction Award	Structure of ceramic superconductors
1990*	Dieter Richter (KFA) and John Huang (Exxon)	Max Planck Research Prize	Dynamics of polymers and microemulsions
1991*	Ken Schweitzer (Sandia)	APS Dillon Medal	Polymer RISM theory
1992*	Glenn Frederickson (UCSB)	APS Dillon Medal	Theory of microsphere polymer structure
1992*	Phil Pincus (UCSB)	APS High Polymer Prize	Theory of complex fluids
1992*	Alice Gast (Stanford)	Colburn Award (American Institute of Chemical Engineering)	Colloids and polymers

* Awards since Seitz-Eastman Report, 1984.

Notes: (1) This table lists U.S. awards together with the recent Nobel Prize of P. de Gennes.
(2) Also, many additional awards from the Department of Energy, Department of Commerce, and Department of Defense have been related to neutron scattering.

awarded to neutron scientists for neutron scattering research. A summary of awards to neutron experimentalists or to theorists strongly influenced by neutron scattering is presented in Table 3.1. Of particular note is the increasing number of such awards since the Seitz-Eastman report in 1984. All but one of these awards derived from research carried out at steady-state sources. This is a trend that probably will continue into the future, although we do expect to see increasing recognition of important research carried out at spallation sources, which have only existed for about a decade.

As noted above, a major use of neutron scattering has been in the fields of condensed matter physics and materials science and this trend is expected to continue well into the future. Accordingly, the past, present, and future applications of neutrons in these fields are reviewed first.

Condensed Matter Physics and Materials Science

The development of modem neutron scattering techniques has enabled scientists to measure the details of the phonon spectra of many solids; to verify the existence of “soft” phonon modes and relate them to structural phase transitions; to elucidate the dynamics of quantum solids and liquids; to quantify the strength of the electron-phonon interaction in metals and in superconductors and use the results to calculate the superconducting transition temperature, T_c, of conventional superconductors from first principles; to observe the effect of the Fermi surface on phonon spectra; to systematically elucidate the often complex spin ordering in a vast number of magnetic materials, notably rare earths and transitions metals; to verify and refine many-body theories of the collective dynamics of both localized and itinerant spin systems; to map out spin density distributions in magnetic crystals; to study phase transitions and critical behavior in one-, two-, three- and even fractal-dimensional systems; and to study the interplay of magnetism and superconductivity in magnetic superconductors and heavy fermion compounds. Neutron diffraction was one of the earliest techniques used to verify the existence of the vortex lattice state in Type II superconductors. It has also been one of the most powerful probes used to study the effects of randomness in mixed magnetic systems, including especially those with competing fields and/or interactions. In these studies of collective phenomena, the response is typically localized in energy and momentum space. For this reason, reactor-based triple-axis spectrometry techniques have played a central role. For almost all of the above areas, neutron scattering has provided information that is essential to physics and often is unobtainable by any other means. It is safe to say that a large part of the conceptual and theoretical underpinnings of our understanding of the modern theory of solids would remain unverified and incomplete today without recourse to this research tool. Many-body theory and the theory of collective excitations, phase transitions, and critical phenomena would not have had important verifications and refinements of their predictions, and there would be no way to predict the properties of magnetic systems and superconductors from first principles or to understand structural phase transitions in detail for most materials of interest.

Over the last 10 years, neutron scattering has continued to play an essential role in condensed matter physics. It has been responsible for the elucidation of the crystal structures of the new high-T_c superconducting compounds and for the discovery of their antiferromagnetism and the nature and role of their magnetic fluctuations, all of which have important implications for the theory of highly-correlated electron systems. Neutrons have been used to observe the existence of the "Haldane gap" in even-integer-spin one-dimensional magnetic systems — a striking verification of the consequences of the topological properties of quantum spin systems. Along with synchrotron x rays, neutrons have been used to study the melting of two-dimensional systems and the nature of correlations in two-dimensional systems without long-range order. They have been used to determine the momentum distribution of quantum solids and liquids, including the "condensate fraction" long predicted for superfluid helium; to determine the nature of the orientational order/disorder transition in the case of fullerene (C_{60}) crystals; to characterize the nature of the magnetic correlations in heavy fermion systems and exotic heavy fermion superconductors; to determine the existence of intermediate-range order and vibrational modes in a variety of amorphous systems; to study surface and interface magnetism in multilayers and single crystals; to study high-energy magnetic excitations such as intermultiplet transitions in rare-earth systems; to probe the local potentials, tunneling, and diffusion of hydrogen in metals and alloys; and to characterize scaling relations and the nature of excitations in highly disordered systems such as fractals. The field is now mature and robust, plays a central role in the characterization of new materials, and exerts great influence in the interplay between theory and experiment in the development of statistical physics and many-body theory — a role that is expected to continue. An important trend over the last decade has been the enthusiastic adoption of the technique by a large community extending far beyond those expert in the techniques of neutron scattering such as triple-axis-spectrometry, who are located mostly in the national laboratories.

Neutron scattering has proved remarkably effective in the study of phase transformations and precipitation. Exciting physics has come from investigations of precursor phenomena such as elastic anomalies in the phonon spectra associated with martensitic transformations. Many types of materials are known to undergo martensitic transformations, where atoms rapidly shuffle to new positions rather than undergo changes by the usual nucleation and growth route. The extraordinary behavior of the various shape-memory alloys, which are used in medical, dental, and structural applications, is based on martensitic transformations. Of even greater economic importance is the martensitic transformation of steel to an especially hard and strong form, martensite. Most high-strength steels in use today are based on martensite. Other advances are discussed in Section 3.3, Technological Applications.

While extrapolation to the future is always fraught with risk, it is certain that numerous opportunities in this country would arise with the advent of a neutron source with intensities an order of magnitude greater than those currently available in the United States and equipped with state-of-the-art instrumentation and cold and hot sources. Collective excitations can, in principle, be studied in new materials, although, for many of these, suitably large single crystals of high quality are almost impossible to obtain. Examples at present are many of the high-T_c, materials and the fullerenes, for which the lack of large high-quality single crystals and the energies of the excitations have made such studies very difficult. The importance of the fact that proportionately smaller samples can be studied with higher intensity sources cannot be overstated. For example, since the time of the Seitz-Eastman report, it has been recognized that studies of the lattice and spin dynamics of varied intercalated graphite single crystals could yield exciting new information. However, available single crystals are limited to 1 to 2 mm^3 in volume, which is an order of magnitude too small for inelastic studies. Since the Seitz-Eastman report, specialists in the field of liquid crystals have learned how to grow high quality free-standing films of “single crystal” hexatic and solid smectic liquid crystals. The free-standing film technique, however, limits the size to about 0.5 mm^3. Again, studies of the dynamics of hexatic liquid crystal should be made possible by a next-generation neutron source. Similar considerations apply to low-dimensional organic conductors, which exhibit numerous fascinating properties (e.g., spin density wave, charge density wave, and superconducting states), but again cannot be studied effectively by neutrons because of size limitations. Another area of study is surface magnetism, for which neutrons are a natural but flux-limited probe to address issues such as surface and interfacial magnetic phase transitions and spin density profiles across surfaces and interfaces. The list of materials with a size that falls an order of magnitude short of the capabilities of existing U.S. neutron facilities is remarkably long. New opportunities made possible by a next-generation source also include the study of excitations in thin films; the separation of coherent and incoherent scattering by polarization analysis, which would greatly facilitate the study of single-particle and collective diffusion in solids and liquids; and the detailed study of vibrational excitations in complex, molecular, and amorphous solids.

Finally, as evidenced by recent discoveries of new classes of materials, such as the CuO_2 superconductors and the C_{60} systems, there will always be new and entirely unanticipated materials discovered by physicists, chemists, and materials scientists. In all such cases, neutron scattering will play an essential role in elucidating the fundamental structural and dynamic properties. In order to stay at the forefront of science and technology, the United States must have its own advanced neutron facilities so that Americans can play a leadership role.

Chemistry

Neutrons provide unique structural and dynamical information for many important chemical systems. The most frequent application of neutrons in chemistry is the use of diffraction methods to determine the structure of both individual molecules and of complex molecular assemblies. As noted in the introduction to this chapter, in many cases the uniqueness of the neutron methods lies in the particular distribution of neutron cross sections across the periodic table and among different isotopes. This distribution, which differs markedly from that of x-ray cross sections, allows one to focus on the diffraction effects of particular atoms. Also widely used are inelastic neutron scattering (INS) methods that probe the dynamics of molecules and molecular arrays. Often these inelastic methods are especially sensitive to the same atoms that were highlighted in the diffraction experiments. The special power of neutrons is highlighted by the ability to measure atomic and molecular processes over eight orders of magnitude in time (10^{-7}-10^{-15} s) and energy (10 neV-1 eV) with a wave-vector transfer regime (0.01-20$Å^{-1}$) that allows a unique probing of geometric aspects.

The availability of higher neutron fluxes would allow experiments on smaller samples or measurements with higher energy resolution. Small samples are often the only ones available because of the difficulties and expense of synthesis, the problems of having a large sample under extreme conditions, or both. In addition, higher fluxes would allow studies of structural changes in a sample in real time or the use of higher energy resolution to focus on slow dynamic processes.

Often, this situation suggests the use of reactor sources at low energy and momentum transfer and the use of spallation sources at high energy and momentum transfer, but the optimum source or combination of sources depends on the details of the experiment. The reactor and spallation sources are complementary.

Recent studies of heterogeneous and homogeneous catalysis serve as an example that illustrates the breadth and depth of neutron research in chemistry. One of the major highlights of the 1980s has been the contribution of neutron scattering to our understanding of heterogeneous catalytic processes in microporous solids such as the aluminosilicate zeolites. These important catalysts, in which the selectivity is controlled by the shape and dimensions of the pores and windows, are used for a wide range of hydrocarbon conversions in the petrochemical industry, including gasoline manufacture and xylene isomerization. Both elastic and inelastic scattering methods have been applied, and the active participation in such work of scientists from many major companies, including Amoco, Chevron, Du Pont, Exxon, Mobil, and Union Carbide, attests to the industrial importance of the field.

A detailed knowledge of the crystalline structures of these materials is essential to proper understanding of their catalytic behavior, and the unique properties of the neutron have facilitated precise refinements of the architectures of a number of important systems. Both the sensitivity of neutrons to the light atoms (silicon, aluminum, and oxygen) that constitute such zeolite frameworks and their ability to differentiate between silicon and aluminum make neutrons superior to x rays for such studies. The sensitivity to light atoms is strikingly illustrated by the direct observation of Bronsted acid sites in lanthanum zeolite-Y, which is an important component of the cracking catalysts used in gasoline manufacture.

The success of studies on zeolite structures has naturally led to more demanding experiments that probe the behavior of adsorbed hydrocarbon molecules inside zeolite cages. Both the structure and dynamics of the sorbates are known to play a central role in zeolite catalysis. In this context, neutron diffraction measurements have established the precise location of benzene and pyridine molecules in the cavities of both Na-zeolite Y and K-zeolite L, and complementary studies by inelastic and quasi-elastic neutron scattering, as well as nuclear magnetic resonance, have been used to elucidate key vibrational and diffusinal properties.

Future challenges in this area will include the extension of these methods to new generations of shape-selective catalysts. These catalysts are certain to include two-dimensional systems, such as the pillared clays, and the recently discovered *mesoporous* sieves (Mobil patent, 1992), with the cavity dimensions as high as 300Å.

The impact of neutron methods in homogeneous catalysis has also been significant. In Ziegler-Natta reactions, for example, which are used in the manufacture of polyethylene and polypropylene, the nature and importance of agostic hydrogens, adjacent to titanium, have been revealed by single crystal neutron diffraction methods. Inelastic scattering has also been used to probe the behavior of hydrogen in such systems and is now being used to examine chemical bonding effects in biological sensors based upon dihydrogen complexes. These metal-dihydrogen complexes can be viewed as arrested-reaction intermediates in the oxidative addition of hydrogen to a metal. The details of the chemical bond formed between the dihydrogen ligand and the metal and the attendant activation of the H-H bond have uniquely been examined by neutron rotational tunneling spectroscopy. This method is extremely sensitive to details of the rotational potential. The rotational barrier of the dihydrogen ligand arises from the electronic interactions between dihydrogen and metal and is sensitive to the nature of the other ligands bound to the metal.

The availability of a more intense neutron source would help to meet the challenges posed by the complexity of modem catalytic materials. In particular, both powder and single crystal work would become feasible on much smaller samples (the availability of the large samples that are required for existing neutron facilities is a recurrent problem), and the interrogation of hydrogenous, rather than deuterated, powder materials would become more viable. Furthermore, rapid *in situ* studies, such as those needed to monitor the high temperature transformation of zeolite precursors into high performance ceramics (e.g., cordierite, which is used for catalytic converter monoliths) would come within reach.

Neutron scattering plays a central role in many other fields in chemistry. For example, neutrons provide local structure information in saline solutions and in molten salts. For metal-hydrogen systems, neutron scattering techniques have provided much of the microscopic knowledge of hydrogen location and motions. Neutrons have also been used to study the structures and excitations of fast ion conductors such as silver iodide, of intercalated materials such as TiS_2 : Li, and nonlinear optical materials such as $KTiOPO_4$. Extensive studies of the structures and excitations of hydrogen bonded systems, such as KH_2PO_4, continue.

A specific issue currently being addressed is the basic mechanism for the essentially. undamped energy transport over long distances in biochemical systems. This issue clearly is of enormous importance for the function of biological molecules and remains largely unsolved. This problem is being addressed with molecular solids that contain chains of H bonds akin to the peptide chain in real biological systems. Prominent examples for such model systems currently under study by various groups are acetanilide and N-methylacetamide. These solids show a large number of anomalous vibrational bands in optical spectra that have been attributed to the existence of nonlinear excitations. The latter were proposed to be vehicles for energy transport in biological molecules. Hydrogen/deuterium substitution is being used with INS to identify vibrational coupling with these molecular vibrations, which may play a role in this energy transduction process. Much higher source intensities will be absolutely necessary if such work, both structural and dynamical, is to be extended to macromolecules.

Neutron scattering investigations significantly enhance our understanding of the structural and dynamical properties of many important new compounds, with the most recent example being the fullerenes and the derivatives based on them. The prototype of this class of materials, C_{60}, displays great chemical versatility, reacting with alkali metals, halogens, free radicals, amino acid adducts, metalorganic complexes, etc. The potential for future applications of these fullerene derivatives is bright, particularly when one considers the surprising properties already discovered, including superconductivity and nonlinear optical effects. Again, next-generation reactor and spallation sources would greatly extend studies of the structure and dynamics of new molecular architectures based on C_{60}, as well as single crystal fullerene-based materials, which are typically very small in volume.

Polymers and Complex Fluids

Polymers in both solid state and solution are the subject of intense and growing scientific interest and are at the heart of the competitive position of many U.S. industries. Complex fluids encompass, aside from polymer systems, colloidal particles, surfactant assemblies, and fluid mixtures integrating smaller hydrocarbons and hydrogen-bonded molecules. The use of cold neutrons to study these systems has led to numerous breakthroughs in the fundamental chemistry, physics, and rheology of complex fluids in solution and in the solid state and, indeed, is the fastest growing area in neutron scattering research. These advances have been paralleled by technological developments made possible only by information obtained from neutron experiments and have provided a competitive edge to specific American industries. For example, neutron research has led to improved thermoplastic elastomers and pressure-sensitive adhesives, to increased design capabilities in the tire and polyolefin industries, to better oil additives, and to improved detergent and emulsification products. Each of these molecular systems constitutes a large portion of the chemical industry and demonstrates the benefits of such sources.

The crux of neutron studies on complex fluids lies in the contrast between the proton and deuteron, which affords a simple, convenient means of labeling molecules with minimal perturbation to the thermodynamics. This led to the characterization of a single polymer molecule in an entangled melt of polymers, which is central to the understanding of bulk polymers. Such studies have provided the only viable route to a definitive description of the size and shape of microemulsion droplets and the role of surfactants. The deep penetration power of the neutrons has led to the quantitative characterization of multicomponent fluids in confined geometries, for example as in porous silica. Neutron reflectivity yields unprecedented depth resolution and sensitivity for studying polymers at surfaces and interfaces. Cold neutron inelastic scattering studies have furnished critical insights into the random motions of polymers and surfactant-laden oil-water interfaces.

An increased neutron flux will significantly impact the fundamental scientific advances and technological use of complex fluids. Increasing the flux of neutrons will allow studies of dilute solutions of macromolecules with a significant improvement in spatial resolution. For revolutionary developments in protein separation and purification processes, the characteristics of isolated, electrically charged polymers or biopolymers must be probed, which mandates the use of dilute solutions. Such information would provide important leverage in the multibillion-dollar industry that relies on these macromolecules and processes.

