A Review of the Advanced Neutron Source

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1. EXECUTIVE SUMMARY

The United States Department of Energy (DOE) has authorized the design of an Advanced Neutron Source (ANS), a new steady-state research reactor, to be built at Oak Ridge National Laboratory (ORNL). The ANS was originally designed to provide a neutron flux of 7.33×10^{19} n/m^{2}s using 93% enriched uranium as fuel, and an operating power of 330 MW. The current design, however, features a new modified core containing three, instead of two, fuel elements. This change will facilitate the use of fuels of lower enrichment. This new core design will reduce the flux by 10-20% from the original design level if 93% enriched uranium is used, and reduce the neutron flux still further if low enriched uranium (20% ^{235}U) is used.

The ANS will be used in the fields of materials science, condensed matter physics, chemistry, biology, materials irradiation, as well as to produce isotopes for both medical and industrial purposes. The minimum flux demanded in a report by a panel of some 70 national and international experts in different areas of neutron research is around 6×10^{19} n/m^{2}s. This is five times higher than the flux obtained at the French reactor at Institut-Laue Langevin (ILL) which at present has the highest flux in the world. The expert panel report was used to update the Basic Energy Sciences Advisory Committee (BESAC) of DOE with the worldwide opinion on the needs for different neutron sources and their applications and capabilities, as well as what techniques and instruments are lacking in the U.S. The recommendation given by the panel of experts was that the U.S. urgently needed to construct the ANS as well as develop a cost-effective design for a powerful Pulsed Spallation Source (PSS) to complement the ANS. The construction of the ANS has not yet begun, but it is scheduled for completion in year 2003 at a projected construction cost of \$3 billion. The total cost over 40 years is estimated to range from \$9 billion to over \$13 billion.

The original plans to use 93% enriched uranium as fuel would clearly be incompatible with the aims of the Reduced Enrichment for Research and Test Reactors program (RERTR), and would establish a double standard for domestic and foreign research reactors, as would any

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[1] A version of this report was prepared as a discussion paper for Natural Resources Defense Council, Washington, DC.

reactor fueled with uranium enriched above 20%. Motivated by the U.S. non-proliferation policy, DOE selected Brookhaven National Laboratory to assess the impact on performance of using fuels with enrichment lower than 93% for the ANS. The Brookhaven report concluded that the use of LEU as fuel would allow for a neutron flux around 2.2×10^{19} n/m^{2}s, which is about twice the flux at ILL, but only about one-third that of the original design. Further development work of high density LEU, which is being conducted at Argonne National Laboratory, could yield a higher flux in the future.

The critical question whether there would be a considerable loss in scientific information if the ANS were to be fueled with LEU instead of HEU, with a corresponding reduction in flux, has not been properly adressed by DOE. The use of LEU fuel is required in order not to violate the RERTR program. If the flux obtained by this fuel is sufficient to the majority of the users, it is interesting to know whether those experiments requiring the highest fluxes could be performed at a spallation source. Spallation sources have lower time-average fluxes than reactors, but emit higher peak fluxes.

Two fundamental issues should be addressed by DOE to provide decision makers with adequate background information: what is the impact of different uranium enriched fuels on the applications, and can a spallation source with high peak fluxes be used for the experiments that require the highest fluxes, leaving the greater part of the users satisfied with a flux from an LEU fueled ANS.

2. INTRODUCTION

The United States is planning to build a new steady-state research reactor, the Advanced Neutron Source (ANS), at Oak Ridge National Laboratory (ORNL), at an estimated construction cost of $3 billion. This new facility for basic and applied research will provide beams of neutrons for measurements and experiments in the fields of materials science and engineering, nuclear science, biology, chemistry, fundamental neutron physics, and materials analysis, etc. Irradiation facilities and production of medical and industrial isotopes will also be provided. At present, two major neutron sources are DOE's research reactors, the high-flux beam reactor (HFBR) at Brookhaven National Laboratory, and the high-flux isotope reactor (HFIR) at ORNL, having neutron fluxes of 5×10^{18} n/m^{2}s, and 1.1×10^{19} n/m^{2}s, and with operating powers of 60 MW, and 85 MW, respectively. These reactors were built in 1965 and 1966 and both are estimated to have remaining lifetimes of around 10 to 20 years. In addition to HFBR and HFIR, major research reactors are located at the National Institute of Standards and Technology, and at Missouri University, as well as some smaller reactors at a few universities. However, the existing facilities are old with long maintenance periods resulting in the facilities being oversubscribed.

