Report of the

Basic Energy Sciences Advisory Committee

on

Neutron Source Facility Upgrades

and the

Technical Specifications for the Spallation Neutron Source

PREFACE

Following the termination of the Advanced Neutron Source, the FY 1996 Energy and Water Development Appropriations Conference Report directed the Department of Energy's Office of Basic Energy Sciences to "evaluate opportunities to upgrade existing reactors and spallation sources as cost-effective means of providing neutrons in the near term for the scientific community while the next generation source is developed. This evaluation shall be available prior to the Appropriations Committee's hearings on the Department's fiscal year 1997 budget submission."

In response to this request, two subpanels of the Basic Energy Sciences Advisory Committee (BESAC) were convened. The first subpanel, chaired by Professor Robert Birgeneau, Dean of Science at MIT, was charged with considering upgrades to the High Flux Beam Reactor (HFBR) at BNL and the High Flux Isotope Reactor (HFIR) at ORNL. The second subpanel, chaired-by Dr. Gabriel Aeppli* of AT&T Bell Laboratories, was charged with considering upgrades to the Los Alamos Neutron Scattering Center (LANSCE) at LANL and the Intense Pulsed Neutron Source (IPNS) at ANL. An additional subpanel was formed at this time; this third subpanel, chaired by Professor Thomas Russell** of IBM Research Laboratories, was charged with considering the technical specifications of the next generation spallation neutron source.

The first two subpanels were to address the following questions: (1) Was there a need to operate both sources (either both reactor sources or both neutron sources) until after the completion of the next generation spallation neutron source? (2) If so, what, if any, upgrades would be necessary to meet research needs? (3) Should both be upgraded? The subpanels were apprised of severe budget constraints now and in the future.

The results of the work and deliberations of the BESAC subpanels were presented to BESAC at a meeting on February 5-6, 1996. This document contains the results presented by the subpanels and the findings and recommendations of BESAC. The following documents are contained herein:

- Letter from Professor W. Carl Lineberger, Chair of BESAC, to Dr. Martha Krebs, Director of the Office of Energy Research, providing the findings of BESAC; membership of BESAC

- Charge letter from Dr. Krebs to Professor Birgeneau; subpanel membership; recommendations of the subpanel and full subpanel report

- Charge letter from Dr. Krebs to Dr. Aeppli; subpanel membership; recommendations of the subpanel

- Charge letter from Dr. Krebs to Professor Russell; subpanel membership; recommendations of the subpanel

As a result of these recommendations, the Office of Basic Energy Sciences initiated enhancements of the High-Flux Isotope Reactor at Oak Ridge National Laboratory and joined with the Department's Office of Defense Programs to upgrade the short-pulse spallation source at the Los Alamos Neutron Science Center. The cost of both efforts is modest, and the enhancements will increase capacity and match the performance of current sources in Europe. Furthermore, the recommendations of the Russell subpanel determined the technical specifications of the Spallation Neutron Source; the Conceptual Design Report was completed and reviewed by a panel of technical experts in June 1997.

* Currently at NEC
** Currently at the University of Massachusetts

Patricia M. Dehmer

Patricia M. Dehmer
Associate Director for Energy Research
for the Office of Basic Energy Sciences

March 1998

University of Colorado at Boulder

W. Carl Lineberger

Department of Chemistry and Biochemistry
JILA

Campus Box 440
Boulder, Colorado 80309-0440
(303) 492-7834
Fax: (303) 492-8994
Internet: WCL@JILA.COLORADO.EDU

March 10, 1996

Dr. Martha Krebs, Director
Office of Energy Research
U. S. Department of Energy
Washington, D.C. 20585

Dear Martha:

This letter is intended to serve as an interim report of BESAC in response to your request for advice on both spallation and reactor sources of neutrons. The findings given here were developed during the regular BESAC meeting in Washington on February 5 and 6, 1996. A final report of these findings will be presented in our annual report.

In your BESAC charge letter dated June 28, 1995, we were asked to provide advice concerning upgrades to the two existing high flux reactors, while paying attention to the severe budget restrictions facing ER. You also requested technical advice concerning the scope of the proposed next generation spallation neutron source project. With the congressional mandate to carry out a study of upgrades of existing neutron sources as a cost effective, interim way to improve capability before the next generation spallation source is completed, the charge to our committee was further broadened.

Based upon conversations with your office and OBES, three panels of experts were convened with purposes of reviewing existing spallation sources and upgrades, reviewing reactor neutron sources and upgrades, and reviewing the technical scope of the proposed next generation spallation neutron source. As stated in your charge letter, the reports of all three. panels were submitted to the Basic Energy Sciences Advisory Committee, which would then utilize these reports to make formal recommendations to the Department of Energy.

Each of these panels met in January 1996, and completed at least a summary report by the time of the February 5 BESAC meeting. Each of the Panel Chairs (Robert Birgeneau, reactor upgrades; Gabriel Aeppli, spallation upgrades; and Thomas Russell, technical issues) presented the findings of their Panel to BESAC. Following these presentations and an extensive question and answer period, the Basic Energy Sciences Advisory Committee makes the following recommendations to the Office of Energy Research.

1) While the proposed upgrades are critically important to the future of neutron scattering science in the United States, the Office of Basic Energy Science faces severe budget restrictions, and the proposed upgrades and construction projects must not come at the expense of the other research activities of OBES.

2) The Panel to address technical issues for the next generation spallation source (Russell Panel) emphasized that there are very formidable obstacles to constructing a five MW spallation source within the $lB design limit and on the suggested time scale. They recommended a strategy to construct a 1 MW, upgradeable, short pulse spallation source. The panel report concludes that “There is an urgent need to build a short pulsed spallation source in the 1 MW power range with sufficient design flexibility that it can be operated at a significantly higher power at a later stage”. Their full six point set of recommendations was adopted by BESAC as our recommendations to the Department of Energy. In addition, BESAC transmits the two page summary report as a recommendation to the Department of Energy.

The Birgeneau Report views the two reactor upgrade proposals as part of a coherent plan to provide cold and thermal neutrons for US scientists. It notes that one reactor is optimized for high thermal neutron fluxes, while the other is optimized for cold neutron production. While the two upgrade project costs are quite uncertain, it appears that the sum of the two falls within the $200 M guideline provided the subpanel. The BESAC recommendations on these two reactor upgrades are presented below.

3) The High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory must be upgraded to obtain essential neutron scattering facilities for the nation’s research community. It is estimated that the upgrade can be accomplished for an incremental cost of $150 M, but there are very substantial uncertainties in the estimate. A full conceptual design will be required before the cost can be better estimated and before the public reaction to this project can be assessed. BESAC recommends that a conceptual design for the high flux beam reactor upgrade be initiated as rapidly as possible, to establish a firmer cost basis. If the total cost remains as estimated, then DOE should proceed with the HFBR upgrade project as a cost effective method to provide needed cold neutron scattering facilities.

4) The proposed upgrade of the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory is of a more modest scale, but it would provide significant additional thermal neutron scattering capability for the United States. The total cost of this project is estimated at $5OM. It must be emphasized, however, that the HFIR upgrade alone is not adequate to satisfy the need for reactor neutrons. The scope and scheduling of the HFIR upgrade is such that it would be completed before the HFBR is taken out of operation for upgrade. BESAC recommends that a conceptual design be initiated to obtain detailed costs for this project. If the costs come in as presently estimated, then BESAC recommends proceeding with this project.

The Aeppli subpanel report makes a compelling case for the need in the neutron scattering community for a short pulse neutron source capability in the ISIS class within the next two-four years. The panel was charged with recommending short pulse upgrades for total project costs of about $100M. While the two proposals received by the subpanel did not meet these requirements, we believe that a short pulse neutron source capability is an essential component of the neutron scattering portfolio. We therefore encourage ER to explore further other affordable options to provide short pulse neutron capability in the ISIS range within a time frame of two-four years. Our specific recommendations on these two projects are given below.

5) The Aeppli Panel report documented the very important case for a short pulsed spallation source of neutrons, and described a $450 M proposed Intense Pulsed Neutron Source (IPNS) upgrade to a power level of 400kW. The cost of this interim upgrade is far beyond the $100M indicated in the charge letter to the Aeppli Panel. Based upon this cost, BESAC does not recommend proceeding with the IPNS upgrade. It is our view that an interim project of this magnitude is not justified.

6) The proposed long pulse spallation neutron source at Los Alamos is in a less advanced stage than the Argonne Proposal and does not meet the short pulse needs of the community. The long pulse offers the possibility of providing a very important source of neutrons and an appropriate collaboration between Defense Programs (DP) and Energy Research (ER). It is the recommendation of BESAC that DP and ER jointly develop a plan to exploit the long pulse spallation source. Within this plan, the ER contribution should support the basic research mission, and should focus on user support and instrumentation. This recommendation is contingent upon clear evidence that DP will play a continuing role in this project and that the facility would continue to be substantially available for ER-related neutron scattering research.

Finally, all of these upgraded neutron facilities have incremental operating costs and additional research costs associated with them. These costs must be fully recognized and plans developed to absorb them prior to initiating an upgrade. We are also concerned that the costs of the upgrades must be stated so as to include the associated new experimental devices. BESAC is not convinced that the upgrades could be appropriately utilized without this explicit recognition of costs. Hence, we present our final recommendations.

7) All of the upgrades involve development of major new experimental end stations as a part of the project. Construction of these major new instruments is critical if the upgrades are to be fully utilized. This instrumentation must not be sacrificed in order to reduce the total project cost of an upgrade.

8) It is critical that ER take explicit recognition of the additional operating costs associated with these various upgrade options and, if they are initiated, to recognize and plan for the increase in operation and research costs. As indicated in the detailed reports, the reactor upgrades have increased operating budgets in the range $3-7 M, the LANSCE upgrade about $11M, and the IPNS upgrade an additional operating expense of approximately $45M. This latter increase is considered to be outside the range indicated in your charge letter to the Panels.

The findings above, as well as the specific parts of the reports which are identified in this letter, represent the recommendations of BESAC. For your information, I am including a more detailed packet of information concerning the activities of each of these committees. These three subpanels have all worked diligently in a pressure packed environment, attempting to provide the best possible advice to the Department of Energy in a very short time. BESAC is very appreciative of the help they have provided us in arriving at our recommendations.

I will be happy to discuss these recommendations in more detail with you at your convenience.

With best wishes.

Sincerely,

W. Carl Lineberger

W. Carl Lineberger
Chair, Basic Energy Sciences
Advisory Committee

WCL: feh

cc: Dr. Pat Dehmer, Associate Director, Office of Basic Energy Science
Dr. Iran Thomas, Director, Material Science
BESAC Members
Dr. Gabriel Aeppli
Dr. Robert Birgeneau
Dr. Thomas Russell

Attachments: Materials for each Subpanel to include:
1) Dr. Krebs charge letter
2) Subpanel membership
3) Subpanel Executive Report summary

BASIC ENERGY SCIENCES ADVISORY COMMITTEE
1995 MEMBERSHIP

Dr. Klaus Berkner
Associate Laboratory Director
Operations
Lawrence Berkeley National
Laboratory
Berkeley, California 94720

Professor Barbara J. Garrison
152 Davey Laboratory
Department of Chemistry
Pennsylvania State University
University Park, PA 16802

Professor Jerry Harris
Associate Professor of
Geophysics
Stanford University
Stanford, CA 94305-2215

Professor Adam Heller
Department of Chemical Engineering
University of Texas
Austin, Texas 78712

Dr. Jan F. Herbst
Department of Physics
General Motors Corporation
Research and Development Center
30500 Mound Road
Warren, Ml 48090-9055

Professor W. Carl Lineberger
Department of Chemistry and
Biochemistry
University of Colorado
Boulder, Colorado 80309

Professor Walter P. Lowe
Department of Physics and
Astronomy
Howard University
7501 Muirkirk Road
Beltsville, MD 20708

Dr. Mary L. Mandich
Materials Chemistry Research
Department
Bell Labs, Lucent Technologies, Inc.
600 Mountain Avenue
Murray Hill, NJ 07974-0636

Professor Carolyn Meyers
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332

Professor Frederick Neidhardt
Associate Vice President for Research
University of Michigan
4082 Fleming Admin. Bldg. 1340
503 Thompson Street
Ann Arbor, Ml 48109-1340

Professor Geraldine L. Richmond
Department of Chemistry
University of Oregon
Eugene, OR 97403-1253

Dr. Thomas P. Russell
Polymer Science and Engineering
Department
Silvio 0. Conte Research Center
University of Massachusetts
Amherst, MA 01003

Professor Robert Street
Vice President for Libraries and
Information Resources
Stanford University
Stanford, California 94305

Dr. John Stringer
Director of Applied Research
Exploratory & Applied Research
Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, CA 94304-1395

Dr. Edel Wasserman
Science Advisor
DuPont Central Research and
Development
P. O. Box 80328
Wilmington, DE 19880-0328

Professor Conrad Williams
Department of Physics
Morgan State University
Cold Spring Lane
Baltimore, MD 21239

Department of Energy
Washington, DC 20585

November 9, 1995

Professor Robert Birgeneau
Dean of Science
Department of Physics
Massachusetts Institute of Technology
Cambridge, MA 02139

Bob

Dear ~~Professor Birgeneau~~:

I would like to ask you to convene and chair a panel of experts for the Basic Energy Sciences Advisory Committee, to help the Department decide the best course of action with regard to the future of the High Flux Beam Reactor at Brookhaven National Laboratory and the High Flux Isotope Reactor at Oak Ridge National Laboratory.

There are several questions that need to be answered. In view of the decisions to terminate the Advanced Neutron Source and begin the design of a spallation neutron source, is there a compelling need to continue operation of the high flux reactors until and after the spallation neutron source is completed? If there is need to continue operations, are upgrades necessary to meet research needs? If so, what upgrades are needed? Should both be upgraded?

There are severe budget constraints, and the expectation is that the constraints will become tighter. The total cost of each upgrade considered should be kept below $100 million. To reduce cost, the panel should consider the extent to which the upgrades can be done using the existing operating budget, as was done at the Institute Laue Langevin.