Essentially, all neutron scattering studies on complex fluids have been performed at equilibrium or under steady-state conditions where the time-averaged shape of the molecules, phases, or colloidal suspensions is unchanged. However, understanding the response of materials to changes in an externally applied field, for example, pressure, shear stress, or temperature, requires the measurement of the real-time changes in scattering profiles. Having the capability of monitoring the rate at which the systems approach equilibrium provides an important link between the thermodynamic forces driving the phase transition and the kinetic response of the system. While time-resolved studies are impossible at present, an increase in the source flux would make them feasible. The largest sector of the American chemical industry consists of commercial processes (e.g., injection molding, cold drawing, and extrusion) that involve polymeric components. The insight provided by time resolved studies would benefit the chemical industry through improved design, control, and reliability. Similar arguments hold for the rheological response and alignment of microemulsions and gels under shear, which have ramifications in the personal care and cosmetics industries.

A significant advance recently made by using neutrons was the measurement of the diffusive motions of molecules by neutron spin echo techniques. These studies furnished the first insights into the distinctive molecular motions underlying the macroscopic behavior of a fluid. There are no capabilities in the United States for such studies. Even with the best existing source, the ILL in Grenoble, France, experiments are time consuming and are rest&ted to strongly scattering systems. Enhancing cold neutron fluxes at longer wave lengths and optimizing the instrument design will reduce the time required for experiments by an order of magnitude and will make the experiments more feasible. Inelastic scattering contains quantitative information on the diffusive motion of polymers, the dynamics of gels and networks, membrane elasticity, and the diffusion of molecules in porous media, that cannot be matched by other techniques. Such research could have a broad impact on a variety of industrial processes.

The interfacial behavior of complex fluids and polymeric materials plays a dominant role in their end use. Multilayered microelectronic circuits, colloidal suspensions, and thrombosis for biomedical implants are just a few examples where the surface and interfacial, behavior of complex fluids and polymers play a key role. Yet, neutron reflectivity has only recently yielded a quantitative description of the interfacial behavior of hydrocarbon materials with a depth resolution comparable to molecular dimensions. Neutron reflectivity has already had an impact on processes involving adhesion, lubrication, and wetting. With more flux from the source, time resolved reflectivity and off-specular scattering studies would become feasible. The former-will be invaluable for studying kinetics of transitions at interfaces and-molecular mobility at surfaces, which are critical to understanding the wear and durability of materials. In the latter, information will be on lateral correlations at interfaces. In an adsorption process, for example, such experiments provide information on the uniformity of the surface coverage, which could spell success or failure for biomedical implants.

In summary, the availability of a higher flux of neutrons with the best possible capability in cold neutron research will have significant impact on the fundamental research that can be performed on complex fluids and polymeric materials and on the realization of technological advances. Both will play an important role in giving American industries a competitive edge in future world markets.

Biology

The biology of living organisms involves a multitude of highly complex, yet organized, series of events. The revolution in molecular biology technology now provides the tools to begin unraveling the pathways and molecular constituents of a number of biological processes. Although knowledge is limited, even in the case of the simplest biological systems, inroads are being made into important areas of medical and biotechnological research. Understanding the processes on a molecular level, which is crucial for biomedical applications, requires knowledge of the organization and structure of the interacting components. Consequently, structural biology is one of the most rapidly expanding fields in science. Of all the structural biology research tools, diffraction techniques have historically been the most illuminating approaches used to extract quantitative information about molecular interactions. Moreover, the impact of newly emerging neutron reflectivity and inelastic scattering techniques is just starting to be felt.

Structure determination through the use of x-ray diffraction is a large and mature field. The neutron diffraction and low-angle scattering community is much smaller primarily because of the limited availability of neutrons. Nevertheless, neutrons have contributed significantly to our understanding of structure-function relationships at different levels of organization, such as the location of hydrogen atoms involved in the enzyme mechanism of the serine protease enzymes, which are involved in the blood clotting cascade, and the complement system and digestion, among others. Neutrons have given an improved description of the hydration shell of proteins and nucleic acids, the location of functionally important water molecules in membrane proteins, and the distribution of protein and nucleic acid in the internal structure of chromatin and viruses. Several years ago, the location of individual proteins in the *E. coli* ribosome, as well as the components of *E. coli* polymerase and their interaction with DNA, were mapped by neutron experiments. Neutrons have been used to describe protein-detergent interactions in membrane protein crystals, lipid and membrane protein structures, and the dynamic transition in myoglobin and its correlation with protein function by INS. It is important to note that such experiments, among others, could only be considered by using neutrons.

An increase in structural work at the molecular level is expected to continue because of the progress in fundamental molecular biology driven by health concerns and the developing biotechnology effort. For the past few years, industry in the United States has been making large investments in the determination of macromolecular structure because it is convinced that the time over which products can be generated and developed can be significantly shortened by detailed structural information. Despite the wealth of information about the atomic structure of a macromolecule obtained by x-ray crystallography, it should be considered a starting point toward understanding a biological problem rather than an end in itself. X-ray structures are limited because only about one-half the atoms are observable (H atoms are not), and these structures are time and spatially averaged over all the molecules in the crystal. While advances in high-resolution NMR offer much key information on hydrogen environments, the ability of neutrons to locate H atoms experimentally continues to offer unique information that underlies biological properties driven by hydrogen bonding and dynamics. Because of their special properties, neutrons can play an increasingly important role in contributing new and important information, provided that experimental conditions are improved sufficiently to create a new scientific impetus in the field. In the past, neutron studies have also been limited by sample preparation, as in the case of the specific labeling of large complexes. The advent of genetic engineering and progress in protein chemistry, however, now provides powerful methods for controlled construction and production in the quantities required for structural study.

Biological studies make use of thermal and cold neutrons in elastic and inelastic scattering experiments over different energy and Q ranges. The wide experience on reactor sources for all classes of experiments permits a quantitative extrapolation of what could be expected from improved sources and instrumentation. At present, too few biological experiments have been done at spallation sources to evaluate their potential accurately. It appears that the best reactor sources will remain preeminent for cold neutron applications. In particular, small-angle neutron scattering (SANS), a technique with applications in a wide range of biological systems where dimensions up to several hundred Å must be explored, attracts the most users. For high-resolution crystallography, however, spallation sources may be competitive if a time-integrated flux of about 10% that of a reactor source becomes available, although new detectors must be developed and data analysis will be considerably more complicated.

In any case, an increase in flux on sample by a factor 10 will almost certainly revolutionize the application of neutrons to the study of biological materials. The potential has always existed; however, low neutron flux coupled with inherently weak diffracting biological material has limited the use of this technique. The protein crystallography situation will be the-most enhanced. Now, crystals can be grown large enough to consider a neutron analysis for only about 1 out of 200 proteins. The proposed increase in flux will increase the number of candidates by an order of magnitude.

Finally, the application of high-resolution cold-neutron spectroscopy (with TOF, back reflection, and spin echo techniques) is in its infancy, with little or no work having been done in the United States. Wave-vector dependent studies of large amplitude biomolecular modes and diffusional and relaxational motions, which are a key to biological processes and activity, offer unique and exciting prospects for the future. They will require the highest possible fluxes of cold neutrons.

For all these research opportunities, sample related improvements, such as the production of genetically engineered fully deuterated proteins, combined with new sources and instrumentation, would open the field to studies on the basis of scientific interest rather than the availability of samples of sufficient size.

Other Scientific Applications

As stated earlier, the primary scientific justification for next-generation neutron sources is their use in neutron beam experiments. There are, however, additional unique and essential applications of neutron sources — most especially nuclear reactors — which include the production of radioisotopes for medical, technical, and scientific applications; fundamental physics studies; and, for spallation sources, muon experiments. In addition, continuing materials irradiation studies are essential for the design and fabrication of next-generation nuclear energy systems, as well as for the assurance of safe and reliable operation of existing light-water reactors.

Fundamental nuclear physics studies of isotopes, which are far from the line of stability (either very neutron rich or very proton rich), have led to better understanding of nuclear structure. The ^{254}Es, which is only made at HFIR/REDC, has been used as a target for heavy ion bombardment (^{18}O and ^{22}Ne ions) to produce many very heavy nuclei, including the most neutron-rich nucleus known. Finally, the study of the chemistry and properties of transuranic elements remains a unique research area in the United States, which is totally dependent on continued production of these heavy elements.

Fundamental and Nuclear Physics

The advent of intense neutron sources for neutron scattering and materials science research has engendered a vigorous program of research in fundamental, nuclear, and particle physics.

Many of these studies with neutrons involve precision measurements of properties of the neutron itself or of its decay. Accurate measurements of the neutron lifetime and asymmetries in the directions of decay products relative to the spin direction of the neutron provide sensitive tests of the Standard Model of elementary particles and the best determination of one of the fundamental coupling constants of this theory. The present experimental upper limit on the size of a permanent electric dipole moment of the neutron rules out a number of proposed explanations about the origin of the time-reversal-violating effects seen in the neutral kaon system; still higher precision measurements are needed. Searches for neutron-antineutron transitions test baryon-number nonconservation that is forbidden in the Standard Model but should occur in a number of supersymmetric grand unified theories; no such transitions have yet been observed.

Studies of neutron interactions play important roles in nuclear physics, stellar and solar astrophysics, and fundamental interactions and symmetries. The gamma-ray induced Doppler broadening technique in (n, γ) is used to measure excited nuclear state lifetimes, which address important questions in nuclear structure physics. Observations of the neutron scattering from heavy nuclei have been used to measure the electric polarizability of the neutron. The measured polarizabilities of the proton and neutron differ significantly from quark-model expectations; further measurements are needed to unravel this puzzle. Scattering of pulsed, polarized neutrons from heavy nuclei has been used to observe parity-violation in a number of compound nuclear states. Large enhancements result from weak-interaction mixing of nearly degenerate s- and p-wave resonances, thus allowing the study of many resonances in the same nucleus at the same time; a statistical analysis then determines the mean squared parity-violating matrix element. There are also indications of the influence of opposite-parity states several megaelectronvolts away that should allow single-particle weak matrix elements to be determined. These studies can also be extended to search for time-reversal-violating effects.

Neutrons can be used to observe a variety of quantum mechanical interference effects. The observation of gravitationally induced quantum interference by neutron interferometry is the only laboratory experiment in which both gravity and quantum mechanics simultaneously play important roles. There is considerable interest in improving the sensitivity of these experiments to smaller, more subtle effects, such as coupling of the neutron spin to rotation, and performing a neutron (i.e., matter wave) version of the Michelson-Morley experiment.

Many topics are not covered in this brief review of fundamental physics at intense neutron sources. An exciting, robust program of fundamental physics will be a natural by-product of any new neutron source.

Positron Spectroscopy of Materials

Positrons and electrons form complementary probes of condensed matter. The use of electron beams, which are readily available as laboratory tools, is widespread and well-known. Positrons provide a qualitatively different probe. Their positive charge repels them from ion cores, for example, so they are effective as a probe of outer electrons in high-Z materials, which are difficult to study with Compton scattering. Positron decay by annihilation with an electron produces two photons. The angular correlation of this annihilation radiation (ACAR) directly reflects the momentum distribution of the annihilating pairs and allows determination of electron momentum distributions. A recent spectacular example is the measurement of the Fermi surfaces in YBCO, Bi2212, and La_2CuO_4-based high-temperature superconductors; these are among the few available experimental results that can drastically narrow theoretical speculation about these materials.

Positrons and the electron-positron bound state known as positronium are currently used to study electronic structure, atomic physics, molecular physics and chemistry (including liquid and gas phases), defects in metals and alloys, semiconductors, superconductors, and polymers. The negative work function of positrons means that they are, in principle, better surface probes than electrons. Positron and positronium physics and chemistry are research fields in their own right.

Positron research has been inhibited by the difficulty of producing slow positron beams of sufficient intensity. The best positron beam currents are presently about 1 nA, compared with about 100 nA in a typical electron microscope. The reactor-produced radioisotopes that yield positron beams (e.g., Cu^{64}, Co^{58}, Kr^{79}) have high specific activity (i.e., short half-lives) to provide sufficient intensity, so that a high time-averaged neutron flux is essential for their production. The source planned for the ANS will yield e+ beams with an intensity (>10 nA from a 0.2 mm source) approaching those found in electron microscopes and will allow positron research to attain its full potential, including new applications such as microprobe analysis and scanning positron microscopy.

Applications of Muons

The positive muons, which are produced by accelerator proton beams like those used in a spallation neutron source provide a powerful nuclear probe for materials and chemical sciences. Implanted in virtually any material, its spin polarization can be monitored through its decay asymmetry to yield information on structural and electronic properties of the host. With its large magnetic moment (three times that of the proton), it is sensitive to local magnetic fields, thus providing data on both the magnitude and the distribution of these fields. Determination of the magnetic penetration depth in superconductors is a well-documented example of the use of this technique. Moreover, both static and dynamic fields can be monitored via the muon relaxation functions and, for example, can give information on magnetic phase transitions. When the μ^+ is implanted in matter, it behaves like a proton, which is especially valuable in situations where hydrogen is difficult or impossible to detect by conventional spectroscopies. For example, virtually all information on isolated hydrogen defect centers in semiconductors comes from studies of the muon analog. Much of our knowledge of quantum diffusion of hydrogen-like defects in metals, semiconductors, and insulators comes from Muon Spin Rotation/Relaxation/Resonance (µSR). Because a muon production target intercepts little (about 2%) of the proton beams used for neutron production, there is negligible loss of neutron intensity in a “dual-use” facility.

Pulsed muons are also useful for a variety of other fundamental measurements. Beams with pulses of muons significantly shorter than the muon lifetime (2.2 µs) greatly reduce beam-associated backgrounds, provide a precise zero in time for measurements that study time evolution of a state, facilitate line-narrowing techniques, and allow studies of laser-induced transitions of atoms containing muons. Studies to be pursued include precision measurements of the hyperfine interval and Zeeman effect splitting in muonium ($\mu^+ e^-$), which are used to determine the fine structure constant and the ratio of the magnetic moments for the muon and the proton; laser-induced transitions in muonium, which are used to precisely measure the muon mass; and laser spectroscopy measurements in muonic hydrogen and helium, which are used to accurately measure nuclear charge distributions. Other studies include a measurement of the muon lifetime, which provides the best determination of the weak interaction coupling constant, and muon capture, which is sensitive to hadronic weak couplings. A pulsed muon facility is also an excellent source of low-energy neutrinos that can be used to study neutrino scattering, which probes higher-order processes in the Standard Model; and neutrino proton scattering, which is an ideal way to determine several weak hadronic coupling constants.

3.3 Technological Applications

Neutron Scattering

Modem technology depends crucially on the development of new materials and processes, whether this technology is applied in the electronic and semiconductor, biotechnology, health care, petrochemical, heavy engineering, food, or packaging industries. While much progress has been made in the past by using fairly empirical methods for developing such materials and processes, it can be justifiably argued that the advanced technology of the next century will demand a detailed and quantitative understanding of how materials behave under various conditions. Crucial to such an understanding is knowledge of the detailed atomic or molecular structure, the phase behavior, and the properties of these materials. This knowledge should include not only their bulk structure and properties but, equally importantly, the structure and properties in the vicinity of surfaces and interfaces and in the vicinity of various kinds of defects. Over the last decade, there has been very rapid growth in the realization that neutrons are an extremely powerful and, in many cases, unique tool for gaining such an understanding of microscopic structure and its relation to material, properties.

Historically, neutron diffraction and inelastic neutron scattering have been used primarily as basic research tools in areas such as condensed matter physics, chemistry, and, to a lesser extent, biology. For instance, the experimental underpinnings of our current understanding of solids in general, including basic theories of crystal structure, electronic structure, magnetism, and superconductivity, contain neutron-related experiments as crucial elements. This consideration is particularly true of new materials with exotic properties that have emerged over the last 10-15 years, such as magnetic superconductors, heavy fermion compounds, organic superconductors, high-T_c compounds, and fullerenes. In each of these, neutron scattering has been used at quite early stages to provide crucial microscopic information about their properties. In recent years there has been a rapid growth of the application of neutron scattering to areas such as materials science, polymers, surface physics and chemistry, colloidal science, and complex fluids. This growth has led to a rapid increase in the number of researchers who have become users of neutron facilities and, in particular, in the use of neutrons as an advanced analytical probe by industrial laboratories.