The need for a new steady-state neutron research facility in the United States was emphasized in a report by the Major Materials Facilities Committee of the National Research Council in 1984 (Seitz, 1984). This was confirmed in 1985 by the Department of Energy's (DOE) Energy Research Advisory Board, with the resulting decision to construct the ANS. In January 1993 the Basic Energy Sciences Advisory Committee's Panel on Neutron Sources issued a report titled "Neutron Sources for America's Future" (DOE, 1993). The report called for a steady-state neutron source that provides a neutron flux, i.e. the number of neutrons per unit area and time, that is at least five times, and preferably ten times, the flux currently available at the French reactor at Institut Laue-Langevin. The recommendation was also to construct a complementary 1 MW pulsed spallation source in the future. The ANS is designed to provide scientists with a new neutron research facility since the existing facilities are oversubscribed. The ANS would at the same time out-perform other research reactors in the world. According to the 1993 DOE report the number of users of neutron scattering, and other neutron researchers doubled from about 750 to 1500 between 1983 and 1991. The ANS is expected to serve 1000-2000 users each year (Appleton, 1994). The total cost over 40 years is estimated to range from $9 billion to over $13 billion.

The highest neutron flux obtainable today is 1.2×10^{19} n/m^{2}s with an operating power of 57 MW at the reactor at Institut Laue-Langevin (ILL) in France. The original ANS design was to provide a flux about seven times higher, using 93% enriched uranium as fuel, and an operating power of 330 MW. Due to U.S. non-proliferation policy, however, there is an interest in using the ANS with lesser enriched uranium. A recent decision to modify the core design by increasing the volume and adding one additional fuel element will provide greater safety margins and the flexibility to use fuel with lower enrichment, but it will also result in lower fluxes. The choice of fuel with different enrichments of ^{235}U, and its impact on flux and overall performance has been investigated by Brookhaven National Laboratory (Bari et al., 1994) on the request of DOE. The study was motivated by the incompatibility of using 93% enriched uranium with the Reduced Enrichment for Research and Test Reactors (RERTR) program. The new core design will make it possible to utilize improved fuels with further reduced enrichment, even to the 20% level, (LEU), as they are developed. [West, 1994; ORNL, 1992; Alston et al., 1994).

This report provides a general description of the ANS, some results from the Brookhaven study on performance versus enrichment, and the applications of neutron beams based on published reports and discussions with scientists involved in the project (see end of reference list). Also included is a discussion of the value of high flux in research, and some alternative approaches for compensating a reduction in flux. Some issues which have not been addressed by the scientific community or by DOE, but which are important to understand for making informed decisions about the ANS, are discussed in the conlusion.

3. GENERAL DESCRIPTION OF THE ANS

The ANS, scheduled for completion in year 2003, will be a new state-of-the-art 330 MW reactor which will use heavy water as coolant, moderator, and reflector. The original baseline core design was a compact arrangement with two annular fuel elements using 93% enriched uranium as fuel with a density of 1.7 g/cc providing a neutron flux of 7.33×10^{19} n/m^{2}s. In the latest design, however, a third fuel element is incorporated allowing the use of lower enriched uranium as fuel. In the new design the core volume is 82.6 L, an increase of 15 L, compared to the two-element core. This will result in a 10-20% flux penalty with high enriched uranium as the fuel, but the greater volume leads to a lower power density and therefore to greater safety margins. This new core design makes it possible to use low enriched uranium (20% ^{235}U) fuel when a fuel meat with higher density, to compensate for the lower enrichment, has been developed (Alston et al., 1994; Bari et al., 1994). The development and testing of new high density LEU fuels is performed at Argonne National Laboratory. The fuel meat will be a mixture of U_3Si_2 powder and pure aluminum powder. The clad and fuel element structure is made of aluminum which has a high thermal conductivity and a relatively low neutron absorption cross section (ORNL, 1992). The operating cycle is set to 17 days, followed by 4 days of refueling operations. The ANS is intended to be used by national and international researchers from industry and universities. The technical objectives of the reactor are to provide neutron beams for scattering studies, energetic neutrons and gamma rays for materials irradiation, and for the production of a variety of neutron rich isotopes (ORNL, 1992). It is designed to have 48 instrument stations provided for neutron scattering applications. The total number of irradiation facilities will be 49 which include transuranium isotope production (30 instruments), other isotopes (8 instruments), and materials testing (11 instruments). There will be 10 materials analysis facilities, and one gamma irradiation and one positron production facility.

Neutrons are divided into three classes: cold (<1 meV), thermal (25-100 meV), and hot (>100 meV). The thermal neutrons are extracted from the heavy water reflector in the reactor assembly with evacuated beam tubes and the instruments using the thermal neutrons are placed as close to the reactor as possible. Cold neutrons are produced by placing vessels filled with liquid deuterium as moderator in the reflector region. These high-wavelength neutrons are reflected off highly polished nickel surfaces which construct the neutron guides. The guides act to transport neutrons with minimal loss to the instruments in a large guide hall. Hot (fast) neutrons are produced by placing a graphite block, heated by radiation from the reactor, in the reflector region. The hot neutrons are transported to instruments just outside the shield using standard beam tubes.