Your panel is one of three panels; the other two are reviewing the existing spallation sources and the technical scope of the proposed spallation neutron source. The reports of all three panels will be submitted to the Basic Energy Sciences Advisory Committee. The advisory committee will use the reports to make the formal recommendations to the Department. The reports should be submitted to the advisory committee by January 31, 1996. Enclosed for your information is a copy of the charge letter to the advisory committee and a copy of a section of the Energy and Water Development Appropriations Conference Report.

Sincerely,

Martha Krebs

Martha A. Krebs
Director
Office of Energy Research

2 Enclosures

MEMBERSHIP LIST

January 5-6, 1996 Conference

Robert J. Birgeneau (Chair)
Dean of Science
Massachusetts Institute of Technology
6-123
Cambridge, MA 02 139
617-253-8900
617-253-8901 (fax)

John J. Rush (Vice-Chair)
Material Science and Engineering Lab
National Institute of Standards
A106, Reactor Building
Gaithersburg, MD 20899
301-975-6231
301-921-9847 (fax)

Frank Bates
University of Minnesota
Department of Chemical Engineering
151 Amundson Hall
421 Washington Ave., SE
Minneapolis, MN 55455
612-625-6606
612-616-1686

Michael Crawford
E.I. DuPont Co.
3561/209 Exper Station
Wilmington, DE 19880
302-695-3045
302-695-8207 - fax

Mujid Kazimi
Massachusetts Institute of Technology
Head of Nuclear Engineering

Cambridge, MA 02139
617-253-4206
617-258-7437 - fax

Bernhard Keimer
Princeton University
Department of Physics
Jadwin Hall
Washington Road
Princeton, NJ 08544
609-258-1537
609-258-1124 (fax)

Anthony Kossiakoff
Director, Protein Engineering
Genentech, Inc.
460 Pt. San Bruno Blvd.
San Francisco, CA 94108
415-225-1332
415-225-3734 - fax

David Long Price
Material Science Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4832
708-252-5475
708-252-7777 (fax)

Tawfik Raby
Chief, Reactor Operations & Engineering
Reactor Radiation Division
Bldg. 235, E151
National Institute of Standards
and Technology
Gaithersburg, MD 20899
301-975-6257
301-975-9427 - fax

Theodore R. Schmidt
Executive Staff
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 97185-0177
505-845-3058
505-844-9756 - fax

EXECUTIVE SUMMARY

Panel on Research Reactor Upgrades
February 1996

In the autumn of 1992 a DOE panel, chaired by Prof. Waker Kohn of U.C. Santa Barbara, carried out a thorough and wide-ranging study of current and future neutron science and neutron facilities in the United States. The Kohn pane1 concluded that neutrons had become an increasingly indispensable tool in broad areas of the physical, chemical, biological and geological sciences as well as materials technology and medicine. They concluded further that the United States was woefully behind Europe, and to a lesser extent, Japan, in the availability of up-to-date sources and instrumentation.

After reviewing different alternatives for capability and cost effectiveness, the Panel concluded that the nation had a critical need for a complementary pair of sources: a new reactor, the Advanced Neutron Source (ANS), which would be the world's leading neutron source and a 1-MW pulsed spallation source (PSS), more powerful than any existing PSS and providing crucial additional capabilities, particularly at higher neutron energies. The ANS was the Panel's highest priority for rapid construction. In the Panel's view, any plan that did not include a new, full-performance, high-flux reactor would be unsatisfactory because of a number of essential functions that could be best or only peformed by such a reactor.

Unfortunately, because of budgeting exigencies Congress concluded that the ANS was not economically feasible in the foreseeable future, and instead recommended the design and construction of a next generation pulsed spallation neutron source. This then raises the urgent question of how the country most effectively could meet the important scientific and technical needs identified by the Kohn Panel which can be optimally or uniquely addressed by steady state neutron sources. Accordingly, this present panel was convened by Dr. Martha A. Krebs, Director of the D.O.E. Office of Energy Research to consider the folIowing questions: Is there a compelling need to continue operation of high flux reactors until and after the spallation neutron source is completed? If there is need to continue operations, are upgrades necessary to meet research needs? If so, what upgrades are needed? Should both be upgraded?

It was further requested that the total cost of each upgrade considered be kept below $100 million dollars.

The Kohn Panel already answered the first two of the above questions quite decisively by making the ANS its highest priority. Specifically, as stated above, reactors play a unique role in neutron science and therefore must be a continuing part of the country's scientific armory even after the PSS is competed. Further, in order to achieve their full potential the existing facilities at the DOE reactors must be significantly upgraded to emulate the instrumentation envisaged for the ANS. Therefore, in the rest of this executive summary we shall focus on the explicit upgrades themselves.

Before discussing the proposed reactor upgrades and our panel's conclusions and recommendations, it will be of value to review the evolution in the international arena since 1992. First, at the premier research reactor facility, the Institut Laue-Langevin (ILL) in Grenoble, France, the reactor has been completely refurbished including replacement of the reactor vessel, thence guaranteeing an additional 25 years lifetime. Second, the Berlin and Julich reactors (Germany) were upgraded with new cold and thermal neutron facilities. Third, the new JRRIII reactor in Japan has come into full operation with 30 neutron facilities and a cold neutron guide hall. Fourth, Germany has approved funding (> $500 million dollars) for a new modernized high flux reactor in Munich with cold neutron facilities equal to those of ILL. Finally, a second guide hall is planned at the Orphée Reactor in Paris, France. In the United States, the only significant development has been the construction and commissioning of the NIST Cold Neutron Research Facility. Thus the gap between U.S. and, especially, Western European capabilities in neutron science has grown dramatically since the Kohn Panel report. This is particularly true for the increasingly important area of cold *neutron* research where in Europe there are 6 cold neutron guide halls compared to 1 in the United States.

In order to guarantee continuing U.S. capabilities in steady state reactor-based neutron science, Brookhaven National Laboratory and Oak Ridge National Laboratory have put forth significant upgrade proposals for the High Flux Beam Reactor (HFBR) and High Flux Isotope Reactor (HFIR), respectively. These proposals would guarantee continued U.S. prominence in neutron science well into the next century, but they would by no means provide pre-eminence.

The more ambitious of the two projects is the proposed upgrade of the HFBR at Brookhaven. The HFBR is a beam reactor with 9 ports designed to operate at 60 MW; it was commissioned in the 1960's. For the last several years the HFBR has operated at 30 MW. Currently, this reactor has an array of high quality thermal neutron scattering instruments including a number which are either newly completed or under construction. There also are several cold neutron instruments; however, because the current HFBR cold source is not optimally placed inside the reactor vessel, these instruments are not competitive with the corresponding spectrometers at ILL. Brookhaven has no thermal or cold neutron guide hall. Besides neutron scattering, the HFBR supports a number of other activities including an extremely active positron beam program and sample irradiation and isotope production facilities.

The most precarious component of the HFBR neutron facility is the reactor vessel itself. The exact lifetime is not known. However, it is clear that. in order to guarantee 25 years of continued operation the-reactor vessel must be replaced in the very near future. There is considerably more uncertainty connected with the thermal shield. It is probable that the thermal shield will remain fully functional for the next 25 years. In any case, this is a programmatic issue and, specifically, failure of the thermal shield would not affect safe shutdown of the reactor. The; integrity of the thermal shield requires further study and, indeed, a final decision on replacement may not be possible until the reactor vessel is removed and an *in-situ* inspection is possible.

Replacement of the HFBR vessel makes possible modification of the cold source to place it in an optimal. position and to allow more neutron guides. The proposed change in the HFBR cold source position would increase the flux at the source by a factor of 3. The Brookhaven design calls for 5 identical guides 2.5 cm wide by 15 cm high with 2.5 deg between the center lines of adjacent guides. The cold neutron guides would service 15 new instruments, 11 of which would be placed in a new guide hall. A representative set of instruments would include 3 small angle scattering spectrometers, 2 reflectometers, 5 inelastic scattering spectrometers and 5 other neutron facilities. It is essential to the effectiveness of the HFBR upgrade, and to make it competitive with ILL, that operations at 60 MW be resumed. The HFBR proposal would more than double U.S. capabilities in the all-important area of cold neutron research and would make us competitive with Westem Europe.

In the absence of a proper Conceptual Design Report (CDR), the estimated costs of the HFBR upgrade project must by necessity have a large uncertainty. Indeed for this reason, the CDR must be initiated as soon as possible. Brookhaven's current best estimate for the Total Project Cost (TPC) is as follows. The TPC for the vessel replacement, guide hall and user instruments excluding contingency is $122 million. In the absence of a CDR., the contingency has the large value of $60 million. Thus the TPC including contingency is $182 million. This cost will be offset by $34 million to account for work done by Reactor Division staff already supported by BES funding over the two year period while the reactor would be down, Thus, the net TPC is $148 million including contingency. A significant feature of the HFBR upgrade is that a net quadrupling of capabilities will be attained with a 25% increase in operating costs from $26M per year to $33M. This increase is dominated by the markedly increased costs of the outside user program. The ideal timeline presented by Brookhaven would lead to a shutdown of the HFBR in mid-2000 and restart in mid-2002.

HFIR at Oak Ridge National Laboratory was commissioned in the mid 1960's at an operating power level of 100 MW for the primary purpose of producing transplutonium isotopes for a variety of medical, industrial, and military applications, Four neutron beam tubes, and numerous experimental facilities in and around the reactor core, also provide access to very high neutron fluxes over a range of energies, for use in beam research, materials irradiation testing, and neutron activation analysis.

HFIR currently operates at 85% of the design power. Surveillance specimens recovered from the reactor in 1986 showed greater than anticipated embrittlement of the pressure vessel after 17.5 effective full power years (EFPY) of operation. Following a lengthy DOE review, operation was resumed in 1989 at reduced power in conjunction with periodic hydro testing of the vessel. That review also endorsed extension of the original 20 EFPY design estimate to 26 ESPY (2004-2005). A recent (1994) analysis indicates that the vessel life can be extended even further, to 50 ESPY, which would permit operation of the reactor at 100 MW until about 2035. This assessment is the most critical technical component of the upgrade proposal and it must be confirmed before committing to the present plan. The proposed changes to the reactor and support facilities are relatively minor variations of the original design and, as a consequence, could be implemented as part of the scheduled in-service inspection and replacement of the permanent beryllium reflector, which would mini&e reactor down-time.

The principal objectives of the HFIR upgrade program are: i) development of an internationally competitive cold neutron scattering facility, and ii) establishment of premier thermal neutron capabilities, while iii) improving isotope production, materials irradiation testing and neutron activation analysis capabilities. The first goaI will be accomplished by inserting a liquid hydrogen cold source in an existing tangential beam tube. Cold neutrons will be fed into a new cold guide hall to be constructed adjacent to the existing reactor building. Three cold guides will service two small-angle scattering instruments, a reflectometer, and a high resolution triple axis machine, each operating at, or above, corresponding ILL performance levels. Five thermal neutron guides, to be inserted into the existing radial beam tube, will deliver high fIux thermal neutron beams to a new thermal guide hall. Nine instruments are planned for this hall including powder and triple axis spectrometers, diffractometers, and residual stress devices. This thermal guide hall constititutes the most significant component of the proposed upgrade, providing the nation with an exceptional capability that will complement other existing or proposed facilities. A variety of enhancements to the existing materials irradiation, isotope production, and activation analysis missions are also planned. Notable improvements include a remote handling facility over. the reactor pool, a neutron radiography beam, and new, enlarged pneumatic tubes for activation specimens.

Subject to the confirmation of the extended lifetime of the reactor vessel, the costs of the HFIR upgrade can be estimated quite reliably. The TPC in constant FY 1996 dollars, measured as the increment over normal operation costs is $60.5M. This has been broken down into three categories: Enhancements of Neutron Scattering Mission ($38.6M); enhancements for materials irradiation, isotope production, and activation analysis missions ($16.5M). reactor improvements ($5.4M). $10.5M in internal and redirected ORNL funds has already been allocated to certain parts of this project leaving a net additional funding requirement of $50.0M. In its present form the proposed operating costs of the HFIR facility would increase only slightly due to the added costs of operating the cold source ($1.2M) and costs associated with an increased user program ($1.4M). In an optimal schedule, the Be reflector would be replaced and the in-service inspection would be carried out in mid-1998 with a 6-month shutdown. The cold and thermal guide halls would be operational in January 1999 and January 2000 respectively. This schedule phases perfectly with the proposed HFBR upgrade schedule provided that the HFBR CDR is completed expeditiously.

We now state our basic recommendations:

RECOMMENDATION

The panel recommends strongly that the Department of Energy proceed with both the HFBR and HFIR proposed upgrades. These are extraordinarily cost effective proposals which will guarantee U.S. prominence in neutron research well into the next century. Without their implementation, even the continuation of current research on new materials and radiation effects as well as the production of certain isotopes is at risk; The HFBR upgrade will provide the U.S. with world class capabilities for both thermal, and, most importantly, cold neutron research with steady state sources. The HFIR upgrade, which is more modest in scope, will strengthen the U.S. thermal neutron program especially for materials science. The Department of Energy should proceed immediately with both of these upgrades in a properly coordinated fashion. The conceptual design study for the HFBR must be started as soon as possible.

The total cost of the two upgrades is about $200 million. This should be compared with a "green field" cost for replacement of the HFBR and HFIR of about $2 billion dollars. It should be emphasized that the HFIR upgrade which we strongly endorse would not by itself meet the country's needs. Specifically, our largest deficit with respect to Western Europe is in cold neutron research which has become increasingly important as the classes of materials studied with neutrons become more complex. In particular, these include industrially important polymeric and soft materials as well as biological materials. The HFBR upgrade is essential to meet this cold neutron shortfall. Finally, to realize the full benefit of an HFBR upgrade it is essential that the reactor operating power be 60 MW, and we urge that the steps necessary to return to this power level begin immediately.