The great increase in the number of industrial researchers working in this area will undoubtedly accelerate the impact of neutron scattering methods on modem technology. This increase is only partly due to the ability of neutrons to answer specific questions about specific materials. More importantly, it is because innovations in new applications of materials or the design of new processes can best be done by researchers who are familiar with the generic behavior of different kinds of materials under various conditions (e.g., the systematic phase behavior of polymer blends under quenching or the kinetics of spinodal decomposition in a two-component alloy system at a submicroscopic level). These sorts of questions are the central focus of much neutron-related materials research. To borrow examples from earlier (non-neutron-related) developments, the use of transistors, superconductors, or lasers would not have been possible if a basic understanding of the underlying quantum processes had not been available.

Some areas of neutron scattering are having an increased impact, or are very likely to have an impact in the near future, on industrial research. Understanding of the phase behavior of polymer blends, block copolymers or polymer solutions is crucial to the design of new polymeric materials with desirable combinations of properties or of new refinery processes for the production of chemical products. Neutron scattering is often the tool of choice for the study of both the equilibrium phase behavior (including a determination of the basic interactions) and the kinetics of phase separation in such systems, because they are often opaque to light and exhibit microphase separation on length scales that cannot be accessed by other probes. (X rays often do not have sufficient contrast for such studies, which for neutrons can be conveniently achieved by selective deuteration of polymer components.)

Polymers and inorganic microporous membranes are vitally important for many modem industrial chemical separation processes and are used in refineries, environmental purification systems, bioprocessing, etc. Neutron scattering is being used to study the internal microstructure of these membranes and their relation to fluid transport through these materials. Preferential wetting and adsorption of various components of heavy oils and other hydrocarbons on the internal surfaces of porous materials can be studied by small-angle neutron scattering and is one of the key scientific issues associated with areas such as enhanced oil recovery, chemical reactions in many supported catalyst systems, etc.

Neutron diffraction has played an important role in elucidating the structure of the class of important catalytic materials known as zeolites. Such studies are currently being carried out by a number of U.S. companies to characterize new zeolite materials. Small-angle scattering studies of zeolite formation from solution offer opportunities for understanding how to control the formation of new zeolite compounds with desired pore structure and hence tailored catalytic properties. Such studies would be enormously advanced by higher fluxes and, for instance, make time-dependent studies possible. High neutron fluxes would also facilitate the detailed study of the adsorption and transport (e.g., diffusion) of adsorbate molecules in zeolites by using the techniques of high resolution quasi-elastic neutron scattering and neutron spin echo. High-energy inelastic scattering with high fluxes could be used to identify vibrational signatures of intermediate products under actual catalytic reaction conditions in a variety of catalyst systems. Catalysts are a vital component in the multibillion-dollar chemical industry and such studies are extremely important.

Neutrons provide an excellent nondestructive method to measure residual stresses. X rays can be used to detect surface stresses, but neutron diffraction permits a three-dimensional (3-D) profile of internal stresses to be mapped out through the thickness of the component. Residual stresses can be beneficial if they are compressive in nature near the surface but extremely dangerous around such stress risers as holes or fillets. Residual stresses in a component can result from the process used during its manufacture, from welding, or from build-up in service if the part is subjected to continued variable deformation (fatigue). In any case, they can lead to early and catastrophic failure. Neutron residual stress measurements have provided unique information, for example, on failure of military and automotive components. At present, the smallest volume that can be resolved in residual stress measurements is about 5 mm^3. With an order of magnitude higher flux this value will drop to around 1 mm^3, thereby increasing the ability to detect sharp, highly localized (and thus potentially the most serious) residual stresses.

In a prototypical application of neutrons to guide the development of an advanced material, SANS is being used to study the effect of changes in composition and processing schedule on the performance of a series of experimental steels. The extraordinarily high strength and high toughness of this steel derives in large part from the nucleation of nanosized carbides in massive numbers during heat treatment and the subsequent control of their growth. SANS has proved to be a far more sensitive and accurate method to follow this process than electron microscopy. Results of the scattering measurements are fed back to fine tune the material

Neutron scattering is used to detect many types of damage at an early stage, and thus catastrophic failure can be avoided or useful information can be obtained about the damage process. SANS is sensitive to the presence of internal microcracks and small voids or pores that occur in metals and ceramics as the result of fatigue or thermal shock. The presence of such flaws in the early stages is difficult to detect by other techniques. Another type of damage that can be tracked by SANS is the loss of strength caused by an increase in size (Ostwald ripening), during prolonged high-temperature service, of the small strength-giving particles in materials such as stainless steels, superalloys used in jet engines, and aluminum alloys.

Advanced ceramics are an important class of materials with an enormous potential for structural applications under service conditions involving high temperatures or corrosive environments. At present, their performance is limited by the presence of flaws (imperfect densification). Multiple small-angle neutron scattering is an exciting new technique for following the densification of ceramics from the powder to the final state. Information is obtained on the kinetics and topography of the sintering process and the influence of various sintering aids that function to assist in producing a flaw-free material. Another class of ceramic material, concrete, is perhaps the most common structural material worldwide, yet relatively little is known of the details of cement hydration. SANS is proving to be a powerful tool in the study of microstructural changes during hydration.

With the new high-flux sources, it will be possible to build a practical high Q-resolution SANS instrument ($Q_{min} \leq 10^{-3}$ nm^{-1}). The maximum size of features that can be studied by SANS then will increase by an order of magnitude (to ~1 µm). Thus, an important size regime in the microstructure (e.g., precipitates and dispersoids) of many engineering alloys will be accessible to investigation. It also is a critical size regime for damage features such as voids, pores, and cracks. With current instrumentation, scattering from these larger (and hence more threatening) flaws comes at too low an angle to be measurable.

Neutron reflectivity is a relatively new technique but offers enormous promise for the study of surface magnetism in materials used for magnetic recording and storage devices. Companies such as 3M and IBM are currently interested in such studies at existing sources. Such studies would be significantly enhanced at the proposed high-flux neutron sources. Neutron reflectivity studies can also be used to study semiconducting thin films, polymer adsorption and polymer coatings, and fundamental problems related to lubrication and adhesion — all of which involve multibillion dollar industries. Time-dependent small angle and reflectivity studies of polymeric materials under pulsed stress conditions should lead to important insights into processing of such materials. For the higher-flux sources, time-scales of seconds to minutes can be studied that are well matched to the time scales for such processes.

Materials Irradiation

The future success of the nuclear power option in the United States (fission and fusion) depends critically upon the continued existence of a healthy national materials-irradiation program and is a central responsibility of DOE. Ultimately, the safety, economics, and viability of nuclear energy systems, which are worth hundreds of billions of dollars, depend on reliable materials performance in neutron- and y-radiation environments. Deleterious effects of intense neutron irradiation, including swelling and other dimensional instabilities, severe reductions in ductility and fracture resistance, and increased susceptibility to chemical attack must be understood in advance through careful materials studies in relevant neutron fluxes and environments.

In order to assure the continued safe operation of existing light-water power reactors, while providing the necessary research and testing to support development of fusion technology and advanced thermal, space, and defense fission reactors, many radiation-induced phenomena must be thoroughly investigated by controlled experiments combined with computer modeling. These phenomena include studies of defect production in primary displacement cascades because of the role these defects play in the evolution of microchemical and microstructural changes, interactions between migrating defects and transmutation products, nonequilibrium phenomena induced by radiation damage (e.g., metastable phase formation, segregation, and amorphization), dose-rate effects in microstructure and microchemistry evolution, and He production by (n, cc) reactions (especially important for fusion technology).

The needs of the materials irradiation community require a variety of neutron fluxes, fluences, and energy spectra in controlled environments. The need for high time-averaged fluxes in large volumes considerably favors reactor facilities, although spallation neutron sources are advantageous for certain experiments. While various nuclear technologies require a number of specific irradiation facilities, a key to both fission and fusion energy development is long-term access to a mixed spectrum research reactor with fluxes up to 5×10^{15} n/cm^2•s.

Materials Analysis

The unmatched sensitivity of neutron activation analysis to very small quantities of elements is important for the detection of trace amounts of elements in technologically critical high purity material, such as silicon for semiconductor applications, or biological samples, such as bodily fluids. For example, only neutron activation can measure with sufficient accuracy and sensitivity the low-level contaminants necessary to assure good yields of multimegabyte memories and the other VLSI circuits. Neutron activation with higher flux will be an essential tool for the characterization and maturation of next-generation dynamic random access memory (DRAM) chips.

Among the important advances in neutron beam research in the last decade has been the development of new capabilities in materials analysis by using neutron depth profiling (NDP) and prompt-y activation analysis (PGAA). NDP is an invaluable technique for nondestructive mapping of a number of near-surface impurities of great interest to industry (e.g., B in semiconductor device materials or Li in aluminum-lithium alloys). Other applications of NDP include analysis of implant-hardened tooling alloys, polymeric films, device implantation, and optical waveguide surfaces. PGAA: is rapidly evolving as a highly sensitive probe of a number of key elements — most notably hydrogen. Absolute concentrations and relative stoichiometry of constituents in many important materials can be obtained *in situ* and without chemical manipulation. Recent applications include studies of H impurities and alkali metal stoichiometry in C_{60} and fullerene derivatives, H and Al/Si ratios in catalysts, impurities in photonic materials, hydrogen distributions in failed turbine blades, and a host of environmental studies.

Exciting new developments in neutron focusing lenses using capillary optics and silicon-based position-sensitive detectors with 10 µm resolution are expected to be incorporated into these techniques during this decade. Consequently, access to a tenfold increase in cold neutron beam flux will create capabilities for two- and three-dimensional mapping of trace impurity profiles at submillimeter resolution — with a wide impact on new industrial products and processes.

Radiographic Imaging with Neutron Beams and Isotopes

Neutron radiography, often using cold neutrons for improved contrast, has demonstrated its great usefulness in nondestructive test studies of defects in airplane wings, engines, and turbine blades, as well as in studies of combustion. With the advent of-higher flux steady-state sources, the extension of such techniques to measuring time-dependent phenomena and. carrying out full 3-D microtomography on micron scales can be anticipated. An example of the application of such imaging techniques could be the. study of the effects of stress and fluid flow through granular media.

Industrial radiography with radioisotopes is a $500 million industry (with a far greater economic impact). U.S. portable x-ray sources based on ^{192}Ir and ^{60}Co have been widely used worldwide to examine weldments on a variety of products such as nuclear submarines, repairs on nuclear system components such as steam generators, petrochemical structures such as hydrocrackers or reactors, process towers and storage structures, pipe lines, offshore platforms and moveable drilling rigs, high vacuum facilities, water storage structures and many others. Neutron radiography based on ^{252}Cf is used to detect plastic explosives and for environmental assays, as well as to detect corrosion and debonding in aircraft parts constructed of aluminum and/or composite materials. It is extremely costly for ultrasonics to provide a permanent record such as that produced by radiography. X rays are less economical to use for steel thicknesses greater than ~1 in. and, unlike radioisotopes, they require electrical power to operate. While ^{192}Ir and ^{60}Co (unlike 25%) do not need the highest flux reactors for their production, a critical shortage of such isotopes is already developing in the United States because of the lack of even suitable medium-flux reactors to produce them.

3.4 Medical Uses of Radioisotopes

Radioisotopes are vital tools for medical diagnosis, treatment, and research. For example, radioactive iodine isotopes are used to treat thyroid disease in more than 15,000 patients per year (among those recently treated were President and Mrs. Bush). More than 10 million medical diagnostic procedures are performed in the United States each year by using radioisotopes. Over 80% of all drugs that win U.S. Food and Drug Administration approval go through a period of research and development that requires the use of radioisotopes, often in tracer studies that show where the drug goes. Other research uses are ubiquitous. Radioisotopes of sulfur and phosphorus are basic to DNA sequencing in biology and thus play a key role in the human genome project. Nuclear medicine practice, radiopharmaceuticals, and instrumentation have a market greater than $10 billion per year in the United States. A common feature of all radioisotopes is the need for a constant resupply since they cannot be stockpiled because of their radioactive decay; half-lives are typically a few days (e.g., ^{131}I) to a few years (e.g., ^{60}C0, ^{252}Cf).

Most commercial medical equipment (e.g., syringes, blood transfusion bags, etc.) is sterilized by radiation, as are blood products (^{60}Co is mainly used). Over 50 radioisotopes are used in routine daily clinical applications in medicine for diagnosis and treatment, as well as for a variety of research purposes. Table 3.2 lists some of the radioisotopes that can be produced only in a high-flux reactor, along with their applications.

The ^{252}Cf, which decays via neutron emission, is providing a new means of treatment for otherwise radioresistant cancers: neutron brachytherapy. In this treatment, the isotope is implanted as a needle or seed directly into the tumor so that damage to other tissues is minimized. Results during clinical trials on some 3,000 cancer patients have generally been excellent. The cure rate for some cervical cancers, for example, has been 95% for 5-year survival. The ^{252}Cf (2.65 year half-life) is produced by multiple neutron capture in $^{244/248}$Cm, so that a very high flux is required. At this time, the only substantial source of ^{252}Cf is the HFIR/REDC located at ORNL.

While neutron-rich radioisotopes are best produced in nuclear reactors, neutron-poor isotopes are produced at proton accelerators. For example, a neutron-poor germanium isotope is used to calibrate Positron Emission Tomography (PET) scanners. In addition to a number of smaller cyclotrons, a PSS facility can be used for such radioisotope production.

TABLE 3.2 Reactor-Produced High-Specific-Activity Radioisotopes for Biomedical and Medical Applications

Isotope	Use
^{32,33}P	Treatment of cancer cell metabolism and kinetics; labeled probes for molecular biology and the human genome project
^{47}Sc	Treatment of cancer
^{64}Cu	Diagnostic studies of cancer and metabolic disorders
^{67}Cu	Labeling of monoclonal antibodies for cancer treatment
^{82}Br	Metabolic studies and studies of estrogen receptor content
^{97}Tc	Heart disease scans
^{133}Xe	Pulmonary ventilation studies
^{153}Sm	Treatment of cancer
^{159}Gd	Treatment of cancer
^{165}Dy	Treatment of arthritis
^{166g}Ho	Treatment of arthritis; treatment of cancer
^{169}Er	Treatment of arthritis
^{177m}Lu	Labeling of monoclonal antibodies for treatment of cancer
^{186,188}Re	Treatment of cancer
^{191m}Ir	Cardiac function, especially in infants and children
^{195m}Pt	Diagnosis and treatment of cancer
^{199}Au	Treatment of cancer
^{252}Cf	Treatment of radioresistant cancer
^{253}Es	Labeling of monoclonal antibodies for treatment of cancer
^{255}Fm	Labeling of monoclonal antibodies for treatment of cancer

4 U.S. Neutron Community

The neutron community in the United States is vital and growing in numbers. The DOE must plan to meet the long-term needs of researchers in the U.S. industrial and university communities, as well as a growing number of users from organizations within DOE and throughout the federal government who need access to the most advanced neutron facilities.

Current Profile

Between 1983 and 1991, the number of neutron scattering scientists doubled from about 500 to 1,000. If all neutron research is included, the number of users doubled from 750 to 1,500 over this time period (not including isotope users). Figure 4.1 (taken from the presentation at the Oak Book Review by the Neutron Scattering Society of America) shows a youthful neutron community — 86% are under age 50 and the age distribution peaks in the range of 30 to 40 years. Nonetheless, the U.S. neutron community is about a factor of 3 smaller than the analogous community in Europe.

The increase in the user base, despite a dearth of neutrons in the recent past, has been driven largely by the growth of research in materials and polymer science and the realization that, in many cases, only neutrons can provide the needed information. While the U.S. neutron community as a whole doubled between 1983 and 1991, the number of users at the National Institute of Standards and Technology's (NIST's) research reactor increased by an additional factor of 2 as new cold neutron instruments became available. The present neutron community comprises scientists and engineers from well over 100 universities and industries in the United States and from diverse government agencies. As an example of current user distribution, the NIST reactor serves outside users from industry (20%), universities (60%), and federal laboratories and agencies (20%).

Educational Issues

Graduate students in research universities around the country receive training in neutron research on a one-on-one basis by their thesis advisers and obtain practical experience at neutron facilities. It should be noted that a much larger user base of x-ray researchers exists in universities, as well as in industrial and government laboratories. Most research universities offer formal training and laboratory courses in diffraction theory, scattering, and crystallography. These courses generally are slanted to x rays, but the formal theory and training is fairly easily transferred to neutron scattering research. It is essential that the infrastructure at U.S. neutron sources be designed to stimulate and effectively train the students who will meet future needs and opportunities. The educational role of university sources, such as MURR, are also important and are addressed in the section below. Past experience has shown that, as neutron facilities improve

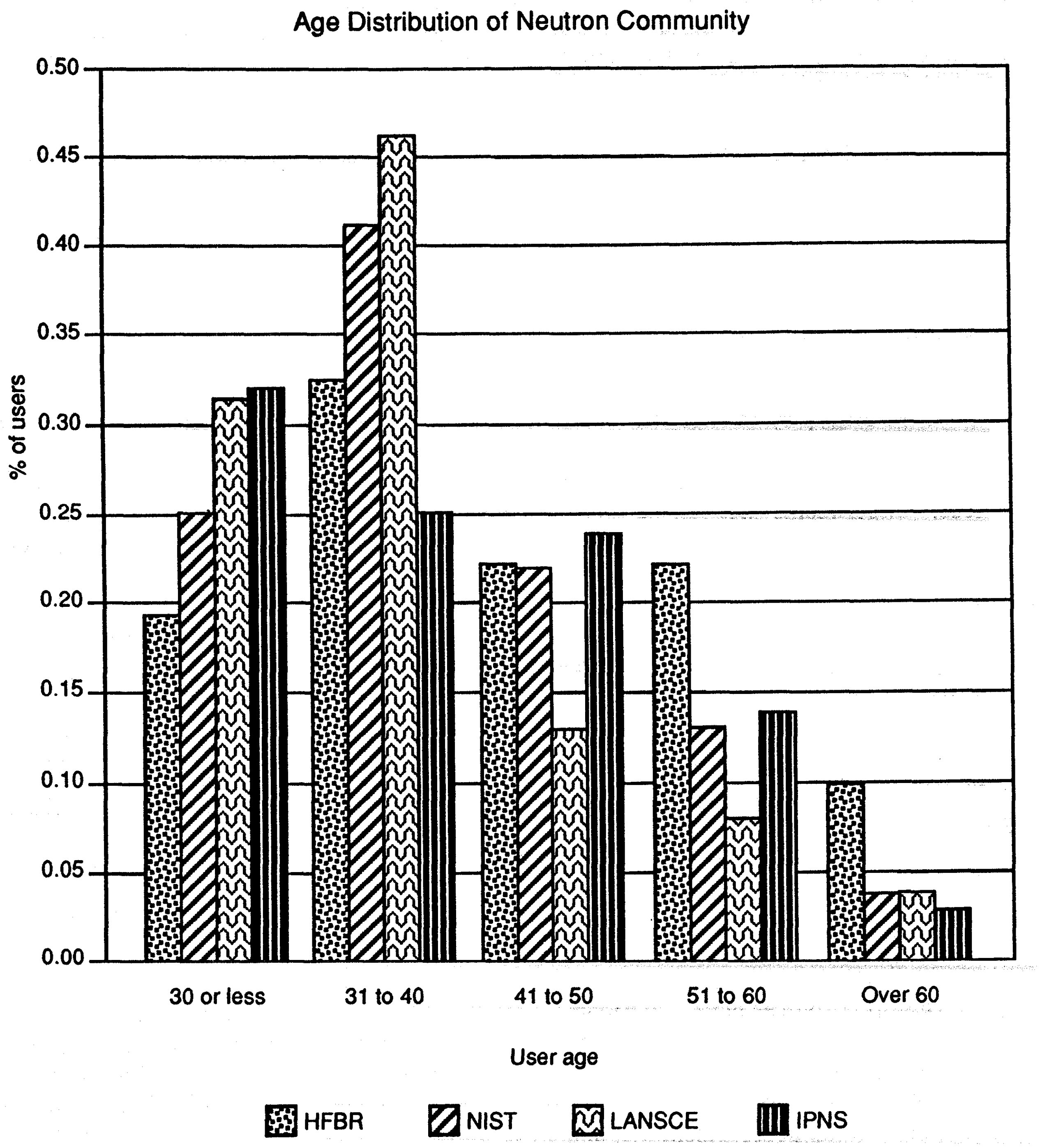

FIGURE 4.1 Age Distribution of the U.S. Neutron Community

in flux, modem instrumentation and beam time availability, the number of users, including students, has increased dramatically. Figure 4.2 compares the increase in users as a function of time after coming on-line for ILL and NSLS. The two curves are remarkably similar. A substantial increase will, no doubt, accompany a new state-of-the-art U.S. source. It is also reasonable to assume that, once a high-flux neutron facility with advanced instrumentation is available, a general population of scientists — with the largest group coming from universities — will move easily between neutrons and photons, depending on the particular needs of the experiment.

Smaller Reactors

The smaller research reactors in the United States, including those at the University of Missouri and MIT, play an important role in neutron research in the United States. The education of students trained in neutron techniques is vital if the new sources prepared in this report are to be effectively used. Part of the instrumentation development should also be carried out at those sources. Experiments that can be done successfully with lower neutron fluxes, as well as preliminary measurements on problems that will eventually be transferred to the major sources, can also be efficiently carried out at the smaller reactors.

Future Needs of Government Agencies

It is clear from the results of the Oak Brook Review and from examination of user patterns in the past decade that both existing and future neutron sources will serve critical needs and missions of a diversity of DOE organizations, which extend far beyond BES. The ANS will be particularly valuable to the Offices of Nuclear Energy and Fusion Energy, while both sources will be of value to the Offices of Health and Environmental Research and Defense Programs. The importance of neutron sources and their funding must therefore be considered in this broad perspective.

High-flux sources have also become increasingly important to the missions and research activities of other government agencies, including the Department of Commerce (DOC), Department of Defense (DOD), and the National Institutes of Health (NIH). This situation presents both an obligation and an opportunity for DOE to actively seek cooperation in research and instrumentation development that could lead to more effective use of these major national resources. Such planning is critical to meet the future national neutron needs of both the private and government sectors, since the number of major sources will be more limited after the year 2000.

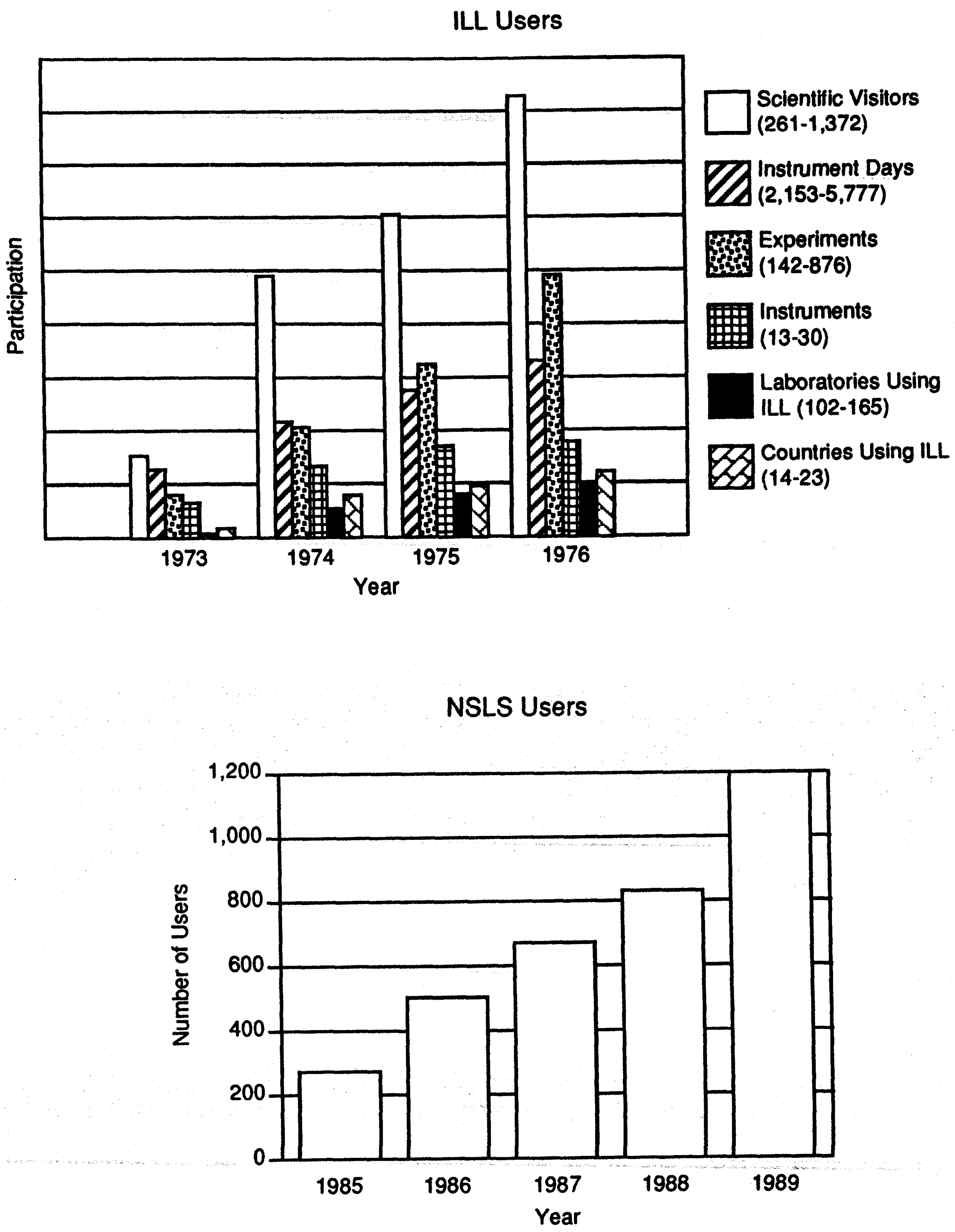

FIGURE 4.2 Number of Users at ILL and NSLS for First Years of Operation

5 Present Status in the United States and Abroad

Over the past two decades, a considerable erosion of the strength of neutron capabilities has occurred in the United States relative to other industrial nations. Since the 1960s, when three major research reactors — HFBR, HFIR, and NBSR — were commissioned, no major, world-class facility has been constructed. By the mid 1970s, the new European reactor at ILL, located in Grenoble, France, which was equipped with an impressive array of tailored cold and hot sources and a broad and innovative assembly of scattering facilities, was already beginning to eclipse the U.S. neutron scattering effort. Since then, the process has accelerated with the advent, in 1980, of a second new-generation reactor in France (Orphée), and the demise of the smaller U.S. reactors at Argonne, Ames, and Oak Ridge National Laboratories. In the field of spallation sources, the story is similar: the pioneering development of these sources began at ANL in the 1970s. It led to the world's first major spallation source, IPNS, and the subsequent development of the more powerful LANSCE facility at LANL. These sources were rapidly overtaken by the British spallation source, ISIS, which was commissioned in 1985 and now stands as the most powerful and best equipped source of its kind in the world. A list of neutron sources in the United States and abroad is given in Tables 5.1 and 5.2.

This situation has been recognized by every national panel that has reviewed the status of neutron sources and science in the United States, starting with the National Academy of Sciences study in 1977 (see Appendix 4). A powerful case was made by the Seitz-Eastman Committee in 1984. After reviewing the situation regarding all major facilities of materials research in the United States, the Committee recommended (1) the rapid construction of a new research reactor with a flux of at least 5.10^{15} n/cm^2•s (the second overall priority after an Advanced Photon Source) and (2) the formation of a deliberate plan toward a major spallation neutron source (the fourth overall priority). Enhancements of existing facilities were also recommended, including (3) the development of new centers for cold neutron research at NIST and BNL (first priority) and (4) a new experimental hall and instrumentation at the LANL spallation neutron source (third priority).

A review of the impact of these recommendations eight years later makes it clear that so far relatively little has been achieved at the DOE laboratories. With respect to (1), a major new reactor, the ANS, which meets or exceeds the required performance characteristics, has been designed but is still awaiting a decision on construction. Regarding (2), no major design work has been funded by DOE, and the limited work performed by the interested national laboratories — ANL, BNL, and LANL — has been funded by the laboratory directors. The major achievements relate to (3), with the commissioning of the Cold Neutron Research Facility (CNRF) ($30 million) at the NIST reactor of DOC, and to (4), with the construction of the new experimental hall ($17.5 million) and instruments at the spallation source at LANL. In addition, only preliminary funds ($2 million out of a total request of $22 million) have been provided to enhance the experimental capabilities for thermal neutron scattering at the HFBR. In summary, substantial design activities and some badly needed improvement of existing sources have been carried out as a result of the recommendations of the Seitz-Eastman Panel, but no new major facility has been implemented.

TABLE 5.1 Major Neutron Sources in the United States

1. Research Reactors

Facility	Year	Thermal Flux/Power	Operation cost ($ million FY 1992)	Operation Schedule (weeks)	Number of Beam Instruments
HFBR (BNL)	1965	10^{15}/60 MW	24	36	–15
HFIR (ORNL)	1966	10^{15}-/85 MW	28	40	10
NBSR (NIST)	1969	4.10^{14}/20 MW	6	40	25
MURR (U. Mo.)	1965	10^{14}/10 MW	5	40	–7
Under consideration:					
ANS		$7.5.10^{15}$/330 MW			

II. Spallation Sources

Facility	Year	Current/ Energy/Target	Operation cost ($ million FY 1992)	Operation Schedule (weeks)	Number of Beam Instruments
IPNS (ANL)	1981	6 kW/^{235}U	6	17	12
LANSCE (LANL)	1985	64 kW/W	10[a]	10	10
Under consideration:					
PSS		1 MW			

[a] LAMPF operations not included.

Notes: (1) All major U.S. reactors are at least 25 years old; also, the spallation sources are based on aging accelerator facilities.

(2) Performance comparisons between research reactors and spallation sources depend on target and moderator design and cannot be made on an absolute basis. Discussion is given in the text and in the Neutron Sources Section of the Oak Brook, Review.

TABLE 5.2 Major Neutron Sources Abroad

I. Research Reactors

Facility	Year	Thermal Flux/Power	Operation cost ($ million FY 1992)	Operation Schedule (weeks)	Number of Beam Instruments
ILL (France) (under reconstruction)	1971	$1.2.10^{15}$/57 MW	23	32	~40
Orphée (France)	1980	3.10^{14}/15 MW	11	40	~20
KFA (Germany)	1962	2.10^{14}/23 MW	15	32	~15
Berlin (Germany)	1991	2.10^{14}/10 MW	12	Starting	~15
Other research reactors in Europe:					
Risø (Denmark), Petten (Netherlands), Studsvik (Sweden)					
JRR-3 (Japan)	1990	3.10^{14}/20 MW	18	32	~20
Under consideration:					
Munich (Germany)		7.10^{14}/20 MW			
KFA (Germany) (replacement of existing reactors)		3.10^{14}/15 MW			

II. Spallation Sources

Facility	Year	Current/ Energy/Target	Operation cost ($ million FY 1992)	Operation Schedule (weeks)	Number of Beam Instruments
ISIS (U.K.)	1985	144 kW/^{238}U	$22	24	13
KENS (Japan)	1980	3 kW/^{238}U	5	9	12
Under construction:					
SINQ (Switzerland)		600 kW[a]			
Under consideration:					
ESS (EEC, site to be determined)		5MW			

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[a] Steady-state spallation source.

Since the publication of the Seitz-Eastman report, several factors have arisen that worsen the U.S. competitive situation relative to the rest of the world. First, a dramatic surge in the range of applications of neutrons has occurred at both ends of the spectrum. For example, cold neutrons have been exploited largely at the best reactor sources with small-angle scattering and spectroscopy to tackle problems relating to the structure and properties of polymers and complex fluids, as well as a host of other scientific and technological areas. Also, higher energy neutrons from spallation sources have been used with great effect to measure the atomic structure and dynamics of new materials. While these fields have been explored to some extent in the United States — particularly at the emerging NIST CNRF and at the IPNS and LANSCE spallation sources — much of the successful work has been carried out in Europe, especially at the well instrumented sources at ILL and ISIS. New research reactor facilities in Germany (HMIR, 1991) and Japan (JRR-3, 1990) are likely to further worsen the competitive position of the United- States. Since 1970, the expenditure in Western Europe on new sourcesand instrumentation has exceeded that in the United States by a factor of 5, while the new JRR-3 reactor center ($300 million FY 1992) recently commissioned in Japan exceeds all U.S. investments for the past 20 years.

Finally, the limited lifetime of the present U.S. research reactors must be pointed out. According to recent estimates, the HFIR may not operate after approximately 2000 because of possible reactor vessel failure, and the HFBR may have to shut down before 2010. Thus, the two major DOE research reactors in this country could be shut down before, or shortly after, a new one can be built, even if a funding decision is made immediately. Given the growing urgency of state-of-the-art neutron facilities, not only for neutron beam research but also for high-flux materials irradiation and production of isotopes for industrial and especially medical uses, this is a prospect of great concern for the U.S. competitive position in science, technology, and medicine. It should be mentioned that, overseas, the ILL and JRR-3 reactors have expected lifetimes of 20 years or more as a result of rebuilt or new reactor vessels, and a major (5-MW) spallation source is being planned in Western Europe along with a new research reactor in Germany.