Robert J. Birgeneau
Chairman

Jack J. Rush
Vice-chairman

REPORT OF THE BASIC ENERGY SCIENCES ADVISORY COMMITTEE PANEL ON RESEARCH REACTOR UPGRADES

MARCH 1996

Research Reactor Upgrades

Report of a Review held at
Massachusetts Institute of Technology
Cambridge, Massachusetts

January 5-6, 1996

R.J. Birgeneau (Chair)
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

J.J. Rush (Vice-Chair)
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

Sponsored by the
U.S. Department of Energy
Office of Basic Energy Services

TABLE OF CONTENTS

1. EXECUTIVE SUMMARY

In the autumn of 1992 a DOE panel, chaired by Prof. Walter Kohn of U.C. Santa Barbara, carried out a thorough and wide-ranging study of current and future neutron science and neutron facilities in the United States. The Kohn panel concluded that neutrons had become an-increasingly indispensable tool in broad areas of the physical, chemical, biological and geological sciences as well as materials technology and medicine. They concluded further that the United States was woefully behind our major international competition in the availability of up-to-date sources and instrumentation.

After reviewing different alternatives for capability and cost effectiveness, the Panel concluded that the nation had a critical need for a complementary pair of sources: a new reactor, the Advanced Neutron Source (ANS), which would 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 was the Panel's highest priority for rapid construction. In the Panel's view, any plan that did not include a new, full-performance, high-flux reactor would be unsatisfactory because of a number of essential functions that could be best or only performed by such a reactor.

Unfortunately, because of budgeting exigencies Congress in 1995 concluded that the ANS was not economically feasible in the foreseeable future and instead recommended the design and construction of a next generation pulsed spallation neutron source. This then raised the urgent question of how the country most effectively could meet the important scientific and technical needs identified by the Kohn Panel which could be optimally or uniquely addressed by steady state neutron sources. Accordingly, this present panel was convened by Dr. Martha A. Krebs, Director of the DOE Office of Energy Research to consider the following questions: **Is there a compelling need to continue operation of high flux reactors until and after the spallation neutron source is completed? If there is need to continue operations, are upgrades necessary to meet research needs? If so, what upgrades are needed? Should both be upgraded?** It was further requested that the total cost of each upgrade considered be kept below $100 million dollars.

The Kohn Panel already answered the first two of the above questions quite decisively by making the ANS its highest priority. Specifically, as stated above, reactors play a unique role in neutron science and therefore must be a continuing part of the country's scientific armory even after the PSS is completed not only for neutron scattering, but for other national needs including isotope production, trace analysis and materials irradiation. Further, in order to achieve their full potential the existing facilities at the DOE reactors must be significantly upgraded to emulate the instrumentation envisaged for the ANS. Therefore, in the rest of this executive summary we shall focus on the explicit upgrades themselves.

Before discussing the proposed reactor upgrades and our panel's conclusions and recommendations, it will be of value to review the evolution in the international arena since 1992.

First, at the premier research reactor facility, the Institut Laue-Langevin (ILL) in Grenoble, France, the reactor has been completely refurbished including replacement of the reactor vessel, thence guaranteeing an additional 25 years lifetime. Second, the Berlin and Julich reactors (Germany) were upgraded with new cold and thermal neutron facilities. Third, the new JRRIII reactor in Japan has come into full operation with 30 neutron facilities and a cold neutron guide hall. Fourth, Germany has approved funding (> $500 million dollars) for a new modernized high flux reactor in Munich with cold neutron facilities equal to those of ILL. Finally, a second guide hall is planned at the Orphée Reactor in Paris, France. In the United States, the only significant development has been the construction and commissioning of the NIST Cold Neutron Research Facility. Thus the gap between U.S. and, especially, Western European capabilities in neutron science has grown dramatically since the Kohn Panel report. This is particularly true for the increasingly important area of cold neutron research where in Europe there are 6 instrumented cold neutron guide halls compared to 1 in the United States.

In order to guarantee continuing U.S. capabilities in steady state reactor-based neutron science, Brookhaven National Laboratory and Oak Ridge National Laboratory have put forth significant upgrade proposals for the High Flux Beam Reactor (HFBR) and High Flux Isotope Reactor (HFIR), respectively. These proposals would guarantee continued U.S. prominence in reactor neutron science well into the next century, but they would by no means provide pre-eminence.

The more ambitious of the two projects is the proposed upgrade of the HFBR at Brookhaven. The HFBR is a beam reactor with 9 ports designed to operate at 60 MW; it was commissioned in the 1960’s. For the last several years the HFBR has operated at 30 NW. Currently, this reactor has an array of high quality thermal neutron scattering instruments including a number which are either newly completed or under construction. There also are several cold neutron instruments; however, because the current HFBR cold source is not optimally placed inside the reactor vessel, these instruments are not competitive with the corresponding spectrometers at ILL. Brookhaven has no thermal or cold neutron guide hall. Besides neutron scattering, the HFBR supports a number of other activities including an extremely active positron beam program and sample irradiation and isotope production facilities.

The component which most affects the long term operation of the HFBR neutron facility is the reactor vessel itself. Its exact lifetime is not known. However, it is clear that in order to guarantee 25 years of continued operation the reactor vessel must be replaced in the very near future. There is considerably more uncertainty connected with the thermal shield. It is probable that the thermal shield will remain fully functional for the next 25 years. In any case, this is a programmatic issue and, specifically, failure of the thermal shield would not affect safe shutdown of the reactor. The integrity of the thermal shield requires further study and, indeed, a final decision on replacement may not be possible until the reactor vessel is removed and an *in-situ* inspection is possible.

Replacement of the HFBR vessel makes possible modification of the cold source to place it in an optimal position and to allow more neutron guides and the development of an ILL-class cold neutron facility. The proposed change in the HFBR cold source position would increase the flux at the source by a factor of 3. The Brookhaven plan design calls for 5 identical guides 2.5 cm wide by 15 cm high with 2.5 deg between the center lines of adjacent guides. The cold neutron guides would service up to 15 new instruments, 11 of which would be placed in a new guide hall. A representative set of instruments would include 3 small angle scattering spectrometers, 2 reflectometers, 5 inelastic scattering spectrometers and 5 other neutron facilities. It is essential to the effectiveness of the HFBR upgrade, and to make it competitive with ILL, that operation at 60 MW be resumed. The final complement of HFBR cold-neutron instruments would be developed in coordination with existing and planned instruments at NIST, HFIR and the new pulsed source. The HFBR proposal would double U.S. capabilities in the all-important area of cold neutron research and would make us competitive with Western Europe.

In the absence of a proper Conceptual Design Report (CDR), the estimated costs of the HFBR upgrade project must by necessity have a large uncertainty. Indeed for this reason, the CDR must be initiated as soon as possible. Brookhaven's current best estimate for the Total Project Cost (TPC) is 182M$ in FY96$. This figure covers the vessel replacement, guide hall and user instruments and includes an exceptionally large contingency of 60M$, which is 100% of all items to be procured outside of BNL. This cost will be offset by $34 million to account for work done by Reactor Division staff already supported by BES funding over the two year period while the reactor would be down. Thus, the net TPC is $148 million including contingency. Given the very large contingency, Brookhaven (and the panel) believes that the project could be completed at this cost, even with re-working or replacing the thermal shield.

A significant feature of the HFBR upgrade is that a creation of world-class cold neutron capabilities will be attained with no increase in reactor operating cost. A $6M increase required primarily for scientific operations will increase overall yearly cost from $25 to $31M. This increase is dominated by the markedly increased costs of the outside user program. The ideal timeline presented by Brookhaven would lead to a shutdown of the HFBR in mid-2000 and restart in mid-2002. Thus successful completion of this upgrade would assure continuing operation of the HFBR with 30 world-class neutron beam facilities beyond the year 2025.

HFIR at Oak Ridge National Laboratory was commissioned in the mid 1960's at an operating power level of 100 MW for the primary purpose of producing transplutonium isotopes for a variety of medical, industrial, and military applications. Four neutron beam tubes, and numerous experimental facilities in and around the reactor core also provide access to very high neutron fluxes over a range of energies for use in beam research, materials irradiation testing, and neutron activation analysis.

HFIR currently operates at 85% of the design power. Surveillance specimens recovered from the reactor in 1986 showed greater than anticipated embrittlement of the pressure vessel after 17.5 effective full power years (EFPY) of operation. Following a lengthy DOE review, operation was resumed in 1989 at reduced power in conjunction with periodic hydrotesting of the vessel. That review also endorsed extension of the original 20 EFPY design estimate to 26 EFPY (2004-2005). A recent (1994) analysis indicates that the vessel life can be extended even further, to 50 ESPY, which would permit operation of the reactor at 100 MW until about 2035. This assessment is the most critical technical component of the upgrade proposal and it must be confirmed by DOE before committing to the present plan. The proposed changes to the reactor and support facilities are relatively minor variations of the original design and, as a consequence, could be implemented as part of the scheduled in-service inspection and replacement of the permanent beryllium reflector, which would minimize reactor down-time.

The principal objectives of the HFIR upgrade program are: i) development of an internationally competitive cold neutron scattering capability, and ii) enhancement of existing premier thermal neutron capabilities, while iii) improving isotope production, materials irradiation testing and neutron activation analysis capabilities. The first goal will be accomplished by inserting a small liquid hydrogen cold source in an existing tangential beam tube. Cold neutrons will be fed into a new cold guide room to be constructed adjacent to the existing reactor building. Three cold guides will service two small-angle scattering instruments, a reflectometer, and a high resolution triple axis machine, each projected to have ILL-like performance levels. Five thermal neutron guides, to be inserted into the existing radial beam tube, will deliver high flux thermal neutron beams to a new thermal guide hall. Nine instruments including 3-4 new ones are planned to be installed in the hall including powder and triple axis spectrometers, diffractometers, and residual stress devices. This thermal guide hall constitutes the most significant component of the proposed upgrade, providing the nation with exceptional capabilities that will complement other existing or proposed facilities in the U.S. A variety of enhancements to the existing materials irradiation, isotope production, and activation analysis missions are also planned. Notable improvements include a remote handling facility over the reactor pool, a neutron radiography beam, and new, enlarged pneumatic tubes for activation specimens.

Subject to the confirmation of the extended lifetime of the reactor vessel, the costs of the HFIR upgrade can be estimated with reasonable certainty. The TPC in constant FY 1996 dollars, measured as the increment over normal operation costs is $60.5M. This has been broken down into three categories: Enhancements of Neutron Scattering Mission ($38.6M); enhancements for materials irradiation, isotope production, and activation analysis missions ($16.5M); reactor improvements ($5.4M). $10.5M in internal and redirected ORNL funds have already been allocated to certain parts of this project leaving a net additional funding requirement of $50.0M. In its present form the proposed operating costs of the HFIR facility would increase only slightly due to the added costs of operating the cold source ($1.2M) and costs associated with an increased user program (~$2M). In an optimal schedule, the Be reflector would be replaced and the in-service inspection would be carried out in early 1999 with a 6-month shutdown. The cold and thermal guide halls would be operational in January 1999 and January 2000 respectively. This schedule phases well with the proposed HFBR upgrade schedule provided that the HFBR CDR is completed expeditiously.

We now state our basic recommendations:

RECOMMENDATION

The panel recommends strongly that the Department of Energy proceed with both the HFBR and HFIR proposed upgrades. These are extraordinarily cost effective proposals which will guarantee U.S. prominence in neutron research well into the next century. Without their implementation, even the continuation of current research on new materials and radiation effects as well as the production of certain isotopes is at risk. The HFBR upgrade will provide the U.S. with world class capabilities for both thermal and, most importantly, cold neutron research with steady state sources. The HFIR upgrade, which is more modest in scope, will strengthen the U.S. thermal neutron program especially for materials science. The Department of Energy should proceed immediately with both of these upgrades in a properly coordinated fashion. The conceptual design study for the HFBR must be started as soon as possible.

The total cost of the two upgrades is about $200 million. This should be compared with a "green field" cost for replacement of the HFBR and HFIR of about $2 billion dollars. It should be emphasized that the HFIR upgrade which we strongly endorse would not by itself meet the country's needs. Specifically, our largest deficit with respect to Western Europe is in cold neutron research which has become increasingly important as the classes of materials studied with neutrons become more complex. In particular, these include industrially important polymeric and soft materials as well as biological materials. The HFBR upgrade is essential to meet this cold neutron shortfall. Finally, to realize the full benefit of an HFBR upgrade it is essential that the reactor operating power be 60 MW, and we urge that the steps necessary to return to this power level begin immediately.

2. INTRODUCTION

Neutron science and especially neutron scattering have been essential components of the U.S. scientific and technological armory for nearly five decades. Indeed, the pioneering research carried out by C.G. Shull at Oak Ridge National Laboratory in the late 1940’s and early 1950’s which served to establish much of the basis of modem neutron diffraction was recognized by the 1994 Nobel Prize in Physics. In the 1960’s three premier research reactor facilities were commissioned in the United States, the High Flux Beam Reactor (HFBR) at Brookhaven, the High Flux Isotope Reactor (HFIR) at Oak Ridge and the NBS Reactor (NBSR) at NIST. These facilities provided the U.S. with world leadership in this field for at least the next decade.

Unfortunately, these U.S. facilities were eclipsed by the commissioning and development of the Institut-Laue Langevin reactor in the 1970’s. The ILL, which by all standards is a remarkable success, has been an extraordinarily well-supported user facility. ILL has 2 optimized cold sources each with a well-instrumented guide hall. Indeed there are now in Western Europe 6 well-instrumented guide halls. By contrast, in the United States there is only one guide hall, the recently commissioned cold neutron guide hall at NIST. In addition, our premier research reactors are now about 30 years old and their continued operation is by no means certain.

A similar situation to that described above for beam reactors pertains for pulsed spallation sources (PSS). Because of widespread concern about the progressively weakening U.S. position in this most important field, in 1992 the Department of Energy through the Basic Energy Sciences Advisory Committee (BESAC) formed a Panel on Neutron Sources. The purpose of this panel, which was chaired by Prof. Walter Kohn of U.C. Santa Barbara, was to report on key issues concerning possible new neutron sources, emphasizing especially the comparison of reactors and PSS’S.

In the autumn of 1992 the Kohn Panel carried out a thorough and wide-ranging study of current and future neutron science and neutron facilities in the United States. The Panel concluded that neutrons had become an increasingly indispensable tool in broad areas of the physical, chemical, biological and geological sciences as well as materials technology and medicine. They concluded further that the United States was woefully behind our major international competition in the availability of up-to-date sources and instrumentation.