6 Comparison of Reactors and Pulsed Spallation Sources

Present-day neutron sources are of two types: reactors and spallation sources. Reactors produce neutrons by nuclear fission, while spallation sources produce them from heavy metal targets struck by high-energy protons from an accelerator. In both sources, neutrons are slowed down to the energies required for scattering experiments by appropriate moderator-reflector assemblies, whose configuration and temperature are optimized for the type of experiment that uses them. Reactors operate in a continuous mode and produce high integrated fluxes of neutrons of cold and thermal energies (typically ~1-100 meV) for both scattering experiments and isotope production. Spallation sources are most effectively operated in a pulsed mode (10400 Hz) and give high peak fluxes of cold and thermal neutrons, as well as large quantities of epithermal neutrons (~0.1-10 eV), for TOF scattering experiments. Reactors and, to a limited extent, spallation sources also produce fast neutrons over extensive volumes, which can be used for materials irradiation studies.

As outlined in the previous section, DOE neutron beam facilities have fallen further behind Europe over the past two decades, while the importance of neutrons in scientific, industrial, and medical applications has continued to increase. This section discusses the complementary strengths and limitations of the two kinds of source, followed by a review of the characteristics of the ANS and a proposed new spallation source. The plans for both sources address the growing gap in capabilities between the United States and other industrial nations, which is summarized in Section 5.

The only current technology for the production of neutron-rich radioisotopes uses nuclear reactors. While many such isotopes can be and are produced in reactors of-modest power, isotopes of high specific activity or transuranics require high-flux reactors such as the proposed ANS. Neutron-poor isotopes are produced by proton bombardment. Although the use of such isotopes in medicine and industry is not as widespread as that of neutron-rich isotopes, several important neutron-poor isotopes are produced at contemporary DOE accelerator facilities. Such isotopes could be manufactured at a 1-MW PSS, but neither the power nor the time structure of such a source is essential for this purpose, which uses accelerator protons rather than spallation neutrons.

The Instrumentation Group at the Oak Brook Review projected that a 1-MW PSS would “basically cover” neutron scattering experiments currently done at a reactor such as ILL and provide additional scattering research capabilities at high neutron energies. One source or the other would have an advantage for a particular class of experiments, depending on the energy and wave-vector regime and resolution required. A similar projection applies to comparison of the scattering capabilities of the proposed ANS and a 5-MW PSS.

The Fundamental and Nuclear Physics Group concluded that research involving beams of cold neutrons would benefit from a high-flux reactor because such experiments. require a high integrated flux. The same conclusion applies to neutron interferometry. For research using ultracold neutrons — a field endorsed recently by the DOE Nuclear Sciences Advisory Committee — a 1-MW PSS may have a potential similar to the proposed ANS, but the necessary technology is untried. Other areas of nuclear physics research would profit from either type of new source in different ways, and the two types should be viewed as complementary in those areas.

Most materials irradiation and testing (such as prompt gamma-ray analysis) are undertaken at reactors, which are superior for these applications as a result of their high integrated neutron fluxes. A 5-MW PSS would be required to produce approximately the same time-averaged thermal flux as a present-generation 10^{15} n/cm^{2}•s flux reactor for these applications. However, if the source design is optimized for neutron scattering, such a PSS would provide considerably less time-averaged flux and in a much smaller volume. A few irradiation and testing studies that are complementary to those currently done at reactors can be performed at a 1-MW PSS in cases where the high-energy spectrum of such sources is an advantage. Not all materials testing applications require the very highest neutron flux, so important programs in this area will continue at medium-flux reactors.

Other uses of reactors and PSSs are specific to one or the other and are not directly comparable. Examples are positron annihilation at reactors and muon spin resonance at PSSs.

In its submission to the panel, the Neutron Scattering Society of America reported a poll of its members who “see reactor and spallation based neutron sources as complementary and mutually supporting. Each has unique capabilities . . .” The Panel agrees with this statement.

An important concept for this report is that of a complementary pair of sources of the two types. If a reactor and a PSS are “complementary,” the majority. of neutron scattering experiments can be performed at some level at either source, although some will be more efficiently done on one or the other. In general, one member of a complementary pair will be more powerful overall for neutron scattering. For example, in the complementary pair of the ANS and a 1-MW PSS, the ANS is overall more powerful, but the PSS excels in certain important areas. A similar relation exists between a successful 5-MW PSS and the ILL. Cold neutron research and experiments will be best done at the ANS, while very high resolution powder diffraction will best be done at the 1-MW PSS. Some experiments are performed almost exclusively at one member of a complementary pair. For example, experiments that rely solely on integrated flux, especially those needing cold flux, require the reactor member of the pair. Examples include activation analysis, neutron depth profiling, cold neutron radiography, and an important subset of nuclear and fundamental physics experiments. On the other hand, experiments that need high-energy neutrons require a PSS. Examples are resonance radiography, high-energy transfer spectroscopy, diffraction measurements that require high neutron energies, and a different group of nuclear physics experiments..

The pulsed or continuous natures of the beams produced by the two types of source determine the methods used for neutron scattering experiments, which can often be performed more naturally and efficiently at one source than at the other. Pulsed beams lend themselves naturally to TOF methods, while continuous beams can either be monochromated by crystals or chopped for TOF experiments. For those experiments (most of which are in the field of neutron scattering) that can make optimal use of the time structure of a PSS, the figure of merit is proportional to the neutron flux in the pulse — the so-called peak flux. The peak thermal flux of a 1-MW PSS at 60 Hz, optimized for TOF resolution (see report of the Spallation Sources Group in the Oak Brook Review) would be about twice that of the ANS, For experiments that do not use the time structure, which includes many beam experiments done at reactors, the time-averaged flux determines the figure of merit, and would be typically -100 times lower than that of the ANS.

The complementary advantages of a reactor and a PSS are illustrated by the following examples in which different measurements required to study a particular problem are best done on one or the other source.

Example 1: Powder Diffraction — New crystalline materials are usually produced initially in polycrystalline form, making powder diffraction an important technique for their characterization. Comparative experiments have been undertaken with the same sample at contemporary reactors and spallation sources (D-2B at ILL and HIPD at LANSCE). For example, a measurement with the goal to determine the structure of P-silicon nitride showed that this structure could be determined to a given accuracy 10 times faster by using equipment at the PSS. On the other hand, characterization of the temperature dependence of a *single* magnetic Bragg peak in Bi_2CuO_4 could be done 10 times faster at the complementary reactor source. With the caveat that these comparisons depend somewhat on the quality of the specific instruments chosen, the results suggest that powder diffraction can be done more quickly at the complementary pulsed source for scans requiring an extended wave-vector range, while the modern reactor is superior for measurements over narrower wave-vector ranges.

Example 2: Lamellar CuO_2 Superconductors — Few, if any, materials have ever received such intensive study as the lamellar copper oxides. With subtle changes in composition, these materials evolve from insulating two-dimensional antiferromagnets to rather novel metals that exhibit 3-D superconductivity at remarkably high temperatures. Powder neutron diffraction at both pulsed- and steady-state sources has been essential in unraveling the structures. Extensive experiments probing the static and dynamic spin fluctuations, as well as the phonon dispersion relations, have also been carried out. These magnetic and lattice dynamical excitation studies have almost all been carried out at the best reactors. Experiments at the ISIS pulsed source have provided important information on high-energy (> 100 meV) spin waves.

Example 3: Recent Studies of Buckminster Fullerenes — Studies of this revolutionary new material with the triple-axis and powder diffractometers at the NIST reactor and with the very high resolution powder diffractometer and inelastic scattering chopper spectrometer at ISIS, illustrate the complementarity and need for both types of source. In this case, the best information on the crystal structure and structural phase transformations was obtained by the high-resolution ISIS powder instrument, while the details of the underlying rotational dynamics reflecting the orientational potential and the diffuse scattering due to molecular disorder were better probed by the reactor crystal spectrometers.

***Example 4: Measurements of Residual Strain* —** Because of their penetrating power, neutrons are used with increasing frequency to study strains in engineered structures such as aerospace and automobile engine components, train rails, and oil pipelines. Reactor instrumentation has proven most successful for measurements of large components or for those situations in which 3-D strain mapping is required with high spatial resolution. On the other hand, when several component phases are present, such as in composites, or when strain information is required for different crystallographic planes, the complementary pulsed source is preferred.

***Example 5: Ultracold Neutrons* —** Experiments that require beams of ultracold neutrons (UCNs) (e.g., measurement of the electric dipole moment of the neutron) can be done only at reactors, while experiments that need bottled UCNs (e.g., measurement of the neutron lifetime) could make use of the peak flux of a PSS if suitable instrumentation can be successfully developed.

With today's instrumentation, some neutron scattering experiments can use only one or other of the sources. For example, polymer dynamics can be probed only by using the neutron spin echo technique, which currently requires a cold-source reactor beam. The measurement of momentum distributions in materials such as helium, on the other hand, needs the high-energy capabilities of a spallation source. Similar arguments apply to other scientific areas, such as neutron-rich isotopes or positron spectroscopy at reactors, neutron-poor isotopes, and muon spin resonance at accelerator-based sources.

Reactors permit a far more extensive use of polarized neutrons, which is important both for probing magnetism and for separating coherent and incoherent scattering. The reactor superiority in this case arises because broad-band, neutron polarizers suitable for use with TOF spectrometers have not yet been developed. A potential area of strength for pulsed sources is neutron scattering from samples subjected to very high pressures (much larger than 10 Gpa) or very high magnetic fields (much larger than 20 tesla) that can be achieved only in short pulses. In these cases, the fixed geometry of spallation source spectrometers and the pulsed nature of the neutron beams provide inherent advantages.

Systematic problems (e.g., background, inadequately known corrections, etc.) afflict many neutron scattering experiments both at reactors and at pulsed sources. However, the types of systematic effects are different for the two types of source and it can often be useful to make the same measurement at each type of source in order to confirm that systematic errors are not perverting a result.

While developments of neutron scattering instrumentation (see Section 7) are likely to increase the extent to which each type of source can address scientific issues in the overlap area, such developments are also likely to expand the areas in which each source excels. In other words, the present complementarity of the two types of source is not an ephemeral situation. For example, development of polarizing filters would allow pulsed sources to address scientific problems that currently are accessible only to reactors and would also extend the range of problems to which polarization analysis can be applied at both types of source. The implementation of higher performance multidetectors will have similar consequences.

The reliability and availability of research reactors have proven to be very high. In contrast, spallation sources have been less reliable and generally have taken longer to commission than reactors. In some cases, a major reason has been that spallation sources have been parasitic operations at nuclear physics facilities. In other instances, difficulties have resulted because of insufficient funds. More generally, PSSs pose more complex technical problems. There appear to be no inherent reasons why a dedicated, well-funded spallation source produced as an integrated design should not be sufficiently reliable to support a high-quality neutron scattering program for users.

U.S. Sources under Consideration

Panel members visited each of the major DOE laboratories engaged in neutron research using reactors and spallation sources (BNL, ORNL, LANL, ANL) to review the status of both existing and proposed research and facilities. In doing so, they were briefed on the Advanced Neutron Source Project at ORNL, which recently submitted to DOE a Conceptual Design Report (CDR) based on seven years of design and analysis. Preliminary proposals were also presented at LANL and ANL concerning plans for development of ~1-MW PSSs. (The LANL and ANL presentations also briefly mentioned prospects about a possible extension to 5 MW.) Thus, a mature design exists for the proposed next-generation reactor, the ANS. A detailed cost estimate has been established for the ANS, and there have been no technical issues identified to prevent its realization. No conceptual design currently exists for a spallation source of 1 MW or more. Expert workshops have been held recently that conclude that a 1-MW PSS can be developed successfully with some extension of existing target-moderator technology. The workshops have also noted that cooling the spallation target of a 5-MW PSS is likely to be close to the limit of current technology.

The characteristics of the Advanced Neutron Source as proposed in the CDR are summarized in the Review of Neutron Sources and Applications (Reactor Group), which contains the results of the Oak Brook Review organized by the Panel in September 1992 and is available as a companion document to the Panel Report. In summary, the ANS would provide a maximum neutron flux (7 x 10^{15} n/cm%) six times that of ILL; it incorporates two large cold neutron sources to meet the fastest growing needs in neutron scattering research, a hot neutron source; 14 guide tubes, and eight thermal neutron beams, which would serve 50 neutron scattering and other beam facilities. In addition, about 20 other facilities for isotope production, materials irradiation, positron research, etc., would be provided, along with an extensive infrastructure of chemical and other laboratories, offices, and health physics facilities. The ANS would be the world’s best reactor neutron source and would provide twice the number of instruments and 10 times the capabilities for beam research compared with the two reactors (HFBR, HFIR) it would replace. It is designed to meet or exceed existing and anticipated DOE and Nuclear Regulatory Commission (NRC) safety and environmental regulations, which include a number of requirements for power reactors, such as remote siting and a reactor containment building.

The preliminary proposals presented by LANL and ANL for development of ~1-MW PSSs are also discussed in the Report on the Oak Brook Review (Spallation Source Group). While these proposals differ in detail, both involve the development of sources by using existing components and buildings of the IPNS and LAMPF/LANSCE facilities, as well as the construction of two separate target/moderator areas to allow optimization of beam pulse and moderation characteristics for different applications. This design would allow installation of 30-40 neutron beam instruments, along with facilities for muon research and proton-rich isotope production, which require a proton accelerator. BNL also informed the Panel of their interest in developing a “green field” proposal for a neutron spallation source that would not rely on existing facilities. Studies on this source concept have been initiated. Any of these proposed 1-MW PSSs would exceed the neutron intensity of the existing ISIS Source (in Great Britain) by a factor of about 6. During the construction and commissioning phases of a spallation source using existing accelerator components, neutrons would be unavailable for an extended period. As noted in Section 5, a 5-MW facility (the European Spallation Source [ESS]) is under planning in Western Europe.

As part of its deliberations, the Panel has reviewed the information provided by ORNL and the other national laboratories, along with the completed conceptual design study for the SNQ Spallation Source in Germany (1984). The Panel also asked ORNL to provide cost estimates, based on the extensive analysis contained in the CDR for the ANS, for the alternative development of a straight replacement for the HFIR reactor and for an ILL-type reactor facility. This information is summarized in Table 6.1, along with general assessments of the research capabilities provided by different combinations of neutron sources, which are derived from the Oak Brook Review and the Panel’s own judgments. Comments about the current status and degree of certainty for costs and development paths are also included in the table. The cost estimates shown are for construction of source and instruments in FY1992 dollars and do not include R&D, inflation, or operating expenses during source construction and commissioning. Even assuming the successful development of the ESS, an examination of Table 6.1 shows that, after 2000, the United States would remain fully internationally competitive in neutron scattering and superior in other applications by developing both the ANS and a powerful spallation source (see Section 9).

It is the view of the Panel that the most important neutron scattering research uses cold and thermal neutrons (approximately less than 100 meV), which are available in beams from both reactors and spallation sources. Neutrons, in this energy regime, are frequently a unique and irreplaceable probe. (All the awards listed in Table 3.1 relate to research using low-energy neutrons.) Their importance is rooted in the nature of condensed matter and its characteristic interatomic and intermolecular structure and dynamics. Epithermal neutrons (energies approximately greater than 100 meV), which are much more readily available for neutron scattering research at PSSs, also have important applications in materials research, but overall are considerably less important than lower energy neutrons.

TABLE 6.1 DOE Neutron Source Combinations: Costs and Capabilities*

	Option	Cost[a] ($ million FY92)	Neutron Scattering[b]	Isotope Production[c]	Materials Irradiation[c]	Other Uses[d]	Comments	Earliest Completion Date for Construction[e]
1	ANS[f] + 1-MW PSS[g,h]	2,200	5	5	5	5	Best scenario; United States at forefront in all areas; serves broadest community	2002
2	ANS only	1,500	4-	5	4	4	United States at forefront of steady-state research and applications, but behind in spallation source research	2002
3	5-MW PSS only[g,i]	1,000-1,500	4-	2	2	2	At forefront in neutron scattering; no isotope or materials irradiation capability at high neutron flux; no operating reactors when HFBR and HFIR shut down (≈2005)	(uncertain)
4	HFIR[j] + 1-MW PSS	1,500	2	5	5	2	Same cost as ANS, but most important uses severely restricted; United States not competitive in next century	2000
5	HFIR′ + 5-MW PSS	1,800-2,300	4	5	5	3	Same capabilities overall as ANS only, but at greater cost; some important fields not covered	(uncertain)
6	ILL′[k] + 1-MW PSS	1,900	3	2	2	2	Worse than other less costly options in all areas	2002
7	ILL′ + 5-MW PSS	2,200-2,700	5	3	3	4	Better than option 6, but more costly than better options	(uncertain)
8	1-MW PSS only	700	2-	1	1	1	Leaves United States behind in all areas if ESS were built; no high-flux isotope or irradiation capability	2000
9	HFIR, HFBR, IPNS, LANSCE		2-	5	4	1	1992 situation	
10	HFBR, IPNS, LANSCE		2-	1	1	1	Possible 2001 situation	
11	IPNS, LANSCE		1	0	0	0	Possible 2007 situation	

Footnotes on next page.

TABLE 6.1 (Cont.)

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[*] The numbers given in the columns labeled Neutron Scattering, Isotope Production, Materials Irradiation, and Other Uses are rough figures of merit, which take account of complementarity but do not always scale with quantitative capability, nor do they take into account the relative importance of different applications.

[a] Costs given are in FY1992 dollars for construction only, including instruments. No R&D or operating expenses during construction and commissioning are included; for the ANS, these expenses will increase the total cost to ~\$1.9 billion (FY1992), assuming construction according to the project schedule; for the PSS, the corresponding cost increases have not been estimated. Anticipated operating costs scale approximately with construction costs for a given type of source. At a given cost the reactor will provide more capability in other uses beyond neutron scattering.

[b] By far the most important scientific use of neutron sources.

[c] Central mission areas for DOE; critical in medical and technological applications.

[d] Very important secondary uses of neutron sources, including neutron depth profiling, materials analysis, fundamental neutron physics, and interferometry.

[e] This date indicates earliest completion of construction. Full operation of the reactors for neutron research would likely occur in this year. Experience suggests that availability of a constructed spallation source for neutron research near design-goal performance levels may not occur until several years beyond these dates.

[f] ANS is the fully developed concept of ORNL for a steady-state reactor with 7×10^{15} n/$\text{cm}^2 \cdot$s (six times the neutron flux and more instrumentation than the ILL); full CDR complete. Cost estimate reflects likely cost savings identified since June 1992. It is agreed that HFBR and HFIR will cease operation when the ANS is operational.

[g] PSSs are identified by the power in the beam. These sources use short pulses of protons impacting on a heavy-metal target to produce short bursts of neutrons. The steady-state flux is low, but the peak flux is higher than at a comparable reactor.

[h] The 1-MW PSS is an extrapolation (six times) of the existing ISIS source. The cost estimates are less certain than for the ANS. There may be significant reductions because of the use of existing components or buildings. The Spallation Source Group of the Oak Brook Review felt that the ANL and LANL estimates, which were on the order of \$500 million (FY1992), were reasonable. However, on the basis of recent cost escalations beyond such preliminary estimates for other major facility construction, the Panel believes that this cost will increase considerably with more refined estimates. (Panel representatives from ANL and LANL believe that the construction cost estimate of \$700 million is too high.)

[i] The 5-MW PSS will require substantial R&D. No such source has been designed. The cost estimate is the result of scaling a 1984 estimate for the German SNQ 5-MW PSS (which was not short burst). The costs have been converted at 1.7 DM/\$ (\$1,400 million, FY1992). New accelerator developments may reduce accelerator costs, but more complex, multiple target/moderator design and more instrumentation will increase costs. Therefore, \$1,000 to \$1,500 million is used, although this estimate is very uncertain and may exceed even the upper limit. Operating costs would be similar to the ANS.

[j] Reactor to replace the existing HFIR reactor to meet current standards with no improvement in performance.

[k] Equivalent of the existing ILL reactor in Grenoble, built to U.S. standards; it includes all instruments and facilities.

In what follows, the ANS will be compared with a proposed 1-MW PSS and a projected 5-MW PSS.

For cold and thermal neutrons, the relative merits of the sources vary with applications, as discussed in the examples given above. Compared to a 1-MW PSS, the ANS would be superior for most neutron scattering research, including cold neutron research; studies of structure and excitations (less than 100 meV) of crystals and ordered materials; studies of structural and dynamical features requiring limited ranges of wave vector Q and frequency ω; and probably for thermal neutron polarized beam research on magnetic and molecular materials. The 1-MW PSS would be superior for high-resolution powder diffraction over an extended Q range and in extreme environments, and for inelastic scattering studies requiring a wide range of Q and ω for polycrystalline and disordered systems.

Either PSS would far surpass the ANS for most neutron scattering and nuclear physics requiring epithermal neutrons (and for materials irradiation requiring neutrons above fission energies).

The most influential scientific work with neutrons in the past two decades has been in the area of cold neutron research on polymers and complex fluids and in studies of the physics of new materials using triple-axis spectrometry (see Table 3.1). This work was done at reactor sources. The Panel believes that cold neutron research and triple-axis spectrometry will continue to play a central and unique role in U.S. science well into the future. They will have increasing impact on virtually all classes of materials, including polymers, biomolecules, and magnetic materials. The ANS would be decidedly superior for these researches compared with a 1-MW PSS and most likely superior to a successfully developed 5-MW PSS (e.g., the proposed ESS in Europe). A successful 5-MW PSS would probably match or exceed the ANS for most other neutron scattering research. These comparisons must be tempered by the uncertainties associated with the development of a 5-MW PSS and related instrumentation. Prospects could be enhanced by major advances in devices and data handling or diminished by technical problems in accelerators or target/moderator assemblies.

There are great and growing contributions of neutron scattering in other areas. Examples include the structure and spectroscopy of catalysts and superconductors, materials science applications in structural materials, and the recent exciting progress in neutron reflectometry studies of surfaces and interfaces — all of which have greatly benefited from complementary work at reactors and spallation sources. The application of spallation sources for TOF diffraction, spectroscopy, and reflectivity have made crucial contributions to much important work in these and other areas, including outstanding powder diffraction studies (e.g., of high-T_c superconductors). Thus, development of a complementary spallation source is also essential for the future.

Finally, the ANS will be decidedly superior compared with a 1-MW (or 5-MW) PSS for other very important uses of neutrons, which often serve central DOE responsibilities and rely on integrated neutron flux, such as isotope production, materials irradiation, neutron depth profiling, prompt-gamma spectroscopy, and fundamental low-energy neutron physics.

7 Instrumentation Development

The size, complexity, and cost of a neutron source and its associated shielding, whether reactor or accelerator based, is so large that it is difficult to keep in perspective the fact that it is only the first element of a usable neutron research facility. Without an appropriate matching investment in instrumentation, the power of the facility can be severely compromised. As noted in the Instrumentation Section of the Oak Brook report — and the observation is not new — the successes of ILL, which is widely regarded as the premier neutron research, facility in the world, did not result only from the design of the reactor, which produces about the same flux as existing U.S. high-flux reactors. The technical innovation was in instrumentation, cold neutron moderators to enhance the cold neutron production, and extensive use of neutron guides to increase the number of instruments that could be employed. These technical developments enabled the growth of a large user community. To ensure the success of a next-generation neutron facility as a research tool for the U.S. community, it is essential that the instrumentation be optimized with respect to number and diversity and be of the highest quality.

Over the years, ILL has also recognized the importance of periodic upgrading of instrumentation. The ILL has financed one major reinstrumentation effort during the first 10 years of operation and is presently planning for another. Most other major European and Japanese neutron facilities have made large investments in neutron instrumentation over the past decade. The NIST is in the process of completing a new cold-neutron guide hall, which has greatly invigorated their program. By contrast, long-standing recommendations from high-level committees for funding to upgrade neutron instrumentation at existing DOE facilities have gone largely unheeded. A corollary to the relative lack of past instrumentation activity in the United States is that a generation of neutron scientists has grown up without adequate experience in instrumentation design. Such activities are viewed-by some as low prestige, unrewarding activities — quite unlike the perception in Europe.

Although it is not yet time to lock into final designs for instruments to be completed in a decade, the size and complexity of the needed instrumentation development relative to the available talent and infrastructure substantiate the argument for immediate and continuous activities in this area for the foreseeable future. The design of 40 or more world-class instruments, which is beyond the capabilities of any single laboratory, must be national in scope and draw on the talents of all existing DOE and non-DOE facilities. The most cost effective way to initiate this activity is through funding for upgrades of outmoded instrumentation at the existing facilities. The instrument concepts so developed, and in many cases the instruments themselves, can be transferred to a new source at an appropriate time. The existing facilities should also be encouraged, where appropriate, to develop several dedicated instrumentation beamlines to serve as a national resource for instrument development that would be accessible to the entire community (probably on a peer-reviewed basis).

The Panel also endorses a suggestion, made by the Pincus Committee (DOE 1988), that the Neutron Scattering Society of America form an instrumentation panel of knowledgeable representatives from several laboratories. By meeting a few times a year, this panel could digest and disseminate new instrumentation concepts, discuss and generally raise user interest in instrumentation issues, and make recommendations to the community and funding agencies regarding the coordination of immediate and future instrumentation needs.

Opportunities in Neutron Instrumentation

Extensive surveys of opportunities in neutron instrumentation are presented in many reports, including the Proceedings of the Shelter Island Workshop [Nuclear Instruments and Methods in Physics Research B12 (1985) 525-561], and are discussed biannually at the International Conferences on Advanced Neutron Sources (ICANS). Examples of the consequences of the lack of existing instrumental capabilities in various fields of study have been discussed in Section 5. The present section documents a few important specific examples of developments that will widely impact the design of future instruments for both reactor and pulsed sources and that will require immediate activity to ensure that developments come to fruition in time for next-generation sources.

It is important to recognize and encourage developments in the general field of neutron optics. Neutron optics includes techniques to transport, focus, monochromatize, polarize, or otherwise manipulate the state of a neutron beam. Neutron guides, which have proven so valuable in increasing the utilization of cold neutrons, have not proven useful for thermal neutrons. The advent of supermirror coatings is about to change this condition. The acceptance angle for a 2.5-Å neutron in a conventional nickel guide is 0.25°, which is too small for most purposes. However, supermirrors with three times that acceptance have been fabricated (although not in quantity), and supermirrors with four to five times that acceptance may be achievable in the near future. With such guides, thermal neutron beams can be multiplexed to accept several instruments instead of only one. This concept could be widely adopted at any next-generation source, and should be proven at existing sources, with substantial and immediate increases in overall neutron utilization. At present, supermirrors are available only in relatively short lengths and are used as beam filters and focusing devices (antitrompette). Production of 0.5-m-long supermirrors with three times the conventional acceptance will require an investment (~$2-5 million) in improved sputtering equipment..

The improvement of single-crystal monochromators is an area where modest investments can be expected to provide quick payback. Synthetic pyrolytic graphite and crystals of plastically deformed metals are in routine use but are not ideal. Specialized instruments call for other materials. In spite of efforts to improve them, existing beryllium crystals, important as hot neutron monochromators, are too imperfect. On the other hand, germanium and silicon, which are widely available and relatively inexpensive and have other desirable properties, are too perfect. Recently, progress has been made in fabricating germanium wafer composite crystals with controllable anisotropic mosaic spread. However, many other promising ideas, such as bent crystals and d-spacing variant crystals that increase the wavelength acceptance without increasing the mosaic spread, remain to be explored. The overall goal is the selective independent manipulation of these various monochromator properties to allow the design of neutron instruments with presently unachievable characteristics.

Cold neutron polarization analysis is currently at a level of development where it is not quite routine and the next-generation source should see it cross that threshold. Magnetic supermirror coatings are becoming sufficiently good so that transmission polarizers are now possible, but more work needs to be done on the divergent beam optics of these devices if they are to be generally useful in real beam applications. Beam-splitting devices, such as polarizing Y-guides, should be considered for beam transport to polarized instruments. Encouraging developments have been made in polarized ^{3}He filters that transmit a white beam of-only one spin state. Such devices would remove a principal obstacle to the widespread use of polarized neutron techniques at pulsed sources.

Increasing the rate of a detector generally provides another way to improve the efficiency of an instrument. Position-sensitive detectors (PSDs) with reduced deadtimes (presently 5-10 µs for ^{3}He gas-filled detectors) and increased spatial resolution (presently 1 mm) are necessary for the higher data rates expected in next-generation sources. Present-day scintillation detectors suffer from high gamma sensitivity or self-opacity. A promising direction for future research may lie in the development of plastic or liquid organic scintillators containing ^{10}B or ^{6}Li, which have dramatically short (1 ns) deadtimes, Such detectors would also be much less expensive and easier to fabricate than existing gas-filled PSDs. The neutron community can profit from ongoing detector developments in the high-energy physics and synchrotron x-ray fields. The parallel development of improved high-spatial-resolution detectors and focusing optics will provide the impetus for new applications involving neutron imaging. For example, 3-D neutron microtomography will facilitate the study of percolation of fluids in porous media — a field of tremendous importance to the oil industry.

8 Prerequisites for a Successful Source

Dedicated Use, Predictability and Reliability

Successful operation of a major scientific user facility, such as a neutron source, imposes stringent requirements on the technical and administrative set-up of the facility. This section presents recommendations for criteria that must be met in the planning, design, and operation of a successful neutron user facility.

Neutron research and application needs are of such importance and magnitude that they must be clearly designated as the principal missions of the new sources. This matter is especially sensitive for accelerator-driven sources, such as spallation sources, where the experience has been often unsatisfactory because facilities for materials science research have operated in a nondedicated mode, in competition with high-energy or nuclear physics. A case in point is the synchrotron radiation laboratory at SLAC, where operating conditions used to be very unsatisfactory, but have been satisfactory since it became a dedicated facility for x-ray science. Two kinds of problems arise in the operation of a nondedicated facility. *Institutional* problems develop because such an operation does not have a priority call on the host institution's financial, human, and physical resources. *Technical* problems can arise because unacceptable technical compromises are made in design and operation. A spallation source operated on an accelerator substantially diverted for particle physics research or other major applications cannot function as a first-class neutron research facility.

Another point concerning priority is that technical choices for a new facility must appropriately reflect the priorities within the various planned neutron applications. For example, the highest priority use of a new high-flux neutron source is unquestionably neutron scattering, which has the highest overall scientific importance as well as the most stringent requirement on performance. This priority should be reflected in the design of any new facility. For example, the retrofitting of a reactor designed primarily for isotope production or materials testing in order to provide neutron scattering capabilities — as in the case of the present HFIR — is inadequate to meet the needs outlined in this report.

Sources should operate with high availability, predictability and reliability. *Availability* refers to the fraction of the year that the source is scheduled to operate for neutron research. For the present U.S. spallation sources, these fractions are woefully inadequate: for financial and/or technical reasons, they typically run for 3-4 months per year, compared with 8-10 months for reactors. Given the thousands of experiments to be performed annually, it is essential that neutron beams be scheduled for 9-10 months per year for each of the major sources in the United States. *Predictability* means that scientific users with an accepted experimental proposal should be informed about the dates of their experiment with sufficient notice to allow for appropriate planning with regard to the availability of samples and apparatus, as well as the arrangements for travel and housing. These dates should be respected by the facility. These considerations are important for all users, but especially for academic faculty and students with class schedules that must be arranged well in advance. In particular, down periods lasting a significant fraction of a typical run time should be kept to an absolute minimum. In the past, research reactors have operated with predictability factors (actual/scheduled operating time) in excess of 90%, and this has also been met by some smaller spallation sources such as IPNS. The corresponding factor at the world's most powerful spallation source, ISIS in the United Kingdom, has been 75-80%, which has resulted in significant difficulties — especially to university users. A figure of 85% should be considered a minimum acceptable level and should be imposed as a performance specification in the design and planned mode of operation of any new neutron source. *Reliability* means that the source operation and performance should be maintained continuously and remain close to that which the user has been given to expect, Reliability is an especially important consideration in the case of spallation sources.

User Issues

The ability to perform experiments in an efficient and predictable manner is the key to successful operation of a neutron facility. Of paramount importance is the development of a user-friendly facility. It is not sufficient to provide a source designed specifically for the needs of those skilled in the field. An advanced source must be readily accessible to a broad user base, including experts in the field (i.e., those researchers who base their research on neutron sources) as well as casual users of neutrons. The more accessible and easier a source is to use, and the fewer impediments in the way of actually performing experiments, the more useful and productive a source will be.