After reviewing different alternatives for capability and cost effectiveness, the Panel concluded (see Appendix 2) that the nation had a critical need for a complementary pair of sources: a new reactor, the Advanced Neutron Source (ANS), which would be the world’s leading neutron source and a l-MW pulsed spallation source, more powerful than any existing PSS and providing crucial additional capabilities, particularly at higher neutron energies. The ANS was the Panel’s highest priority for rapid construction. In the Panel’s view, any plan that did not include a new, full-performance, high-flux reactor would be unsatisfactory because of a number of essential functions that could be best or only performed by such a reactor.

Unfortunately, because of budgeting exigencies Congress in 1995 concluded that the ANS was not economically feasible in the foreseeable future and instead recommended the design and construction of a next generation pulsed spallation neutron source. This then raised the urgent question of how the country most effectively could meet the important scientific and technical needs identified by the Kohn Panel which are optimally or uniquely addressed by steady state neutron sources. Accordingly, this present panel was convened by Dr. Martha A. Krebs, Director of the DOE Office of Energy Research to consider the following questions: **Is there a compelling need to continue operation of high flux reactors until and after the spallation neutron source is completed? If there is need to continue operations, are upgrades necessary to meet research needs? If so, what upgrades are needed? Should both be upgraded?** It was further requested that the total cost of each upgrade considered be kept below $100 million dollars.

The membership of this BESAC Reactor Upgrade Panel is as follows:

Robert J. Birgeneau (Chair)
Massachusetts Institute of Technology
School of Science
(Condensed Matter Physics)

Frank Bates
University of Minnesota
Department of Chemical Engineering
(Complex Fluids)

Mujid Kazimi
Massachusetts Institute of Technology
Department of Nuclear Engineering
(Reactors)

Anthony Kossiakoff
Director, Protein Engineering
Genentech, Inc.
(Biology)

Tawfik Raby
Chief, Reactor Operations & Engineering
NIST, Reactor Radiation Division
(Reactors)

John J. Rush (Vice-Chair)
Material Science and Engineering Lab
National Institute of Standards
(Chemistry)

Michael Crawford
E.I. DuPont Co.
Central Science & Engineering Dept.
(Materials)

Bernhard Keimer
Princeton University
Department of Physics
(Solid State Physics)

David Long Price
Material Science Division
Argonne National Laboratory
(Disordered Materials)

Theodore R. Schmidt
Executive Staff
Sandia National Laboratories
(Reactors)

Parallel to this, two additional panels were formed, one to recommend on the nature of the putative 1MW PSS and the other to assess proposed upgrades of existing spallation sources. The reports of these two committees should be read in conjunction with the present document. The Kohn Panel report provides the basis for all three new studies.

The format of this report is as follows. In Section 3, we describe current scientific and technical opportunities with neutrons with an emphasis on neutron scattering. We then review the international scene in neutron science followed by a summary of the proposed upgrades. Section 4 contains a description of the HFBR and HFIR upgrade proposals together with a discussion of their complementarity. Section 5 contains our conclusions and recommendations. In a set of appendices, we collect ancillary information including the authorizing letter from Dr. Krebs for this panel, a listing of the Kohn Panel recommendations and a discussion of the overall current situation vis-a-vis medical and industrial-use isotopes in the United States.

3. THE SCIENTIFIC & TECHNOLOGICAL CASE

3.1 SCIENTIFIC & TECHNOLOGICAL OPPORTUNITIES

3.1.1 Condensed Matter Physics

Since the pioneering work of Shull and Brockhouse, neutron scattering has played an eminent role in condensed matter physics. Neutron spectroscopy is the only experimental technique capable of providing maps of the vibrational and spin excitation spectra of condensed matter systems over wide ranges of energy and momentum. Detailed information about these collective modes is often unobtainable by any other means and has proven crucial for many seminal developments in the field. To name a few, theoretical constructs such as the "soft mode" mechanism of structural phase transitions and the "roton minimum" in the vibrational spectrum of liquid helium could not have been directly verified without neutron scattering. Modem many-body theory and statistical mechanics have drawn major motivation and experimental support from neutron scattering studies of the dynamics and critical behavior of localized and itinerant spin systems. As another example, phonon spectra and electron-phonon interaction parameters measured by neutron scattering are indispensable ingredients in our present quantitative description of conventional superconductors.

As a structural probe neutron diffraction is unique by virtue of the neutron's ability to penetrate deeply into the bulk of most materials and the existence of a large magnetic neutron scattering cross section. The often complex spin arrangements in a vast number of magnetic materials and artificial multilayer systems have been determined by neutron diffraction. Neutron diffraction has also played a key role in elucidating the properties of the flux line lattice in type-II superconductors and the interplay between magnetic order and superconductivity in rare-earth ternary and heavy fermion materials. In addition, its great sensitivity to important light elements such as hydrogen and oxygen makes neutron diffraction a powerful and often unique probe of the lattice structure of new materials.

Not surprisingly, this trend has continued over the past decade as numerous exciting new materials have been discovered. The last ten years have seen a revolution in our understanding of transition metal oxides, driven in part by the promise of technological applications of high temperature superconductivity in the cuprates and, more recently, extremely large magnetoresistance effects in manganate perovskites. Neutron scattering has played a central role at all stages of research on these materials, from the determination of their crystal structures to the discovery of magnetic fluctuations which provide direct and incisive information about their microscopic electronic states. Progress in the quest for a microscopic theory of strongly correlated electron systems, currently at the frontier of condensed matter physics, depends critically on information derived from such experiments. Important recent results which have given new directions to the field include the discovery of novel spin density wave, charge density wave and spin-charge modulated phases in transition metal oxides, and the detailed determination of the spin correlations in quantum spin chain compounds.

Neutron scattering has also played an outstanding role in revealing both the static and dynamic aspects of systems without translational long-range order, such as random and geometrically frustrated magnets, classical and quantum liquids, amorphous solids, and glasses. For. example, glasses relax on long time scales and can be very efficiently studied by cold neutron spectroscopy. Indeed, experiments using the neutron spin-echo technique were the first to reveal the dynamical aspects of the glass transition at a microscopic level.

Small angle scattering of cold neutrons has also recently been very successful in providing microscopic information about the structure and phase behavior of flux line arrays in high-T, and other superconductors, both in equilibrium and under current flow. The statistical mechanics of these systems is currently of intense interest, from both fundamental and applied perspectives. In contrast to other imaging techniques, neutron diffraction probes the entire length of the flux lines in the bulk of the superconductor and is applicable over a wide range of magnetic fields and temperatures.

Most studies of collective excitations have been carried out with triple-axis spectrometers in high flux reactors. These instruments have proven uniquely efficient in detecting response functions which are localized in energy and momentum space and allow for the effective use of spin polarization analysis. With the implementation of continuing innovations in measurement technology, reactor-based triple-axis spectrometers are expected to remain the mainstay of neutron spectrometry in condensed matter physics for many years to come. The proposed upgrades are vitally important for the preservation and modernization of the fund of existing instruments. A new cold neutron guide hall at Brookhaven would provide vastly enhanced opportunities for the rapidly growing applications of cold neutron research in condensed matter physics.

3.1.2 Materials Science

The value of neutron scattering and absorption to materials science is indisputable. The wide range of available neutron techniques can be used to probe many important materials properties including magnetism, short and long range order, crystal structures, molecular and ionic dynamics, impurity concentrations and spatial distributions, stress and strain, and the effect of extreme conditions of temperature and pressure upon many of these properties. The insensitivity of neutron scattering lengths to atomic number gives neutrons distinct advantages over x-rays for the determination of the crystal structures of materials composed of both light and heavy elements, such as the high temperature superconductors and numerous catalytic materials such as polymorphs of $A1F_3$ and zeolites.

The cold neutron capture prompt gamma activation analysis technique has the unique ability to measure quantitatively hydrogen concentrations in materials, and this information is directly related to issues as different as the durability of metallic components of machinery such as aircraft turbine blades and hydrogen analysis in proton conductors for fuel cells.

The new giant magnetoresistive perovskite oxides are presently being explored with neutron scattering techniques both to elucidate the crystal structures of these materials at various temperatures and to unravel the nature of the magnetism which is so strongly coupled to their electronic transport properties. These unusual properties may find use in a future generation of magnetic recording systems.

Properties of many types of thin films such as magnetic multilayers and polymeric films, are accessible to cold neutron reflectometry, and neutron depth profiling allows the near surface distributions of a number of isotopes to be determined. The latter type of studies have been of importance to the semiconductor industry where, for example, near surface distributions of implanted B in Si wafers have been measured.

Neutron scattering provides important insights into structure-property relationships in disordered materials, enabling design of optimized materials for new technological applications. Metallic glasses have unique mechanical and magnetic properties which make them the preferred choice for many industrial uses. Amorphous semiconductors have wide use in the electronics industry and solar energy conversion. Molten salts have important applications in electrochemical industry which are as wide ranging as plating of steel and waste treatment. Understanding of aqueous solutions is essential in electrochemistry (corrosion), solution crystal growth, biological structures and functions, and has increasing relevance for the development of biomaterials. Non-aqueous solutions such as Li-loaded polymers have new applications as light-weight batteries. Glasses are essential components in the fiber-optics industry for long-distance communication. Integrated optical systems including lasers and transmission channels are becoming the cornerstone of the modem opto-electronics industry, while improved characterization of oxide liquids and glasses is crucial for understanding the detailed structure of the earths mantle. A knowledge of the relationships existing between structure and macroscopic properties is essential for optimizing materials for such applications. In some cases neutron scattering by itself can supply the required information. In others, complementarity with other techniques can be exploited. For example, the use of neutron scattering combined with anomalous x-ray scattering at synchrotron x-ray sources can often provide a complete picture of the structure of a multicomponent system.

Finally, the relevance of many neutron techniques to American industry should be emphasized. The greater availability of high flux neutron sources, particularly cold neutron facilities, will enhance the ability of such measurements to contribute to materials science research and development in corporate laboratories large and small.

3.1.3 Polymers and Soft Materials

Over the past few decades a new class of materials exhibiting both solid-like and liquid-like phenomena has emerged as a major commercial enterprise. Polymers, colloidal suspensions, surfactant assemblies, and a wide range of biological composites constitute this diverse and complex group of compounds often referred to as soft materials or complex fluids. Unlike conventional solids and liquids, soft materials generally combine short-range disorder that tends to reduce the modulus of elasticity with some degree of long-range order that impedes simple Newtonian flow. Despite their great practical importance in products like plastics, bulk elastomers and adhesives, cosmetics and food, the understanding of soft materials has until recently been chiefly Edisonian.

However, during the last decade we have witnessed a dramatic expansion of activity in this area, due in large part to the availability of advanced structural probes that access length scales from several to hundreds of nanometers. One feature that makes neutron scattering uniquely attractive to the investigation of soft materials is the contrast between the proton and deuteron, which affords a simple and chemically benign means of labeling molecules. This led to the quantitative characterization of molecular shapes and sizes in polymer melts, which is central to the understanding of the processing and properties of plastics and rubbers. Through contrast matching with heavy and light water, neutron scattering offers the most effective method for unraveling the complex molecular arrangements that lead to surfactant stabilized oil and water microemulsions, and lipid-based cell membranes. Identifying how block copolymers and Langomuir-Blodgett films organize as thin coatings on semiconductor and other organic and inorganic substrates requires neutron reflectivity measurements. Accessing the desired static or steady-state properties in commercial products inevitably requires non-equilibrium processing. The deep penetration power of neutrons permits investigation of these processes under actual confined conditions. The capability of monitoring the rate at which the systems approach equilibrium can provide an important link between the thermodynamic and mechanical driving forces that govern the kinetic response of the system.

Some of the largest sectors of the American chemical industry rely on commercial processes such as injection molding, extrusion, mixing and coating that involve polymers, microemulsions, gels, and other complex fluids that are best optimized based on knowledge acquired through small-angle, backscattering, and spin-echo neutron scattering, and neutron reflection. These studies require the highest possible cold neutron fluxes. It can be generally stated that the availability of high flux neutron sources, with the best possible capability in cold neutron research, will play an important role in giving American industries a competitive edge in future soft materials world markets.

3.1.4 Chemistry

The application of neutron scattering and trace analysis methods in chemistry is of growing importance and diversity. The trend is toward measurements requiring higher resolution and or greater sensitivity. As pointed out in the Kohn Report the power of modem neutron methods to measure atomic and molecular processes over eight orders of magnitude in time (10^{-6} to 10^{-14} s) and energy (10^{-9} eV- 1 eV) with a wave-vector regime(10^{-3} - 10 nm^{-1}) tuned to geometric features from the atomic to the micron scale has wide impact in chemical applications.

There has been an enormous increase in recent years in the application of high resolution powder diffraction and spectroscopy in studies of new molecular solids (e.g. fullerenes), newly tailored zeolites and other cage-like oxides for chemical catalysis, sieves and storage materials, and a host of other materials including fast ion conductors, non-linear optical materials, etc. Moreover, new developments at high performance reactors in Western Europe, and more recently at NIST and other U.S. facilities, have created new approaches in the use of neutron guides and choppers, focusing and polarizing devices, and large monochromator arrays to increase greatly sensitivity for studies of molecular bonding states and dynamics at high resolution, particularly for subthermal neutrons. This has greatly enhanced the ability to study small samples of new chemicals, dilute concentrations of molecules in disordered molecular solids, catalysts, alternative refrigerant storage systems, new multilayer materials and even time-studies of molecular scale curing processes in concrete, to mention a few examples.

The recent development of in-situ, non-destructive analysis of chemicals and other materials by cold-neutron prompt-gamma analysis with focused cold neutron beams is also having an increasing impact on chemical research with neutrons, providing trace and stoichiometric assays of great importance in diverse applications including, e.g., chemical synthesis studies, quantification of Bronsted sites in solid acids, and environmental and food and drug surveillance. In addition, neutron reflectivity is being used or explored in an increasing number of important interfacial studies, in areas such as electrochemistry and Langmuir-Blodget films. Current trends in chemical research often involve the sequential use of cold neutron spectroscopic methods with powder diffraction and in-situ chemical analysis, along with molecular dynamics simulations - with a widely expanding university and industrial user community.