To this end, it is necessary for all qualified users to have ready access to the experimental station. This requirement necessitates a careful design of the source to eliminate potential security risks and radiation hazards which could present substantial obstacles in experiment accessibility. Procedures for rapid access of all users, including foreign nationals, to the experimental facilities must be developed. Also, access training must focus on' needs and take advantage of the educational level of the trainees.

In line with the development of a truly user-friendly source, general user facilities, as well as participating-research-team (PRT) beamlines that are designed, operated, and funded by individual scientists to meet specific needs, are required. The needs of the broad user base can be met only in this manner. The PRTs, particularly those that combine industrial and academic efforts, are especially important because multiple needs are fulfilled. Such beamlines not only provide competitive advantages to American industries, but also stimulate academic/industrial interactions and promote the training of young scientists. Although many researchers are not willing or able to make the commitment necessary to become involved in a PRT, they still require the use of neutrons to solve specific problems. Consequently, from an academic and industrial viewpoint, it is essential to provide instruments/beamlines that are simple to use and from which useful results can be obtained. It is clear that neutron research will impact a very large number of communities; however, the extent of the impact and the usefulness of a neutron source will be far below its potential unless the needs of the users are taken into account.

International Cooperation

The Panel feels strongly that collaborative research and exchange of ideas with foreign scientists is highly productive and essential for the scientific enterprise. Thus, new sources in the United States should be open to proposals for use by foreign scientists, just as U.S. researchers are currently granted use of ILL and ISIS, for cooperative research. Proposals with U.S. participants should be given preference. Of course, the use of special capabilities of new U.S. facilities by foreign companies for proprietary research should be subjected to different guidelines that include — as they do for U.S. firms — the payment of full cost recovery for source and instrument operational expenses, as well as any other conditions that are deemed appropriate if questions of technological competitiveness arise.

It should also be noted that some savings in both cost and time, as well as improved measurement capabilities, can be attained by cooperative development of neutron instrumentation and devices with foreign organizations. Such collaborative arrangements should be sought, along with agreements, where appropriate, for shared funding and use of special U.S. facilities (e.g., for isotope production and materials irradiation). The possible participation of foreign countries in the construction of U.S. neutron sources will not be discussed in this report.

Environment, Safety, and Health Regulation and Management

The Panel believes that DOE must improve its management structure to effectively manage and regulate the construction of the type of facilities considered in this report. The discussion below on environment, safety, and health (ES&H) pertains to both the proposed facilities, while the discussion on regulation and management primarily refers to the ANS.

1. *ES&H:* The DOE has placed tremendous emphasis on ES&H in the past several years, and this effort has rightly increased the awareness of these problems in the laboratories. Clearly, ES&H are critical issues for any facility involved with nuclear radiation, but the hope is that more efficient processes than the current plethora of DOE directives and regulations can be put in place. Over the past five years, ES&H changes have very greatly increased operation costs of the HFIR and HFBR. It appears to the Panel that, in many cases, more elaborate procedures than necessary have been introduced. An effective management process for ES&H programs that carefully factors in risk assessment to balance costs versus benefits is essential. If not, the costs of construction and operation of the proposed facilities could become prohibitive.

2. *Regulation:* So far, DOE has not established the process to regulate the construction or operation of the ANS from a nuclear safety point of view. Plans must be put in place for this function. The ANS has been designed to meet NRC regulations, but DOE has not stated whether this criterion is acceptable. All experience of the nuclear industry demonstrates that it is

extremely expensive, as well as very risky in terms of schedule, to change regulations after the project is under way. The DOE needs to establish the regulatory process and work with ORNL to ensure that the design will satisfy the proposed regulations.

3. *Management: The* Panel perceives that a management structure in which the Office of Energy Research (OER) is responsible for the funding and technical program of the ANS while the Office of Nuclear Energy is responsible for the construction is likely to lead to difficulties in the future. The Panel submits that one organization needs to be responsible for funding, cost control, and construction. Since OER is the end user of the ANS and must provide the funding justification, it is the Panel's view that they should also provide management of the project. Other offices within DOE should provide independent oversight of nuclear safety, quality assurance, and similar concerns, as appropriate.

9 Findings and Recommendations

Summary of Findings

1. Neutrons have become an indispensable tool for large areas of physics, chemistry, biology, and materials science. Cold and thermal neutron scattering is the most important scientific use. (In the last decade, 13 major scientific awards were strongly related to low-energy neutron scattering research.) For example, neutrons are especially useful for the study of light atoms (H, O, C, ...) in chemical and biological materials and of excitations in condensed matter.

2. Much of the scientific research using neutrons has had, and will have, large technological and economic payoffs. Examples are plastics, magnetic materials, and high-temperature superconductors. Generally, neutrons are a critical research tool for the development of new and better materials.

3. Neutrons are also used for many practical measurements of direct technological and industrial value such as radiation damage of reactor and fusion devices, impurity and defect distributions in semiconductors and structural materials, analysis of stress distributions in metals and ceramics, etc.

4. Neutron science and applications are intensity limited, in large part because neutrons interact very weakly with matter. Thus, major advances have been, and will be, directly associated with increased fluxes.

5. Neutron sources are of two types: reactors, which produce neutrons by nuclear fission, and the newer PSSs, in which neutrons are emitted by targets struck by high-energy protons.

6. For neutron beam research, reactors provide predominantly low-energy (1-100 meV) neutrons continuously with a high time-averaged flux; PSSs produce high intensity bursts of neutrons with a large high-energy (>l eV) component but relatively low average flux. The bursts are especially appropriate for TOF measurements. Reactors are more appropriate for applications that require very low energy neutrons and/or high total intensity. The two types of source are complementary.

7. Radioisotopes for many essential medical and technological applications are primarily produced by reactor neutrons, A smaller class of radioisotopes are produced by proton accelerators, including those of PSSs. Radioisotopes also have many important industrial applications in radiography. Medium-flux reactors can produce many isotopes. A very high flux reactor is required for transuranic and

high specific activity isotopes and can, if necessary, produce all neutron-rich isotopes.

8. The two major DOE reactors, HFBR and HFIR, were built more than 25 years ago and have remaining possible lifetimes estimated at approximately 10 to 20 years. The HFIR's status is the more precarious. Their capabilities for neutron beam research were eclipsed by the European reactor at ILL, Grenoble, beginning about 20 years ago.

9. The American PSSs — IPNS at ANL and LANSCE at LANL — have been overtaken by the British ISIS, which was commissioned, in 1985.

10. Europeans have also dominated recent developments in neutron scattering *instrumentation,* particularly at ILL and ISIS, in spite of the excellent emerging cold neutron research facility at NIST and more modest investments at other American facilities.

11. The U.S. investment in neutron facilities since 1970 has been exceeded five-fold by the Europeans. Furthermore, Japan's $300 million (FY 1992) investment in the JRR-3 reactor center exceeds all U.S. investment in recent years.

12. Table 6.1 shows the capabilities and costs of possible new U.S. sources and their combinations.

13. Dedicated use, predictability, and reliability are key aspects of any successful major neutron user facility.

14. As of the writing of this report, continued operation of the LAMPF accelerator for the LANSCE spallation source at LANL is still in question for FY 1994. In the past, LAMPF has primarily been operated for and supported by DOE's Division of Nuclear Physics.

15. The IPNS at ANL has been a successful and reliable source. Its current operating period of about 15 weeks per year could be approximately doubled at the cost of an additional $4 million per year.

16. Upgrading the instrumentation at the two DOE reactors, especially the HFBR, presents an opportunity for enhancing neutron scattering research in the United States and developing needed instrumentation for the ANS. Similarly upgraded instrumentation at the DOE spallation sources can be transferred to a future PSS.

17. R&D is critically needed in many areas of instrumentation, especially neutron optics (transport and manipulation of beams), monochromators, polarizers, and detectors.

18. Effective and stable management and regulatory procedures are critically important for the efficient and cost-effective construction and operation of major facilities.

Recommendations

As a technologically leading nation, the United States urgently needs to construct a complementary pair of neutron sources: a next-generation research reactor and a powerful PSS. These facilities are essential to maintain or reestablish U.S. leadership in broad areas of physical, biological, and materials sciences, in radiomedicine, and in associated technologies. While the required investment is substantial, the payoff in terms of both directly associated jobs and enhancement of the nation's technological and economic power will be much greater and will extend far into the next century.

Recommendation 1: Complete the design and construction of the ANS according to the schedule proposed by the project.

Recommendation 2: Immediately authorize the development of competitive proposals for the cost- effective design and construction of a 1-MW PSS. Evaluation of these proposals should be done as soon as possible, leading to a construction timetable that does not interfere with rapid completion of the ANS.

Because the ANS is the highest priority, the construction of the PSS should not interfere with its development. If the ANS is not built, a 5-MW PSS would be needed to basically cover its capabilities in neutron scattering. Other essential capabilities of the ANS would not be available.

Considerations relating to these recommendations are:

1. The agreed-on need for a new, powerful reactor, alone capable of producing transuranic isotopes and unmatched for triple-axis spectroscopy, cold neutron research, and other essential applications.

2. The advanced and highly satisfactory design of the ANS would result in the world's best neutron source. The design meets or exceeds currently projected NRC and DOE safety and environmental regulations. It will also contribute to future nuclear power technology.

3. Failure to proceed rapidly with the ANS would lead to the loss of transuranic isotope production and other isotope and irradiation applications that require very high neutron flux, perhaps by the year 2000.

4. The HFBR and HFIR would shut down when the ANS comes on-line, offsetting the ~$80-million annual operating costs of the ANS by ~$60 million.

5. The combination of a ~7 x 10^{15} neutrons/cm^2•s flux reactor and a 1-MW PSS would complement the anticipated European configuration of a rebuilt ILL reactor (~1.2 x 10^{15} neutrons/cm^2•s; less powerful than the ANS) and the ESS (a planned 5-MW PSS, more powerful than the proposed U.S. PSS).

6. The ANS will provide functions that are vital to a number of central mission programs in DOE besides those in BES. These functions include production of isotopes for diverse applications and materials irradiation for development of fission and fusion power. The construction cost should be justified on a department-wide basis.

7. High-flux neutron sources have also become increasingly important to the mission and research activities of other U S government agencies, including DOC, DOD, and NIH. There will be fewer neutron sources in the United States to serve a growing need after the year 2000. Thus, there is both an obligation and an opportunity for DOE to actively plan to serve the needs of other agencies and, as ANS and PSS construction proceeds, to seek cooperation in research and instrumentation development that would lead to more effective use of these major national resources.

8. The commercial use of neutrons for medical isotopes, materials analysis, depth profiling, etc., would help to pay for operating costs.

9. Availability, predictability, and reliability are of the essence for neutron beam research. Since the latter activity is the strongest motivation for any new neutron source, the design of such a source must ensure availability, predictability, and reliability, and other uses of the facility must not be allowed to compromise these essential features. For example, accelerator components of the PSS should not substantially be diverted for other purposes, and a reactor’s isotope and irradiation facilities must not significantly reduce its usefulness for beam research.

10. Several DOE laboratories with major credentials in accelerator design and neutron science and different scientific infrastructures have strong interests in proposing a 1-MW PSS. The nation would be best served by having a

rigorous technical and economic comparison of proposals from these laboratories available before design and site selection. Each of the interested laboratories should be given the opportunity to develop a proposal of sufficient detail to allow meaningful comparisons. Input from the user community should be sought and given great weight by DOE.[†]

11. The 1-MW PSS would exceed the world's current most powerful spallation source capabilities by a factor of about 6 and assure U.S. competitiveness for important areas of thermal and epithermal neutron science in the future.

12. The 1-MW PSS would offer the possibility to participate in the developing technology of better and more powerful spallation sources.

13. Rapid completion of both projects would be most cost-effective and limit the era of U.S. backwardness in neutron facilities to no more than approximately 25 years.

14. Examination of alternative possibilities for future DOE neutron sources shows that any plan to serve DOE and national needs without an ANS-type beam reactor would be unsatisfactory and not cost-effective. Thus, an approach that would combine a possible future 5-MW PSS (if successfully developed) with a new HFIR reactor would provide capabilities comparable overall to the ANS alone (e.g., much better at high energies but considerably worse for a number of important beam research areas, particularly with cold neutrons), but at a considerably greater estimated cost of construction and operation (see Table 6.1). Compared with the Panel's recommended complementary pair, the latter combination would provide significantly lower capability in neutron beam research at about the same overall cost.

15. The Panel recognizes the scientific merit of a dedicated 100-µA spallation source, as recently proposed by LANL, and believes that LANSCE could be run effectively in this mode. (This proposal may no longer be active.) However, the proposal to construct and operate a dedicated 100-µA neutron source by using the LAMPF linac is not a cost-effective option when compared with the funding levels and opportunities at other U.S. neutron facilities. If LAMPF continues to operate with funding from other sources, the Panel recommends that BES continue to support LANSCE at approximately the current level.

[†] The two nonvoting Panel members from LANL, H. Frauenfelder and R. Pynn, disagree with the recommendation of competitive proposals for the PSS as unnecessarily delaying its construction.

16. The recommended construction program requires special appropriation and should not be carried out at the expense of individual investigators. While neutron sources for research are by their nature large facilities, they are used primarily to conduct small science experiments.

Recommendation 3: Enhance operation and instrumentation of existing neutron sources.

Enhancement of existing sources and instrumentation is urgently needed as part of the transition to the world leadership role that would result from Recommendations 1 and 2. These enhancements are also urgently needed to prevent the serious decline that could occur over the next decade while the new sources are developed.

The following considerations are related to this recommendation:

1. The IPNS has had an outstanding history of cost-effectiveness and reliability over the 10 years it has operated. Present budget levels severely limit the operating time of this facility (projected to be only 15 weeks in FY 1993). An addition of $4 million to the IPNS operating budget would allow it to approximately double its operating schedule. As discussed below, this increase becomes especially urgent if LAMPF, and thus also the LANSCE spallation source, are shut down at the end of FY1993 as a result of LAMPF’s decreased priority in nuclear physics.

2. Improved effectiveness of existing sources can also be achieved by modernized instrumentation and by increased power levels. The highest priority for capital equipment funding is the $20-million upgrade of the neutron instrumentation at the HFBR reactor. It should be noted that cold neutron instrumentation at research reactors was the highest upgrading priority of the Seitz-Eastman report in 1984: cold neutron instrumentation has been. successfully developed at NIST, and the HFBR upgrade represents a similar opportunity for thermal neutrons. Also, in view of the general disadvantage of the United States *vis-à-vis* Europe in research reactors, a prompt return of the HFBR to full-power operation is essential. The HFBR instruments will be transferred to ANS at an appropriate time.

3. If, as a result of Congressional or other actions, LAMPF continues to operate in FY1994 and beyond, the Panel gives the increase in operating schedule for IPNS lower priority than the HFBR upgrade. LANSCE can then continue to meet part of the demand for spallation source neutrons.

4. Development of spallation source instrumentation is also essential. For example, IPNS capabilities can be increased by a factor of approximately 2-3 by an investment of $8 million in instrument enhancement, solid methane

moderators, and new spectrometer development. Instrumentation developed at existing sources could be transferred to a 1-MW PSS when completed.

5. The full utilization of the present U.S. research reactors can be achieved by also enhancing the instrumentation at HFIR, both for ongoing neutron research and for development of new instrumentation concepts and components for the ANS.

Recommendation 4: Devise a strategy for sustained R&D of neutron instrumentation.

As a first step, the Panel recommends that a program in neutron optics be funded to explore and develop promising techniques for transporting, focusing, polarizing, and otherwise manipulating neutron beams. This research will help to develop the instrumentation ideas and expertise necessary for successful next-generation sources. The Panel urges that this effort involve the entire U.S. neutron community, including NIST and the smaller reactors. The Neutron Scattering Society of America could become a focal point for the coordination of such a nationwide program.

Recommendation 5: Effective management by DOE of the proposed facilities is essential.

Three issues with respect to the DOE management of construction and operation of neutron sources have become apparent in the Panel‘s investigations. While these issues have immediate consequences with respect to the ANS, they are important for either source.

1. The DOE must impose an effective management process to control the plethora of ES&H directives and regulations and to factor in risk assessment to balance costs versus benefits.

2. The DOE must rapidly establish clear regulatory responsibility for the construction and safe and secure operation of these facilities.

3. The OER should assume responsibility for the funding, cost control, and construction of these facilities.

In the Panel’s view, appropriate steps to improve management and regulatory procedures will lead to major cost savings and increased effectiveness in both construction and operation without sacrifice of safety, security, or environmental standards.