3.1.5 Biology

Structural biology is one of the most intensely studied areas in science. This interest is driven by the revolution in molecular biology that allows the facile cloning, mutageneses and expression of biologically important molecules. Neutron scattering has the potential to play an expanding and fundamental role in the structure elucidation process because it has the capability to observe certain types of structural features not attainable by other techniques. These special properties are derived from the neutron technique's ability to locate hydrogen and deuterium atoms in macromolecules. To appreciate the importance of this feature it should be recognized that about one-half the atoms in a biological macromolecule are hydrogen, and much of the chemistry of building blocks of biological systems is driven by hydrogen and water and their interactions particularly hydrogen bonding. Neutron structure studies span orders of magnitude in length scale in the detail they provide. They range from studies of partially ordered biological samples at low resolution that give information about orientations of proteins in complicated macromolecular assemblies, to high resolution crystallography where atoms in a protein molecule can be precisely located.

Wide use of neutron scattering has been limited by the fact that there are few neutron sources with the flux and appropriate wavelength spectrum to study biological systems effectively. The proposed upgrades offer exciting possibilities to extend significantly the viability in this country of using neutron scattering for biological structure analysis. Increased cold neutron capabilities are of particular importance. Longer wavelengths have been the mainstay for low angle studies for some years. Recently new technologies for example, image plates have been proposed in neutron Laue crystallography using 3-5 Å neutrons that will not only increase the throughput of protein crystallography projects by at least an order of magnitude, but also make possible many projects that simply could not be attempted under current situations. Increases in the availability of high neutron fluxes at subthermal energies would have a major impact on structural biology. This will set the stage for investigating a whole new set of biological problems. not addressable by other techniques.

Examples of important areas in neutron biological structure that would be greatly enhanced include: 1) high resolution crystallographic studies of the detailed role of water and hydrogen-bonds in protein folding, enzyme reactivity and the stereochemistry of protein-protein interactions; 2) medium resolution studiesof proteins and protein complexes embedded in lipids; and 3) unique measurements by neutron reflectivity of molecular arrangements on biological surfaces like membranes. This latter technique should be a very powerful method to obtain information about changes in organization of multimolecular complexes undergoing transitions between their inactive and active forms. Such changes in molecular organization have been proposed, for instance, as a method whereby cell-surface receptors communicate biological signals into cells. Finally, cold neutron inelastic scattering capabilities are required to open up new opportunities in studies of biological dynamics which are expected to supply information crucial to understanding biological functions and processes.

3.1.6 Other Applications

There are a number of other critical neutron applications which demonstrate the long term need for access to the high integrated fluxes provided by high performance reactors such as the HFBR and HFIR. These important national needs, which are amply summarized in the Kohn Report, include isotope production, materials irradiation for fission and fusion power, trace analysis, and production of sources for positron research. In particular, the long-term assurance of the U.S. supply of isotopes for medical, industrial, and research purposes is a major national issue. An updated summary of the US and DOE isotope needs and programs is provided in Appendix 3.

Some of the examples discussed above are presented together in Table 1.

Table 1: Some examples of neutron scattering techniques in a number of scientific research areas (see text for details).

	Neutron Techniques					
	Diffraction	Inelastic Scattering	Small Angle Scattering	Quasielastic Scattering[1, 2]	Reflectivity [1]	Activation Analysis[3]
Condensed Matter Physics	magnetic structures, short and long range order	phonons, magnetic excitations, rotons in He	flux line lattices in superconductors	glass dynamics		
Materials Science	crystal structures of superconductors, magnetoresistive oxides			diffusion	thin films, surface depth profiling	trace element analysis
Chemistry	fullerene and catalyst structures	adsorbates on catalyst surfaces			electro-chemistry, Langmuir-Blodgett films	acid catalysts environmental research
Polymers & Soft Materials	polymer structures	vibrational spectroscopy	structures of polymer melts and micro-emulsions	polymer dynamics	polymeric thin films	
Biology	protein crystal structures		tertiary structures of proteins	dynamics of biological macromolecules	biological membranes	

[1] Cold neutrons are particularly useful for these techniques.
[2] Including time-of-flight, backscattering and spin-echo techniques.
[3] For example, neutron activation and prompt gamma activation analyses.

3.2 THE INTERNATIONAL ARENA

A detailed overview of Reactor Neutron capabilities worldwide was provided in the Kohn Panel Report three years ago. Since that time, in Western Europe, the ILL has been refurbished for an additional 25 year lifetime, including a replacement of the reactor vessel (completed in 1995), and the upgraded Berlin and Julich reactors have come on line with new cold and thermal neutron facilities. The new JRR III reactor in Japan has also come into full operation with 25-30 neutron instruments, including a cold neutron guide hall. In the United States during this period the Cold Neutron Research Facility at NIST has come into full operation and several other thermal neutron instrument improvements have come on line at HFBR and HFIR.

By far the greatest lag in U.S. research reactor capabilities is in cold-neutron research, which is the fastest growing area of neutron research applications worldwide. Examples of important new scientific applications of cold neutrons are given in the previous section. Whereas Western Europe now has six cold neutron guide halls with state-of-the-art instrumentation (~60 beam instruments) the U.S. has only one state-of-the art instrumented guide hall at NIST with 12 instruments and 3 under construction, plus 3 less optimized cold neutron instruments at BNL. Moreover, the German and Bavarian governments have approved 500M$ (European accounting) for the construction of a modernized design high flux reactor with cold source capabilities essentially equal to those of the ILL. If steps are not taken by the DOE, this facility, when completed in about 2002, will leave the U.S. even further behind.

The consequences of the dearth of modem neutron facilities in the U.S. compared to Western Europe is demonstrated by the relative user communities. In Western Europe, neutron beam users exceed 4000, a number similar to the synchrotron radiation community. By comparison the U.S. neutron community, in spite of being doubled in the last decade is -1700. Neither of these figures includes neutron-rich isotope applications which vastly increase the impact of reactor neutron sources. As an example of the rapidly emerging need for state-of-the art neutron instruments, particularly for cold neutrons, the number of NIST research participants has increased by a factor of 3 since the CNRF opened in 1990. However, this single facility cannot meet expected future demands. Thus our country faces increasingly inadequate capabilities to meet growing scientific and engineering applications of small angle scattering, high resolution spectroscopy, in-situ chemical trace analysis and other emerging neutron methods in chemistry, physics, biology and materials research. These needs were identified by the Kohn panel in 1993 and have only increased over the last several years.

3.3 THE FUTURE

As noted previously in its report of January 1993, the Kohn Panel (Appendix 2) made two principal recommendations:

1. Complete the design and construction of the Advanced Neutron Source (ANS) according to the schedule proposed by the project.
2. Immediately authorize the development of competitive proposals for the cost-effective design and construction of a 1-MW Pulsed Spallation source (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.

As is well known, the ANS project was terminated and the ANS itself was postponed indefinitely in the President's budget for the Department of Energy (DOE) for Fiscal Year 1996, nullifying the first recommendation. The same budget proposed the development of a l-MW PSS, in line with the second recommendation. The Congress conferees reviewing the DOE request instructed the Department to determine the siting of this project in a "fair and unbiased manner" and, at the same time, directed the Department to "evaluate opportunities to upgrade existing reactors and spallation sources as cost-effective means of providing neutrons in the near term for the scientific community while the next generation source is developed." The present report is issued, at the request of Dr. Martha Krebs, Director of the DOE Office of Energy Research, as part of this evaluation process.

It was made clear in the Kohn Panel's 1993 report that, while a 1-MW PSS offers exciting prospects for many types of neutron scattering experiments, there are areas of science, including cold neutron beam research, materials irradiation and isotope production, where reactor neutron sources are essential. As we discuss in detail in the final section of this report, it is the strong opinion of this panel that upgrading and ensuring the continued operation for the foreseeable future of the nation's two high-flux reactors, the HFBR at Brookhaven National Laboratory and the HFIR at Oak Ridge National Laboratory, are essential for the well-being of U.S. science and technology for the next quarter century.

4. PROPOSED UPGRADES AND NEW CAPABILITIES

4.1 HFBR Proposed Upgrade

The High Flux Beam Reactor at Brookhaven National Laboratory is the nation's premier thermal neutron beam reactor, with 9 high flux beams currently serving fifteen neutron scattering instruments. The HFBR, which was commissioned in 1965, pioneered a new concept in production of high thermal fluxes in the reflector surrounding an undermoderated core. At 60 MW power the peak thermal flux is 1.2 x 10^{15} n/cm^2-s and all the thermal beams view unperturbed fluxes ~10^{15} n/cm^2-s with low contamination of epithermal and fast neutrons. The present cold neutron source is installed in a flux region down by a factor of 4 from the peak flux and does not provide optimal performance. The HFBR also serves a number of other applications, including the production of isotopes, such as Sn- 117 for treatment of bone cancer, nuclear physics, neutron trace analysis and production of a high intensity source for positron research.

During the last three decades the HFBR neutron scattering program has made major seminal contributions to many areas of science, including condensed matter physics, structural biology and chemical structure research. The major thrusts of the Brookhaven proposal are to expand greatly the capability of BNL and the U.S. in cold neutron research, the fastest growing area in neutron science, and to carry out a major refurbishment to extend the lifetime of the reactor by at least 25 years.

The HFBR upgrade proposal involves a replacement of the aluminum reactor vessel, whose lifetime is largely determined by radiation embrittlement, to assure an extension of operating lifetime beyond 2025. As part of this replacement, the hydrogen cold source thimble will be extended 30 cm into a flux region about three times that of the existing source, and accessibility will be improved to allow up to five neutron guide tubes to visualize the source, utilizing the latest supermirror coating technology to provide high cold neutron fluxes for many instruments. The Brookhaven plan would extend these guides into a new 16000 square foot cold neutron guide hall to allow the development of up to 15 new cold neutron instruments, whose capabilities would closely match the world's best cold neutron capabilities at the Institut Laue Langevin. Two additional floors below the guide hall would provide needed offices, laboratories and storage space to support the much expanded needs of users and BNL staff. Successful development of this new facility together with the smaller facility proposed at Oak Ridge would more than double the current U.S. cold neutron capabilities, thus addressing the most urgent U.S. scientific and technological needs in neutron research. An important component of the Brookhaven plan is to precede the upgrade with a return of the HFBR to its 60MW power level. This is clearly essential if the projected equivalence to the ILL is to be achieved.

The most difficult part of the upgrade is the reactor refurbishment. It is clear that the plan to replace the reactor vessel is feasible, as evidenced by the recent completion of a very similar vessel replacement at the ILL reactor in Grenoble. There are some uncertainties, however, which cannot be resolved at the outset, particularly the issue of whether or not the thermal shield should be replaced as part of the refurbishment. Such a replacement, if deemed necessary, can be achieved, but at an increase in cost and project completion time of up to a year. The BNL fiscal plan has covered any likely cost increase necessitated by this replacement by adding an exceptionally large contingency (60M$).

4.1.1 Reactor Issues

The proposed HFBR upgrades do not involve changes in the core design, which implies that the prior experience of the reactor during 1982 to 1989 when it operated at 60 MW remains relevant and testifies to the feasibility of renewing operation at this level once the safety questions are satisfactorily resolved. Two questions had arisen during the shutdown period of 1989-1991 which led to limiting the power level to 30 MW. These issues are the flow reversal following loss of pump power, and the shutdown capability under seismic loading condition. In order to answer the first issue, thermal hydraulic tests have been undertaken at Columbia University. The results of these tests have convinced BNL safety staff and an external review committee that flow reversal can occur without fuel damage, and with considerable safety margin, if the reactor operated at 60 MW. Based on these tests, DOE is currently reviewing a BNL request to increase power to 40 MW. To operate at the 60 MW level, additional analysis of the seismic loadings are contemplated by 1998 which will again require DOE approval.

A review of the life-time limiting components of the HFBR has determined that the vessel and the thermal shield are the two critical components. The aluminum vessel has been losing ductility due to neutron irradiation which reduced its tensile elongation from 10% to 7%, still much higher than the minimum allowable level of 2%. Nevertheless, lack of data on the life-time of aluminum at much higher levels of neutron fluences suggests that it is prudent to replace the vessel in the near future to ensure long operational time in the next century. Additionally, the thermal shield has shown significant loss of fractional toughness, which largely occurred during the early years of operation. While the 30 year operating history suggests the lack of crack initiation mechanisms, and any shield failure does not present a reactor safety issue, it could be desirable to use the vessel disassembly time to renovate the shield, or perhaps to replace it. It will be useful to examine methods for in-situ repair to minimize the potential downtime of the reactor in the event that the heat shield requires attention after refurbishment and re-start.

4.1.2 Scientific Capabilities

As stated above, the proposed HFBR upgrade is designed to meet the most critical emerging neutron research needs of the U.S. scientific community, namely for cold-neutron research instrumentation. The provision of up to 15 world-class cold neutron experimental stations, while extending the lifetime of the nation's highest flux beam reactor for at least 25 years, would provide absolutely critical capabilities for both medium and long-term needs of DOE and the nation.

Among the facilities suggested by BNL for development are three small angle scattering instruments, with varying resolution, two neutron reflectometers, five inelastic neutron scattering instruments, including medium and high resolution time-of-flight spectrometers, a crystal spectrometer, back-reflection and spin echo instruments, a neutron tomography station, a prompt-gamma trace analysis facility, and an optical bench dedicated to instrument development. Brookhaven has wisely maintained that this instrument profile should only be considered as representative. Recent experience at NIST and at the European and Japanese cold neutron centers has shown the necessity of responsiveness to new opportunities and scientific and technical needs. The panel feels strongly that Brookhaven and Oak Ridge should plan the development of the proposed new neutron beam instruments in coordination with NIST and the DOE pulsed sources to provide balanced capabilities for the U.S. This is particularly true, since successful completion of these upgrades would still leave the U.S. with less than half the number of state-of-the-art cold neutron facilities compared to reactors in Western Europe, particularly with the construction of the new Munich reactor (FRM II).