Appendix 1

Department of Energy
Washington, DC 20585

JUN 01 1992

Professor Leon Silver
California Institute of
Technology, MS 170-25
1201 E. California Boulevard
Pasadena, California 91125

Dear Professor Silver:

Since my Basic Energy Sciences Advisory Committee (BESAC) charge letter to you of April 22, 1992, a Department of Energy (DOE) concern has arisen with regard to neutron sources that I wish BESAC to address. We are designing a new high flux research reactor, the Advanced Neutron Source, to eventually replace our two aging research reactors. In the meantime, progress is being made on the production of neutrons using accelerator-based systems and in the use of these higher energy neutrons and their time structure. It would be useful to the Department at this time to review the strengths and weaknesses of the two methods for producing neutrons and how and where they complement or duplicate one another. I ask that you please put together an expert, balanced panel to provide a report to me by the end of September 1992, addressing the following:

1. Review the strengths and weaknesses of reactor and spallation sources of neutrons for:

   - production of isotopes;
   - neutron scattering;
   - neutron irradiation effects; and
   - other neutron research.

   Where do they complement or duplicate each other?

2. Taking into consideration their strengths, weaknesses, cost, readiness, and other appropriate factors, discuss the design goals for:

   - a reactor only;
   - a spallation neutron source only; and
   - a combination of the two.

   Recognizing the design for a new reactor is underway and that similar data does not exist for a spallation neutron source, please extrapolate from existing facilities or studies.

3. From the available information, discuss the proper timing for:

   - a reactor only;
   - a spallation neutron source only; and
   - a combination of the two.

4. Discuss the major uncertainties in the analysis where additional information would permit more definitive conclusions.

In view of the very challenging task we have placed on BESAC this year and this additional study, let me try to give you our priorities to assist you in carrying out the charge. The main task you should concentrate on in addition to the above study is the review of Basic Energy Sciences (BES) activities at the major laboratories. We have started a project-by-project review of the BES program using the Office of Program Analysis (OPA). Your review should cover the laboratory BES programs in areas which OPA will not review. These areas which BESAC should especially review include: the management and directions of the research, the operation of the user facilities, and the relevance of the research to DOE and the National Energy Strategy. My original charge letter also asked that you provide me with your recommendations on the Advanced' Neutron Source and Chemical Dynamics Research Laboratory, within certain budget constraints. The third task in my charge letter of April 22, 1992, asked for an all-industry panel to review the research thrusts in the laboratory programs. Realizing your limited time and also the fact that several members of BESAC are from industry and other members have significant experience and background with industrial technologies, emerging and mature, I suggest that you address this latter task within your committee as a whole during your reviews and not set up a special panel.

I appreciate your willingness to take on this important review of BES. Please let me know if I can provide further guidance.

Sincerely,

William Happer

William Happer
Director
Office of Energy Research

Appendix 2

NIST
UNITED STATES DEPARTMENT OF COMMERC
National Institute of Standards and Technology
[illegible]

July 12, 1992

Professor Wafter Kohn
Department of Physics
University of California at Santa Barbara
Santa Barbara, CA 93106

Dear Walter,

On behalf of the Basic Energy Sciences Advisory Committee (BESAC) and its Chairman, Leon Silver, I thank you for agreeing to chair a special panel on neutron research and sources. As I have discussed with you, this a critical time for U.S. neutron research, since the cost estimate for the Advanced Neutron Source (ANS) is now available and makes it clear that construction will require a major National commitment similar to that required for the SSC. At the same time, our existing sources are all more than 25 years old, and the operating costs for the reactors within the Department of Energy (DOE) continue to escalate, seemingly without limit. Dr. Will Happer, Director of the Office of Energy Research (OER), has requested the present study to help him and the DOE make the best possible choices for the future. As can be seen from the charge letter to BESAC (copy attached), this includes a consideration of both reactors and pulsed spallation sources as options to serve the nation's needs in isotope production, neutron scattering, materials, and other uses of neutrons. This is a very broad charter, and the panel which has been convened is faced with an enormous task.

Therefore, we have extended the deadline from mid September to January, 1993 for the final report of your panel. However, Dr. Happer would very much like to have a letter report by September 15 which includes any short term recommendations, so that they may be included in Department planning for the FY1994 budget. I must also emphasize that the final report must be in our hands as soon after the first of the year as possible, since BESAC exists only on a year to year basis.

As we discussed, the first, organizational meeting will be held at NIST on July 31, and Dr. Happer has agreed to attend the meeting from 10:00 to

11:00 AM. I have also arranged for a short tour of the NIST facilities if you want one. John Axe has arranged to have those members who are available visit the HFBR at Brookhaven National Laboratory on July 30, starting at 10:00 AM, and ending by 3:00 PM, as you requested. John has blocked out rooms for up to 10 people for the meeting there, but will require an accurate head count as soon as possible. Ms. Carol O'Connor will handle arrangements at NIST (301-975-6240), including hotel reservations for those who desire them.

Once again, I thank you for agreeing to chair this panel. I can assure you that BESAC, and the Department of Energy, will take full account of your advice.

Yours sincerely

Mike

J. Michael Rowe
Vice-Chairman, BESAC

cc: L. Silver
L. Ianniello
BESAC Membership

NIST
UNITED STATES DEPARTMENT OF COMMERC
National Institute of Standards and Technology
[illegible]

July 14, 1992

Dr. John D. Axe
Associate Director for Basic Energy Sciences
Physics Department
Brookhaven National Laboratory
Upton, NY 11973

Dear John,

Thank you for agreeing to serve on the panel on neutron sources, which has been organized by the Basic Energy Science's Advisory Committee (BESAC) at the request of Dr. Will Happer, Director of the Office of Energy Research (OER) of the Department of Energy (DOE). The charge to BESAC is attached to this letter, as is the charge from the BESAC vice-chairman, J. M. Rowe, to me as chair of the panel. (Please note that as a Brookhaven employee, you will be a full, non-voting member.) The charge is ambitious in light of the time scale (note that the charge from BESAC extends the time for the, final report until January 1993), and will require a great deal of work from all members if it is to be done properly. Dr. D. L. Price (ANL) and Dr. J. J. Rush (NIST) will be vice-chairs. Our liaison with BESAC, will be Mike Rowe, liaison with DOE will be Lou Ianniello, and travel reimbursement will be handled by Tony Aldred (ANL). In the near future, we will also appoint a technical secretary, who will then deal with the details of future meetings.

DOE has agreed to pay travel and living expenses for members and consultants (excepting staff from the National Laboratories, who will be paid directly by their respective organizations). In order to ensure that we avoid both actual and perceived conflict of interest problems, those persons who are from the DOE National, Labs will be full, *non* -voting members. In all cases, members should declare any conflicts at the first opportunity, and recuse themselves from any areas affected by such conflicts. Obviously, for deliberations on projects involving particular labs, members from the lab at issue should remain mute unless requested to comment by the chair or another member. Although this is somewhat cumbersome, it avoids the necessity for exclusion of those best qualified to add to the quality of the panel's deliberations.

We have now planned the first full panel meeting, which will be held on Friday, July 31, 1992, from 8:30 AM until 4:30 PM in Gaithersburg at the Reactor Building, NIST, with Mike Rowe (301-975-6210) as host.

Before the panel completes Its deliberations, I intend that we will have visited all four major neutron scattering centers In DOE - Argonne, Los Alamos, Oak Ridge, and Brookhaven. In order to minimize travel, we have scheduled a site visit to Brookhaven National Laboratory for Thursday, July 30, with John Axe (516-282-3821) as host. Tentative agendas for both the Brookhaven site visit and the organizational meeting are attached, along with telephone numbers which can be used to obtain additional information', or assistance with lodging. Please let Mike Rowe know about your plans for both meetings, so that we can obtain an accurate count of attendees as soon as possible.

Once again, I thank you on behalf of myself, BESAC and DOE for agreeing to assist in this critically Important study, which will help to set the future possibilities for neutron research in the U. S.

Appendix 3

DEPARTMENT OF PHYSICS

University of California
Santa Barbara, California 93106–9530

Telephone: (805) 893-3888

September 15, 1992

Dr. W. Happer, Director
Office of Energy Research
U. S. Department of Energy
Washington, DC 20585

Dear Dr. Happer:

I am writing to you on behalf of the Panel on Neutron Sources, which was set up in response to your letter of June 1, 1992 to Professor Leon Silver, Chairman of the Basic Energy Sciences Advisory Committee. Pursuant to your request at our first meeting, the present letter presents our unanimous recommendations that relate to your FY'94 budget request. Our full report, on whose essentials our panel is in full agreement, will be forwarded to you by the end of the year.

In the past two months we have worked intensively to meet your request, including site visits to the four DOE neutron sources, a three-day review of Neutron Sources and Applications at Oak Brook, Illinois, involving over 60 national and international experts in the different areas of neutron science and technology, and a two-day meeting of our Panel to discuss and agree on recommendations. These activities have been carried out on an accelerated time-scale in order to meet your deadline of September 15.

Our studies have confirmed the extreme importance of neutron techniques for the scientific, technological, economic and medical well-being of the Nation. The opinions expressed by the U.S. neutron community and the deliberations of international reviewers lead to the inescapable conclusion that scientists need access to a balanced pair of complementary sources, more, powerful than those currently available,: the Advanced Neutron Source (ANS) and a powerful spallation source. A broad range of tasks can be addressed with either source, but some can only be effectively carried out at one source or the other.

For the three decades following the construction of the first nuclear, reactor, U.S. neutron research led the world. However, the facilities available for neutron research in the U.S. have fallen increasingly behind those in Europe since the ILL reactor was commissioned in the early 1970's. The lag has been exacerbated in the 1980's by the success of the ISIS spallation source in the U.K., which is complementary to the ILL. At present, the U.S. has no dedicated sources to match either of these. Since neutron science contributes directly to U.S. technology and industry and has spawned entire new neutron scattering communities in areas such as polymers, complex fluids, and high-temperature superconductivity, construction of new U.S. neutron sources is essential. We believe that our recommendations will ensure that a sound course is set for the next 10-20 years.

Recommendations

A. Principal Recommendations

Because of its much higher average flux, the ANS will be the world's most powerful source for steady flux neutron scattering and will perform necessary functions (such as isotope production for technological and medical applications, and materials irradiation) not accessible to a matched spallation source. Furthermore, it is at present in an advanced and fully documented state of design.

The Panel's paramount and unanimous recommendation is that the DOE provide the funding requested by the ANS Project to ensure an early start as well as timely completion of its construction.

The Panel also recommends a strategy, which will be developed in our full report, for the subsequent design and construction of an advanced pulsed spallation source.

B. LANSCE

Neutron scattering experiments at a 100 μA pulsed spallation source ideally complement those at the best contemporary reactors. A pulsed spallation facility of this type is recognized as a great asset to the U.S. neutron scattering community. LANSCE provides an internationally recognized source of this caliber, but is reliant on an insecure source of protons, which has seriously compromised its reliability, and operates for only a smal part of the year. The Panel recognizes the scientific merit of a dedicated 100 μA source and believes that LANSCE could be run ef'fectively in this mode. However, the proposal to construct and operate a dedicated 100 μA neutron source using the LAMPF linac is not a cost-effective option, when compared with the funding levels and opportunities at other U.S. neutron facilities. If LAMPF continues to operate with funding from other sources, the Panel strongly recommends that BES continue to operate LANSCE.

C. Enhancement of Existing Sources

Although our over-riding priority is the ANS, there are other urgent needs which should be addressed in the FY 1994 budget in order to prevent a scrious decline of the U.S. neutron community in the 1990's.

Barring unforeseen events, it appears that the operation of LANSCE will be terminated for lack of funding. The most immediate and cost-effective partial relief can be provided by increasing operating funds for IPNS. Four million dollars additional funding will allow this facility 'to approximately double its DOE-supported operating schedule. We strongly urge the DOE to provide this critically needed research capacity.

Improved effectiveness of our existing neutron sources can also be achieved by modernized instrumentation. Our highest priority for capital equipment funding is the HFBR upgrade. This highly cost effective upgrade will provide essential additional capibilities for a broad range of research in materials science, chemistry and biology. Equally important, this project will contribute directly to the instrument development goals of the ANS.

In the event that LANSCE does continue to operate in FY'94, the urgency for increasing the operating time at IPNS is lessened. In this case we recommend that the increase in IPNS operations be given lower priority than the HFBR upgrade.

The highly desirable instrument upgrades at IPNS and HFIR have a lower priority under present circumstances.

In view of the urgent need for the ANS to be constructed on budget and as quickly as possible, we urge the Department to promptly improve the management structure and. regulatory environment within the Department. We consider implementation of this recommendation (which will be more fully addressed in our final report) to be a prerequisite for success.

My colleagues, Drs. D. L. Price and J. J. Rush, as well as I would be pleased to meet, with you either in conjunction with the Townes Committee or on some other date.

Sincerely Yours,

W. Kohn

Walter Kohn, Chair
BESAC Panel on Neutron Sources

WK:cp
cc:
BESAC Panel on Neutron Sources Members
Professor L. Silver, Chair, BESAC
Dr. J. M. Rowe, Vice-Chair, BESAC

Appendix 4

Selected Reports of Previous Major NRC or DOE Studies of Neutron Facilities and Research

1. NRC Solid State Sciences Committee, Neutron Research on Condensed Matter: A Study of the Facilities and Scientific Opportunities in the United States. National Academy of Sciences, Washington, D.C., 1977.

2. Ames Laboratory, Report of the Review Panel on Neutron Scattering, IS-4761, Ames, Iowa October 1980.

3. NRC Solid State Sciences Committee, Panel on Neutron Scattering, Current Status of Neutron-Scattering Research and Facilities in the United States. National Academy Press, Washington, D.C., 1984.

4. National Research Council, Major Materials Facilities Committee. Major Facilities for Materials Research and Related Disciplines. F. Seitz and D.E. Eastman, Co-Chairs, National Academy Press, Washington; D.C., 1984.

5. DOE Council on Materials Sciences, Committee on Neutron Scattering Facilities Supported by the Department of Energy, Report on Neutron Scattering Facilities Supported by the Department of Energy, 1988 (unpublished, available from DOE).

Appendix 5

List of Acronyms

The following is a list of acronyms, initialisms, and abbreviations used in this report.

ACAR	angular correlation of annihilation radiation
ANS	Argonne National Laboratory
ANS	Advanced Neutron Source
BES	Office of Basic Energy Sciences, DOE
BESAC	Basic Energy Sciences Advisory Committee
BNL	Brookhaven National Laboratory
CDR	Conceptual Design Report
CNRF	Cold Neutron Research Facility, NIST
	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DRAM	dynamic random access memory
EEC	European Economic Community
ES&H	environment, safety, and health
ESS	European Spallation Source
HFBR	High-Flux Beam Reactor, BNL
HFIR	High-Flux Isotope Reactor, ORNL
HIPD	High Intensity Powder Diffractometer, LANSCE
HMIR	Hahn-Meitner Institute Reactor, Berlin
ICANS	International Conferences on Advanced Neutron Sources

ILL	Institut Laue-Langevin, Grenoble, France
INS	inelastic neutron scattering
IPNS	Intense Pulsed Neutron Source, ANL
ISIS	Rutherford Laboratory (U.K.) Pulsed Spallation Source
JRR	Japan Research Reactor, Tokaimura
KENS	KEK (Japan High-Energy Physics Laboratory) Neutron Source, Tsukuba
KFA	Kernforschungslage Jülich, Germany
LAMPF	Los Alamos Meson Physics Facility
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Scattering Center
MURR	Missouri University Research Reactor, Columbia, Missouri
NBSR	Neutron Beam Split-Core Reactor, NIST
NDP	neutron depth profiling
NIH	U.S. National Institutes of Health
NIST	National Institute of Standards and Technology
NMR	nuclear magnetic resonance
NRC	U.S. Nuclear Regulatory Commission
NSLS	National Synchrotron Light Source, BNL
OER	Office of Energy Research, DOE
ORNL	Oak Ridge National Laboratory
PET	positron emission tomography
PGAA	prompt-gamma activation analysis
PRT	participating research team

PSD	positron-sensitive detector
PSS	pulsed spallation source
REDC	Radiochemical Engineering Development Center, ORNL
R&D	research and development
SANS	small-angle neutron scattering
SINQ	Schweizerisches Institut fur Nuklearforschung Quelle (Swiss Institute of Nuclear Research Source), Villegen
SLAC	Stanford Linear Accelerator Center
SNQ	Spallations Neutronen Quelle (Spallation Neutron Source, Germany)
TOF	time-of-flight
UCN	ultracold neutron
VLSI	very-large-scale integration
μSR	Muon Spin Resonance
3-D	three dimensional