As outlined in the science updates in section 2, the proposed cold neutron facilities at the HFBR would make major and essential contributions to many of the most important areas of scientific and industrial concerns in physics, chemistry, biology and materials science - particularly as new products and technologies are driven by the properties of complex and "soft" materials. The BNL guide hall would provide, for example, critical new high-resolution measurement capabilities in studies of polymer structure and the submicron behavior of colloids and other complex fluids under stresses relevant to processing or applications; structure of thin films and interfaces of importance in the chemical, computer and magnetic recording industries; molecular dynamics and bonding in oxide catalysts and sieves; biomolecular structure features and dynamics important in biological function and biotechnology; and unique in-situ chemical trace analysis and tomographic imaging of many materials and structures directly relevant to their use in transportation, chemical processing and other technological applications.

The HFBR upgrade would greatly increase the spectrum of users at Brookhaven, including those from universities, industry, and government laboratories. The increased academic activity would have a strong positive impact on the training of students in neutron techniques. Experience at the ILL, NIST and other cold neutron centers suggests that the number and diversity of research participants at the HFBR could triple within a few years of completion of the upgrade. Successful development and service to the U.S. user community will only be possible if adequate funds are added to the Brookhaven neutron budget for cold-neutron facility maintenance and operations. This will be discussed briefly in the next subsection.

Finally, in our examination of U.S. neutron research needs, the panel concluded that it is important for the DOE to provide necessary funding (~2M$) for the development of a hot neutron source, most likely at the HFBR. While existing and future pulsed sources will meet most needs for higher energy neutrons (~100-500 meV), the availability of one U.S. reactor hot source for studies, for example, of high energy excitations in materials, quasielastic scattering in magnetic systems, and for crystallography and liquid diffraction applications is, in our view, very important.

4.1.3 Cost and Schedule

The projected cost of the HFBR proposal, which is the more ambitious of the two proposed upgrades, has a considerable uncertainty and cannot be ascertained accurately until the completion of the CDR. Brookhaven supplied our Committee with bounding direct costs estimates of between 81M$ and 162M$, based upon a feasibility study from an engineering consultant firm, Gilbert/Commonwealth (G/C)/ The large range reflects both uncertainty in the project scope (whether or not to replace the thermal shield) and the (unsubstantiated) sense of a BNL-sponsored expert review that the G/C estimates were low. Subsequently, at our urging, BNL has supplied us with a preliminary estimate for the total project cost (TPC, which in addition to direct costs includes overhead, pre-construction R&D, pre-operation start-up costs, etc) for what they consider to be the most likely project scope. The estimated TPC is 182M$ FY96$ including a 100% contingency of 60M$ on items procured outside BNL. Taking into account 34M$ of services to be provided by Reactor Engineering and other staff, this provides an estimated incremental cost of 148M$, including 62M$ for experimental facilities including the cold source, guides, guide hall and 15 instruments. Given the very large contingency, BNL (and the panel) believes that the project could be completed at this cost even with re-working or replacing the thermal shield. This contingency can be reduced only by a proper CDR.

The BNL schedule is clearly dependent upon the completion of a CDR including a decision on the thermal shield. The panel strongly urges the DOE to provide funding for this step at the earliest possible time. Given completion of the CDR by the end of 1997, Brookhaven anticipates that the project could be completed, including the first complement of instruments, by the year 2003.

Finally it should be noted that the HFBR upgrade is highly cost effective in terms of increased operating costs. Reactor and cold source operations are estimated to increase by less than 10% to 25M$ due to the increase in reactor power to 60MW. Total yearly operating costs, including the panel's estimate of a 6M$ increase for scientific operations, will be 31M$ (FY '96), or approximately one-half of the reactor and scientific operating costs at the Institute Laue-Langevin. The increase for user support is essential to serve the hundreds of additional scientists and engineers who would use the HFBR facilities.

4.2 HFIR Proposed Upgrade

Oak Ridge National Laboratory currently operates the highest thermal neutron flux research reactor in the Western World. HFIR was commissioned in the mid 1960's at an operating power level of 100 MW for the primary purpose of producing transplutonium isotopes for a variety of medical, industrial and military applications. Four neutron beam tubes, and numerous experimental facilities in and around the reactor core, also provide access to high neutron fluxes with a range of energies for use in beam research, materials irradiation testing, and neutron activation analysis. ORNL proposes to upgrade this facility in order to enhance its potential to serve the neutron scattering community while maintaining or improving irradiation and isotope production capabilities.

HFIR was designed to accommodate a wide range of irradiation facilities for the purpose of producing transplutonium elements and other isotopes requiring high neutron fluxes. For many needs HFIR offers unique capabilities. For example, Californium-252, which is only produced in the western world at ORNL, finds applications in several forms of cancer research and nuclear power applications, along with radiography uses in DOD, DOE and NASA laboratories. The need for a wide range of medical radioisotopes is increasing in the U.S., and HFIR will play a key role in meeting future demands. Commercial radioisotopes such as Iridium-192, which is used to examine metal welds by gamma radiography, are currently produced at ORNL. In addition the materials testing facilities at HFIR provide a crucial mix of radiation environments for the evaluation of new fusion and fission reactor materials. These isotope and materials irradiation capabilities represent the major mission of the HFIR. Neutron scattering for materials research is an important secondary mission.

The principal objectives of the HFIR upgrade program are i) development of several internationally competitive cold neutron scattering instruments, and ii) better utilization of the high flux thermal beams at the HFIR, while iii) improving isotope production, materials irradiation testing and neutron activation analysis capabilities. The first goal will be accomplished by inserting a liquid hydrogen cold source in an existing tangential beam tube. Cold neutrons will be fed into a new cold beam room to be constructed adjacent to the existing reactor building. Cold guides will service two small-angle scattering instruments, a reflectometer, and a high resolution triple axis machine, projected to operate with performance levels equivalent to or better than ILL. Five thermal neutron guides to be inserted into the existing radial beam tube will deliver very high flux thermal neutron beams to a new thermal guide hall with lower background from fast neutrons. Nine instruments are planned for this hall for materials research, including 3-4 entirely new machines. This thermal guide hall constitutes the most significant component of the proposed upgrade, providing the nation with exceptional capabilities, which will complement those at other existing or proposed U.S. facilities. Overall this upgrade will produce seven new thermal or cold instruments, giving HFIR a total of 18 scattering instruments.

A variety of enhancements to the existing materials irradiation, isotope production, and activation analysis missions are also planned. Notable improvements include a remote handling facility over the reactor pool, a neutron radiography beam, and new, enlarged pneumatic tubes for activation specimens.

4.2.1 Reactor Issues

The HFIR upgrade program is designed to minimize the impact on the reactor and involves no changes in the reactor core configuration, fuel type, or power level. Since 1989, the reactor has operated at 85 MW, while from 1966 to 1986, the reactor operated to 100 MW The Safety Analysis Report is currently being modernized to support a return to a power level of 100 MW. The proposed modifications within the vessel region involve changes in the target bundle, five additional rabbit tubes, enlarged neutron activation analysis pneumatic tubes, and the addition of a cold source in the HB4 beam tube.

Most of these changes involve the beryllium reflector which has been replaced twice before and is due for replacement in 1999. The proposed changes as well as the required in-service inspection can be made as part of this scheduled activity and thus reduce down time. Installation of a cold source presents no safety issues that have not been addressed at other facilities or during the ANS development. Location of the cold source in a beam tube may present some design challenges due to limited space.

A concern developed in 1986 for the integrity of the HFIR pressure vessel when surveillance specimens showed greater than anticipated embrittlement after reactor operation of 17.5 effective full-power years (EFPY). A conservative evaluation at that time concluded that the reactor vessel was capable of safe operation through 26 EFPY, corresponding to 2004-5. A new evaluation completed in 1994 indicated that the vessel life can be extended to 50 EFPY (2035) with probability of failure below 10^{-6}/year. It is anticipated that this analysis will be supported by periodic in-service inspections, hydrotests and surveillance specimen tests to validate the extension. As such, the HFIR vessel is no longer considered by ORNL to be a life-limiting component. This evaluation for vessel life extension is scheduled for an external peer review. We believe this assessment to be the most critical aspect of the upgrade proposal including costs, and must be confirmed by DOE before committing to the upgrade plan. If for some unforseen reason the present vessel proved unsuitable, ORNL has an alternate upgrade plan that would interpose a pressure boundary tube around the existing core. The current vessel would remain in place, but would no longer be a pressure vessel. This would involve modest increased cost.

In a reactor of this vintage, age and obsolescence are important issues. The ORNL program recognizes that other elements of the plant must be renewed. The plan includes renewal of emergency diesels, plant instrumentation and control systems, mechanical and electrical systems, control plates, and other ancillary systems.

4.2.2 Scientific Capabilities

The proposed improvements to HFIR will significantly enhance access for U.S. scientists and engineers to world class thermal and cold neutron scattering instrumentation. The most significant aspect of the HFIR upgrade deals with the construction of a thermal neutron guide hall to be serviced by five supermirror guides emanating from the HB-2 radial beam tube. At least nine spectrometers will be located in this facility including 3-4 entirely new instruments, which are projected to achieve performance competitive with the world's best. Two powder instruments, three diffractometers and two triple axis spectrometers will provide ORNL with a state-of-the-art thermal neutron scattering facility. A variety of important scientific subjects including magnetism, superconductivity, liquid state structure, catalysis, chemical crystallography and phase transitions in alloys will be imparted by this development. Oak Ridge National Laboratory has recently established the capability to characterize residual stress in engineering materials using neutron scattering. This enterprise has important commercial applications and the present facility is heavily over-subscribed. Two residual stress instruments that will operate at a significantly higher flux than that currently available at HFIR are planned for the thermal guide hall. These instruments will provide an important service for the U.S. structural materials community.

The proposed cold neutron beam hall, although it will be modest in size compared to the NIST facility or the large guide hall proposed for the HFBR, will house two high intensity, high resolution small-angle neutron scattering (SANS) instruments. Calculations indicate that the neutron fluxes available to these instruments will be comparable to those at the SANS equipment at ILL. SANS is one of the most versatile of the neutron scattering methods with a wide range of applications in fields as diverse as molecular biology, polymer science and engineering, surfactancy, colloids, porous media, superconductivity, and metallurgy. The feasibility of many SANS experiments hinges on flux limitations, particularly at longer wavelengths. Typical biological experiments, which require many hours of data collection at even the best sources, will become feasible at ORNL, along with studies of many transient phenomena, such as phase separation in polymer blends and solutions. Two other high intensity instruments, a reflectometer and a high resolution triple axis spectrometer, are also planned. Neutron reflectometry has become an important tool in inter-facial and surface science and engineering. Such instruments currently are heavily oversubscribed, so that the proposed HFIR instrument would provided needed new capabilities, particularly for the hardest experiments.

4.2.3 Costs and Schedule

The total estimated project cost in constant FY 1996 dollars, measured as the increment over normal operating costs is $60.5M. This has been broken down into three categories: enhancements of neutron scattering mission (38.16M); enhancements for materials irradiation, isotope production and activation analysis (16.5M); reactor improvements (5.4M). $10.05M in internal and redirected ORNL funds have already been allocated to certain parts of this project including the cold source and cold guide hall, leaving a net additional funding requirement of $50.0M. In its present form, the proposed operating costs of the HFIR facility would remain at current levels, aside from the added costs of operating the cold source and new user support. The latter two will lead to a net increase in operating cost of about $3M per year.

As stated above, aspects of the HFIR upgrade are already in motion. Internal ORNL funds are being applied to the cold source and associated guide hall. Because the reactor modifications are not major, they can be implemented with an estimated operating down time of about six months. The most attractive time period to schedule these improvements is during the in-service inspection and beryllium reflector replacement in mid 1998 or 1999. Subsequently, new beam tubes would be installed followed by construction of the thermal guide hall and the remote handling facility. Barring procedural or funding delays the reactor and beam hall projects could be completed by the year 2000 after which the instrumentation would be gradually brought into operation. This coordinates very well with the proposed HFBR upgrade schedule.

4.3 Complementarity

The Kohn Panel Report stressed the complementary nature and uses of reactors and spallation sources. 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 (10-100 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.

Both the report of the Kohn Panel and that of the Oak Brook review, which served as a major resource for the Panel, list numerous examples of the complementary nature of the two types of source. For example, cold neutron research is generally best done at reactors, while high-resolution powder diffraction experiments are best done at spallation sources. Experiments which rely solely on integrated flux are performed almost exclusively at reactors; these include activation analysis, neutron depth profiling, cold neutron radiography, and many nuclear and fundamental physics experiments. On the other hand, experiments that need high-energy neutrons require a PSS, including resonance radiography, high-energy-transfer spectroscopy, diffraction at high neutron energy and a different group of nuclear physics experiments. The Kohn report articulates some outstanding recent accomplishments where coordinated experiments at both steady state and pulsed sources have been crucial in attacking a particular scientific problem. A related symbiosis occurs between neutron and synchrotron x-ray scattering sources.

A further level of complementarity exists between two types of reactor, one optimized for high thermal neutron fluxes and one where a cold neutron source formed an integral part of the original reactor design. The U. S. is fortunate to have, in HFIR and HFBR, high-flux reactors which represent excellent performance in the two types of facility. This complementarity is nicely exploited in the respective upgrade proposals submitted by Oak Ridge and Brookhaven discussed in the previous subsections. The Oak Ridge proposal includes a thermal neutron guide hall with instruments generally optimized for performance at thermal energies (~10-100 meV), while the Brookhaven proposal includes a high-performance liquid hydrogen cold source and a cold neutron guide hall with a comprehensive set of cold neutron (~1-10 meV) facilities. In addition to the technical differences embodied in these two different approaches, they nicely complement each other from the point of view of scientific emphasis and the make-up of the respective user communities. The Oak Ridge proposal will provide outstanding capabilities for traditional areas of materials science, for example powder diffraction, residual stress analysis and materials irradiation, while the Brookhaven proposal provides unequaled opportunities for cold neutron research, especially in the areas of “soft” condensed matter and materials of increasing complexity, eloquently discussed in the proposal.

A new development subsequent to the Kohn Panel deliberations should be mentioned for completeness, although it is not included in the purview of the present Panel, namely the concept of the long-pulse spallation source proposed by Los Alamos National Laboratory. This type of source consists of a target placed in the beam of a high-current proton accelerator and includes moderators (of appropriate temperatures) whose dimensions are long compared with a typical neutron slowing-down length. This is in contrast to the thin moderators required to produce short pulses for the time-of-flight experiments that form the staple of spallation sources like the PSS discussed in the Kohn Panel report. While with present technology the integrated fluxes are an order of magnitude below those of the high-flux reactors, for particular experiments, notably those involving cold neutrons, this may be made up, and in some cases exceeded, by exploiting the high signal-to-background within the pulse and other features of the special time structure of these sources. It is not clear when, if ever, this type of source will out-perform a high-flux reactor capability or cost effectiveness. However, it appears to this Panel that a source of this type at reasonable cost and performance levels deserves further exploration.

5. CONCLUSIONS AND RECOMMENDATIONS

In this study we have reviewed and updated the Kohn Panel scientific and technological case for neutron science in the United States. We have confirmed their basic findings. In agreement with the Kohn Panel we have determined that neutrons have become an indispensable tool for large areas of physics, chemistry, biology and materials science. Cold and thermal neutron scattering are the most important scientific uses although there are also important applications for epi-thermal neutrons. Neutrons are especially useful for the study of light atoms (H, O, C, ...) in chemical and biological-materials and of excitations in condensed matter. We also concur that much of the scientific research using neutrons has had, and will have, large technological and economic payoffs. Examples of fruitful areas are plastics, magnetic materials, and high-temperature superconductors. Generally, neutrons are a critical research tool for the development of new and better materials. 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, and the analysis of stress distributions in metals and ceramics.

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. For problems which we deem to be of major importance over the next one or two decades, increased fluxes and improved instrumentation in the cold neutron energy range are of particular significance.

The highest priority of the Kohn Panel recommendation was the construction of a next generation steady state neutron source, the Advanced Neutron Source. As discussed in this report, because of budgeting exigencies Congress in 1995 concluded that the ANS was not economically feasible in the foreseeable future and instead recommended the design and construction of a next generation pulsed spallation neutron source. This then raised the urgent question of how the country most effectively could meet the important scientific and technical needs identified by the Kohn Panel which can be optimally or uniquely addressed by steady state neutron sources. This challenge was immediately met by both Brookhaven and Oak Ridge National Laboratories who have proposed significant upgrades to the HFBR and the HFIR, respectively. We have reviewed the technical and scientific aspects of both of these proposals in detail and we have confirmed their viability and integrity.

Our basic recommendations are as follows:

RECOMMENDATION

The panel recommends strongly that the Department of Energy proceed with both the HFBR and HFIR proposed upgrades. These are extraordinarily cost effective proposals which will guarantee U.S. prominence in neutron research well into the next century. Without their implementation, even the continuation of current research on new materials and radiation effects as well as the production of certain isotopes is at risk. The HFBR upgrade will provide the U.S. with world class capabilities for both thermal and, most importantly, cold neutron research with steady state sources. The HFIR upgrade, which is more modest in scope, will strengthen the U.S. thermal neutron program especially for materials science. The Department of Energy should proceed immediately with both of these upgrades in a properly coordinated fashion. The conceptual design study for the HFBR must be started as soon as possible.

The total cost of the two upgrades is about $200 million. This should be compared with a "green field" cost for replacement of the HFBR and HFIR of about $2 billion dollars. It should be emphasized that the HFIR upgrade which we strongly endorse would not by itself meet the country's needs. Specifically, our largest deficit with respect to Western Europe is in cold neutron research which has become increasingly important as the classes of materials studied with neutrons become more complex. In particular, these include industrially important polymeric and soft materials as well as biological materials. The HFBR upgrade is essential to meet this cold neutron shortfall. Finally, to realize the full benefit of an HFBR upgrade it is essential that the reactor operating power be 60 MW, and we urge that the steps necessary to return to this power level begin immediately.

The panel would like to conclude with one final observation. With the demise of the SSC, the United States has conceded leadership in particle physics to Europe. With the drastic cut in the FY97 DOE fusion budget, we have forfeited leadership in fusion energy research. It is our strong view that we must not also accept second class status in neutron science with its many benefits for U.S. science and technology.

APPENDIX 1
Charge Letter

Department of Energy
Washington, DC 20585

November 9, 1995

Professor Robert Birgeneau
Dean of Science
Department of Physics
Massachusetts Institute of Technology
Cambridge, MA 02139

Bob

Dear ~~Professor Birgeneau~~:

I would like to ask you to convene and chair a panel of experts for the Basic Energy Sciences Advisory Committee to help the Department decide the best course of action with regard to the future of the High Flux Beam Reactor at Brookhaven National Laboratory and the High Flux Isotope Reactor at Oak Ridge National Laboratory.

There are several questions that need to be answered. In view of the decisions to terminate the Advanced Neutron Source and begin the design of a spallation neutron source, is there a compelling need to continue operation of the high flux reactors until and after the spallation neutron source is completed? If there is need to continue operations, are upgrades necessary to meet research needs? If so, what upgrades are needed? Should both be upgraded?

There are severe budget constraints, and the expectation is that the constraints will become tighter. The total cost of each upgrade considered should be kept below $100 million. To reduce cost, the panel should consider the extent to which the upgrades can be done using the existing operating budget, as was done at the Institute Laue Langevin.

Your panel is one of three panels; the other two are reviewing the existing spallation sources and the technical scope of the proposed spallation neutron source. The reports of all three panels will be submitted to the Basic Energy Sciences Advisory Committee. The advisory committee will use the reports to make the formal recommendations to the Department. The reports should be submitted to the advisory committee by January 31, 1996. Enclosed for your information is a copy of the charge letter to the advisory committee and a copy of a section of the Energy and Water Development Appropriations Conference Report.

Sincerely,

Martha Krebs

Martha A. Krebs
Director
Office of Energy Research

2 Enclosures

APPENDIX 2
Kohn Panel Recommendations

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 deveiopment 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%; 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 LANCE 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 FY1993). 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 LAMPFs 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 FY 1994 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 3
Radioisotope Production

Radioisotope Production

For forty years, in accordance with the provisions of the Atomic Energy Act of 1954, the DOE and its predecessor agencies have been producing and distributing isotopes for medical and industrial applications. The national laboratory system has been the primary source of these isotopes. In 1990 Congress established through Public law 101- 101 the Isotope Production and Distribution Program (IPDP) in DOE to consolidate DOE isotope sales activities under one program [1,2]. Production of specific radioisotopes is also supported by other DOE offices. IPDP uses or has used production facilities at several laboratories including Brookhaven National Laboratory and Oak Ridge National Laboratory. The main mission of these laboratories is not isotope production; however, IPDP uses the excess capacity of selected facilities to produce sellable isotopes, both stable and radioactive. Many of these facilities have unique capabilities, and hence there are no other sources in the Western hemisphere for many of the isotopes produced by IPDP. DOE's annual isotope sales, as of 1993, represent 10 to 20 percent of the world market [1]. The market for radioisotope sales and demand is composed of three segments:

1. Medicine - use of isotopes in medical diagnosis and treatment
2. Industry - use of isotopes in radiography, product sterilization, food processing, lighting, and other non-medical applications.
3. Research - use of isotopes in testing commercial, medical and industrial applications.

The worldwide market share of radioisotopes in 1993 was estimated at 48% for medicine, 50% for industry and 2% for research. The medical and industrial segments are characterized as using relatively few high-volume isotopes whereas the research segment requires many low-volume isotopes. For example, Mo-99 represents 70% of the radioisotopes used by medicine and Co-60 represents 80% of the radioisotopes used by industry [1]. The DOE program, which produces more than 30 radioisotopes, primarily targets the rest of the market, particularly research, since it does not produce significant amounts of Mo-99 and Co-60. The situation could change in the near future with DOE plans underway to produce a large fraction of the US demand of Mo-99.[3] All of these isotopes need continual resupply because of their radioactive decay. The radioisotopes are manufactured based on neutron reactions with specific nuclei, and neutron rich isotopes are best produced in nuclear reactors. For example, Mo-99 is a product of a fission reaction of uranium due to neutron absorption. Similarly, Cf-252 is produced by multiple neutron captures in Cm-244/248, so that very high fluxes are required.

The use of radioisotopes is growing rapidly. Diagnostic radiopharmaceuticals provide over 36,000 procedures per day and 100 million laboratory tests each year. Therapeutic radiopharmaceuticals are the fastest growing segment with 50,000 therapies per year with promise to surpass quickly the diagnostic segment [2]. The total market value of nuclear medical activities in the United States exceeds $10 billion annually. Industrial radiography with radioisotopes is a $500 million industry. X-ray sources based on Ir-192 and Co-60 have widespread use in the examination of welds in a variety of products. Neutron radiography and tomography are superior to x-ray tomography techniques to detect corrosion in aluminum based structures such as aircraft bodies or steel components when they are thicker than about 1 inch. Neutron radiography depends on the availability of Cf-252 as a portable neutron source.

Neutron sources are important in other technological applications. The use of neutron activation analysis as a tool for detection of trace amounts of elements has been a source of critical information about high purity products in the semiconductor industry. Similarly, prompt gamma activation analysis has in recent years been invaluable to studies of catalysis, photonic materials, and environmental investigations.

The HFIR was originally designed to produce transuranium element isotopes, including Cf-252, and continues to produce such isotopes as well as many other isotopes. Oak Ridge National Laboratory is the largest supplier of isotopes and typically accounts for over half of the revenue from isotope sales [1]. The reactor has 37 irradiation locations in the central basket region and 42 locations in the beryllium reflectors. A modification to be made when the beryllium reflector is replaced will enhance isotope production by adding 5 more rabbit tubes, a gas loop for I-125 production and other improvements. The HFIR appears to be absolutely essential for the production of transuranic radioisotopes. The upgrade of the facility for neutron scattering research recognizes the dual nature of the reactor and is designed to accommodate both capabilities.

The HFBR was designed primarily as a beam tube reactor for neutron scattering research; however, with its high flux it is also useful for isotope production. The HFBR has 7 irradiation thimbles, with 3 in the reflector that provide thermal neutrons for isotope production. Isotopes have been produced for medical research, and Cu-64 is the source of the positron facility which is part of the lab's comprehensive suite of radiation producing facilities. The upgrade proposed for the HFBR continues the capability for isotope production, but with primary emphasis, as appropriate, on increasing the scope and fidelity of neutron scattering research.

References

1. U.S. Department of Energy Isotope Production and Distribution Program, Management Study, Arthur Andersen and Company, SC, March 1993.
2. Independent Assessment of the DOE Plan to Establish a United States Production Source for Molybdenum-99, Robert A. Savoie, B.P. Singh, JUPITER corporation, September 30, 1994.

3. Medical Isotopes Production Project Molybdenum-99 and Related Isotopes, Draft Environmental Impact Statement, U.S. DOE, Office of Nuclear Energy, Washington, DC, December 1995.

Department of Energy
Washington, DC 20585

November 9, 1995

Dr. Gabriel Aeppii
AT&T Bell Laboratories
600 Mountain Avenue
P. O. Box 636
Murray Hill, NJ 07974

Dear Dr. Aeppli:

I would like to ask you to convene and chair a panel of experts for the Basic Energy Sciences Advisory Committee to help guide the Department in its decisions regarding the Los Alamos Neutron Scattering Center (LANSCE) at Los Alamos National Labaratory and the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory.

The Department is just beginning the conceptual design of a new spallation source, LANSCE and IPNS will be the mainstays in the U.S. for research using spallation neutron sources for the immediate future. There are several questions that need to be answered. Is there a compelling need to continue operation of both existing spallation sources until after the new spallation neutron source is completed? If there is a need to continue operations, are upgrades necessary to meet research needs? If so, what upgrades are necessary? Should both be upgraded?

There are severe budget constraints, and the expectation is that the constraints will become tighter. The total cost of each upgrade considered should be kept below $100 million. To reduce cost, the panel should consider the extent to which the upgrades can be done using the existing operating budget, as was done at the Institute Laue Langevin.

Your panel is one of three panels; the other panels are reviewing the two high flux reactors and the technical scope of the proposed spallation neutron source. The reports of all three panels will be submitted to the Basic Energy Sciences Advisory Committee. The advisory committee will use the reports to make the formal recommendations to the Department. The reports should be submitted to the advisory committee by January, 31, 1996, Enclosed for your information is a copy of the charge letter to the advisory committee and a copy of a section of the Energy and Water Development Appropriations Conference Report.

Sincerely,

Martha Krebs

Martha A. Krebs
Director
Office of Energy Research

2 Enclosures

Subpanel on Spallation Source Upgrades

Dr. Gabriel Aeppli
NEC Research Institute
4 Independence Way
Princeton, NJ 08540
Tel: 609-951-2658
Fax: 609-951-2482
gabe@research.nj.nec.com

Professor Collin Broholm
Physics Department
Johns Hopkins University
Baltimore, MD
Tel: 410-516-7239
Fax: 410-516-7239

Dr. Tim Broome
ISIS Facility
RAL
Oxon, OX 11, OQX,
United Kingdom
Fax: 44-l235-44-5383
tim.broome@ri.ac.uk

Professor Michael Craddock
TRIUMF
4004 Wesbrook Mall
Vancouver, BC, Canada V6TZA3
Tel: 604-222- 1047
Fax: 604-222-1074
craddock@triumf.ca

Dr. William Hamilton
Neutron Scattering
HFIR
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, TN 37831
Tel: 423-576-6068
Fax: 423-574-6268

Dr. David Finley
Accelerator Division
Fermi National Accelerator Laboratory
P. O. Box 500
Batavia, IL 60519
Tel: 708-840-4620
Fax: 708-840-4552
finley@fnal.gov

NEC

NEC Research Institute, Inc.
4 Independence Way
Princeton, New Jersey 08540
Tel 609-520-1555
Fax 609-951-2481

February 1, 1996

Dr. M. Krebs, Director
Department of Energy
Washington, DC 20585

Dear Dr. Krebs:

Thank you very much for your letter of November 9,1995. As per your request, I have convened a panel of experts to help guide the Basic Energy Sciences Advisory Committee (BESAC) in its deliberations concerning the Los Alamos Neutron Scattering Center (LANSCE) and the Argonne Intense Pulsed Neutron Source (IPNS). A list of the panelists is attached. We held a meeting in Washington on January 18 and 19 to listen to oral presentations of the Argonne and Los Alamos proposals and to formulate our recommendations. A copy of the meeting agenda is also attached. It is the purpose of this letter to summarize our findings; a more detailed report is in preparation and will be forwarded to you before the end of February.

In your letter, you ask several questions:

1. Is there a compelling need for continued operation of both existing spallation sources until after the new spallation source is completed?

2. If the answer to 1. is yes, are upgrades necessary to meet research needs?

3. If the answer to 2. is yes, which upgrades are needed?

4. Can upgrades be performed within existing operating budgets, as was done at the Institut Laue-Langevin?

Our responses are as follows:

1. There is a compelling need for continued operation of both sources. This follows from the excellence, utility, and uniqueness of the scientific programs at the two sources. Particular recent successes which will serve as the foundations for near-term (over the next five years) high-impact research include crystal structure determinations of highly magnetoresistive materials (Argonne) and strain distribution measurements in engineering composites (Los Alamos). Both of these successes take advantage of the high peak fluxes associated With the existing short-pulse spallation sources as well as "the collocation of the sources with lively materials science and engineering laboratories. Closing down either source, even given that in most respects, neither has had the investment required to perform as well as ISIS, the world's most powerful pulsed spallation source, would terminate ongoing world-class research efforts in the us.

2. Upgrades are necessary to meet research. needs because US scientists and engineers need access to an ISIS-class source to perform leading edge experiments in areas as diverse as solid-state chemistry and surfactant design. In addition, both IPNS and LANSCE are oversubscribed in the sense that there are more good proposals for experiments than can actually be accommodated. Finally, upgrades are necessary to move the US up the learning curve, on spallation source instrumentation and operation and to train the generation of neutron facility users, operators, and managers who will, eventually be associated with the 1-MW$^+$ large spallation source currently under consideration by the Oak Ridge National Laboratory.

3. Both the Los Alamos and Argonne upgrades areneeded because they are qualitatively different and serve very different scientific needs. In particular, the pulse length determines the minimum wavelength for which a spallation source is effecient, and so dictates the science for which the source is optimal. Thus, the short pulse (IPNS) source will excel at atomic-scale structure determination, and far to mid-infrared spectroscopy, while the Los Alamos long-pulse machine will be a world leader in large-scale structure determination and fundamental physics with neutrons.

4. The upgrades cannot be performed within existing (ER-derived) operating budgets because these budgets are simply too small relative to the upgrade costs to permit upgrade completion over a realistic time period. In any case, the upgrade cost estimates of both Argonne and Los Alamos are predicated on continued operations during upgrade implementation, and these operations would provide funding for staff crucial to the upgrades.

In addition to the explicit questions which you pose, you note severe budget constraints and a desire to keep the upgrade cost below $100 million per facility. The Argonne proposal does not fall within this cost envelope. However, it is technically sound and will exceed the performance of the world's best pulsed spallation source (ISIS) by at least a factor of two for all applications. It has a realistic cost which will be impossible to reduce significantly. Our positive conclusions are based on Argonne's excellent performance in building and operating IPNS and delivering the Advanced Photon Source (APS) as well as the extensively reviewed design process Argonne has already undertaken on its proposed I-MW spallation source, which is the parent of the 400kW source described to the subpanel.

Furthermore, the existing IPNS is a fully optimized and developed source, where upgrading or replacing individual subsystems (ranging from ion source to neutron moderators) would not enhance the research performance. For all of these reasons, as well as the fact that producing a simple copy of the existing IPNS would cost on the order of $100M, the marginal benefits of investments below $200M (total estimated cost or TEC) at IPNS are negligible.

The Los Alamos proposal is at a less advanced stage than the Argonne proposal. Although there is no operating experience with long-pulse spallation sources, the panel judges the project technically feasible, and senses the present cost estimate to be conservative. Los Alamos will attempt to secure partial funding from the Defense Programs (DP) division of the DOE, and if successful, will require even less Energy Research (ER) investment to produce a source which will significantly exceed the performance of the world's best cold neutron facility (ILL) in many applications.

We strongly advise ER together with DP to fund the long pulse source upgrade at Los Alamos. We recognize that only this proposal falls within the budgetary constraints mentioned in your letter. For many experiments involving cold neutrons, well matched to large-scale structures and slow dynamics, the Los Alamos facility should perform better than any existing reactor or spallation source. However, it will also lack many essential capabilities. For example, it will not lead the world in the determination of atomic-scale structures and chemical bonding, an area which is unquestionably served best by a short pulse spallation source. This area is of such central scientific and economic importance that it is extremely unwise for the US to be without a world class short pulse source for much longer. We therefore recommend that unless the new 1-MW$^+$ short pulse source were to begin producing neutrons (at the ISIS' level) within the next 7 years, that BESAC and the DOE fund the IPNS upgrade. In this context, it is useful to remember that the conceptual design of the APS, a project of similar scale and whose schedule is considered aggressive, began in 1984, while the project is about to be completed in 1996.

After almost thirty years of negligible investment in new neutron sources, the US has considerably fewer capabilities than Europe. Should the Japanese build the $ISIS^+$ machine which they are nearly committed to today, the US will, by the turn of the century, also lag behind Japan. Given the importance of neutrons as well as the contributions of neutron research to US science and technology, a large program of capital investment to correct for the thirty years of virtual neglect is clearly justified.

Our panel urges BESAC to consider that the US should invest in a portfolio of sources defined not by the methods of neutron production as much as by scientific capabilities. As far as the latter are concerned, we agree with the finding of the Berkeley Workshop on Long Pulse Spallation Sources (chaired by T.Russell and R. Pynn) that the Los Alamos upgrade will yield a source in the same class as the NIST reactor and the (upgraded) HFIR and HFBR reactors. If they perform as planned, each of these four sources will be competitive with or generally superior to the world's best steady state source, the ILL. In contrast, the only ISIS-class source proposed to this panel is the IPNS upgrade. Thus, maintaining a balanced portfolio of sources clearly mandatesthe IPNS upgrade or an accelerated construction schedule for the 1-MW^+ spallation source

Sincerely,

Gabriel Aeppli

Department of Energy
Washington, DC 20585

November 9, 1995

Dr. Thomas Russell
Senior Scientist
Almadcn Research Center K91-802
IBM Research Laboratories
650 Harry Road
San Jose, CA 95120

Dear Dr. Russell:

I would like to ask you to convene and chair a pane1 of experts for the Basic Energy Sciences Advisory Committee to help guide the Department's conceptual design of a spallation neutron source.

To guide the design effort, the panel should consider: (1) source characteristics, icluding pulse length, power, and neutron energy spectrum; and (2) trade-offs such as an upgradable source, full performance but with limited instrumentation, and low-performance source with full instrumentation.

There ate severe budget constraints, and the expectation is that the constraints will become tighter. The total cost of a new spallation source should be kept below $1 billion.

Your panel is one of three panels; the other two are reviewing the existing spallation sources and the two high flux reactors. The reports of all three panels will be submitted to the Basic Energy Sciences Advisory Committee. The advisory committee will use the reports to make the formal. recommendations to the Department. The reports should be submitted to the advisory committee by January 31, 1996. Enclosed for your information is a copy of the charge letter to the advisory committee and a copy of a section of the Energy and Water Development Appropriations Conference Report.

Sincerely,

Martha Krebs

Martha A. Krebs
Director
Office of Energy Research

2 Enclosures

Next Generation Spallation Source Committee

Members and Affiliations

- *Thomas* P. Russell, Chairman (IBM, San Jose)
- Andrew Taylor (ISIS, Rutherford Appleton Laboratory, England)
- Gunther Bauer (Paul Scherrer Institut, Switzerland)
- Jack Carpenter (Argonne National Laboratory)
- Alessandro Ruggiero (Brookhaven National Laboratory)
- Herb Mook (Oak Ridge National Laboratory)
- Robert Macek (Los Alarms National Laboratory)
- Daniel Neumann (National Institute of Standards and Technology)
- Jose Alonso (Lawrence Berkeley National Laboratory)

IBM

International Business Machines Corporation

T. P. Russell
Department K13/802
IBM Research Division
Almaden Research Center
650 Harry Road
San Jose, CA 95120-6099
TEL: (408) 927-1638
FAX (408) 927-3310

February 1, 1996

Professor Carl W. Lineberger
Department of Chemistry and Biochemistry
University of Colorado
Boulder, CO 80309

Dear Carl:

In response to the charge letter from Dr. Martha Krebs, a panel was assembled on January 16-17 to delineate a series of recommendations for the spallation neutron source, A copy of the meeting agenda is attached, The panel, whose membership is attached, contained internationnal expertise covering the different technical aspects of a pulsed spallation source and representation from the user community. The recommendations of the committee (attached), provide a broad guideline for the design of the future spallation source and provide a mechanism by which a state of the art facility can be made operational in a timely manner under the restricted budget specified in the charge letter, The recommendations of this committee will be presented at the BESAC meeting to be held on Februtary 5-6, 1996 along with the recommendations of the committees dealing with the current neutron source upgrades.

If you have any questions concerning these recommendations, please feel free to contact me.

Sincerely,

Thomas P Russell

Thomas P. Russell

Next Generation Spallation Source Committee

Committee Report

Introduction

The importance and need for neutron scattering have been the subject of several recent, reports in the United States and abroad, From its original domain in the physics community, the use of neutron scattering has expanded widely and is now being used in a broad range of disciplines including materials science, chemistry, biology, earth science and, most recently, engineering. Not only has neutron scattering proven to be crucial in answering fundamental questions in each of these fields, but it has also been used effectively on applied research problems. The availability of neutron sources has given a large number of individual scientists access to an indispensable resource not available through their individual grants. As discussed in the Kohn Panel report, to meet the current and future needs of the American scientific community, the present sources are inadequate and require expansion, both in terms of flux and availaility.

The European and Japanese communities have responded to this need, but efforts in the: United States have been hindered by the lack of investment in the national reactor sources and a lack of development of pulsed spallation sources, a concept pioneered in the United States at Argonne in the late 1970's. It is well past time for the United States to respond to its scientific community with state of the art neutron scattering facilities.

The Kohn Panel recognized (as has been the experience of the past decade in Europe with ILL and ISIS) that a combination of a pulseded source and a reactor source was necessary, With the cancellation of the Advanced Neutron Source project, the Kohn Panel stated that *"a 5* MW *pulsed spallation source would be needed to basically cover its capabilities in neutron scattering."* It should be noted that there are technological uncertainties in the development of a 5MW pulsed source with respect to the accelerator, target and ion source designs and to the instrumentation necessary to fully utilize the enhanced flux which will require time to overcome but are in hand at the ~1MW level. In each of these areas R&D is necessary and a coordinated effort on an international scale would benefit everyone. in Europe, future plans are to complement the world-leading ILL reactor source with a third generation 5 MW short pulsed spallation source, the ESS. In the United States the situation is different. The current reactor and pulsed source capabilities in the United States are inferior to those in Europe and the funding climate will not support the anticipated cost of construction of strictly a 5MW facility. Therefore, a carefully developed strategy is needed to provide the scientific community in the United States with world-class facilities.

A prerequisite for the development of a next generation pulsed spallation source is the accommodation of the current broad user base in academia and industry. This must be addressed with urgency, on a time scale significantly shorter than that for the realization of the next generation pulsed spallation source. This requires upgrading the current reactor and spallation source facilities. These upgrades atone, however, *will not satisfy* the Nation's needs on the ten to twenty year time scale. Flux limitations and neutron beam availability at these upgraded facilities will, still prevent the realization of the scientific and technical opportunities identified by the Kohn Panel. Thus, the development and construction of the next generation pulsed spallation some is crucial.

Recommendations

The committee recommends a strategy that has as its goal the highest power short pulsed spallation source. The recommendations of the committee arc as follows.

1. *There is an urgent need to build a short pulsed spallation source in the 1 MW power range dedicated to neutron scattering with sufficient design flexibility such that it can be operated at a significantly higher power in a later stage.*
2. *The linear accelerator design should be chosen so as not to exclude direct injection of long pulses into a viable spallation target.*
3. *The source must have a predictability and reliability as set forth in the Kohn report and should be capable of operating at least 240 days annually.*
4. *A carefully selected initial set of instruments is required to maximize the early scientific impact.*
5. *The Department of Energy should proceed with Title 1 design in FY1998 and proceed with the full construction project in FY1999 leading to initial scientific operation of the facility in 2005.*
6. *The design must rely on low risk technology initially. In parallel, there is a critical need for R&D on ion sources, beam chopping, low energy beam transport, charge exchange injection, moderator and target technologies to reduce risks to acceptable levels.*

In addition, the committee also recommends that this pulsed spallation source have the following characteristics:

- *horizontal beam injection into the target*
- *nominal 1 microsecond proton pulses*
- *a set of moderators to provide neutrons with appropriate spectral and temporal characteristics in the epithermal, thermal and cold range*
- *initially one target with a 30-60 Hz repetition rate*
- *capability of additional targets, as required, with multiplexing to accommodate an expanding experimental instrument suite*

Maintaining the cost of the initial project within the $1 billion dollar limit demands: the exploitation of existing studies, in the United States and abroad, on the next generation pulsed spallation source; a broad based collaboration an the design of source components and instrumentation; and continuous cost monitoring within the project. In addition, a staged approach to the construction of the spallation source and an aggressive time table must be established to meet the budgetary constraint on the initial phase (~1 MW) and to ensure an operational and usable facility at this point, as well as at other key points in the evolution of the facility to its ultimate performance level. The project should develop a decision tree to identify options and scientific goals for use early in the conceptual design process. This should provide a basis for responding to the evolution of funding and to international developments in neutron science and accelerator and target technologies that will impact the course of the project. Adherence to these recommendations by the design team along with the strong support of the Department of Energy will ensure the realization of a first-rate, versatile facility that is urgently needed in the United States.