The ANS is to be designed, built, and operated under DOE ownership and is not subject to the Nuclear Regulatory Commission (NRC) licensing process. However, DOE orders require its reactors to meet the standards, codes, and guides that are applied to comparable NRC-licensed facilities (ORNL, 1992).

Performance Versus Uranium Enrichment

According to the International Atomic Energy Agency (IAEA), low enriched uranium (LEU) is defined as uranium containing less than 20% ^{235}U, and high enriched uranium (HEU) is defined as uranium enriched above 20%. The Reduced Enrichment for Research and Test Reactors (RERTR) program, initiated in 1978 by the United States, is aimed at replacing the HEU fuels used in both domestic and foreign reactors. The development and testing of new high density LEU fuels is being conducted at Argonne National Laboratory. Motivated by the goals of the RERTR program, and thus by U.S. non-proliferation policy, the Office of Management and Budget directed DOE to quantify the impact on ANS' performance if LEU or HEU was used in the design. DOE selected Brookhaven National Laboratory to lead this study (Bari et al., 1994). Two parameters were independently varied to compensate for decreased ^{235}U content in the lower enriched fuels. One parameter is the uranium fuel density which has to be increased, and the other parameter is the reactor core volume, which also has to be increased to compensate for reactivity losses. The cases had to meet the criteria for sufficient initial reactivity, safe power density, and the desired 17-days operating cycle. The result of the study was 19 cases with various combinations of fuel density, operating power, flux performance, and core volume. A key finding was that the three-element core fueled with 93% ^{235}U, would give a flux penalty of 10-

20% from the original baseline design with a flux of 7.33×10^{19} n/m^2s. If the enrichment were to be reduced to 35% within the three-element core, the fuel density would have to increase to 3 gU/cc to give a flux of 5.7×10^{19} n/m^2s. This would incur an additional cost to the project of approximately $400 million, 3-5% of estimated total cost, over the lifetime of 40 years of the plant. If LEU were to be used, the fuel density would have to increase to 3.5 gU/cc and the operating power decreased to 125 MW to yield a flux around 2.2×10^{19} n/m^2s, i.e. about twice the flux obtained at ILL. The additional cost to the project would be approximately $90 million, or 1% of total projected cost. There is currently no LEU fuel that satisfies the requirements dictated by the design of the ANS but the Brookhaven study concludes that there is a good chance that fuels meeting the ANS requirements can be successfully produced. It is estimated in the report that the probability of succeeding in the development of fuel densities between 1.3-3.5 gU/cc is 95-100%. Higher fuel densities require further research and development, but are given a 50-95% chance of success.

4. NEUTRON APPLICATIONS OF THE ANS

The basic applications of neutron sources are for scattering experiments, materials irradiation, and isotope production. Different experiments require neutrons of different energies. Cold neutrons have long wavelengths and low energy and do therefore not change the material's atomic framework. Cold neutrons are used in scattering experiments in biology, and chemistry where the samples often consist of large molecules, as well as in materials science. Thermal neutrons have higher energy but are also non-destructive and are widely used in scattering and radiography experiments. High-energy neutrons may change the atomic structure of the material placed in their path. High-energy neutrons are used by the scientists to study the effects of intense radiation on different materials, such as fission or fusion reactor walls which are constantly subject to radiation (Skold, 1986).

In July 1992 the Basic Energy Sciences Advisory Committee (BESAC) of the Department of Energy set up a Panel on Neutron Sources, chaired by Professor Walter Kohn of the University of California, Santa Barbara. The Panel was asked, at the request of Dr. William Happer, then Director of the Office of Energy Research, to provide advice and guidance on the future of neutron sources and related scientific and technological applications in the United States (DOE, 1993). In order to provide the Panel with a sense of the current thinking worldwide on the perceived needs for neutron sources of different types and their applications and capabilities, a Review of Neutron Sources and Applications was held at Oak Brook, Illinois, in September 1992 (DOE, 1994). The review involved some 70 national and international experts in different areas of neutron research, sources, and applications. The experts were asked to review the current status of advanced research reactors and spallation sources, as well as to provide an update on scientific, technological, and medical applications, neutron scattering research in a number of disciplines, isotope production, materials radiation, materials analysis, fundamental neutron physics, and what techniques and instruments are lacking in the U.S. The recommendation was to build the ANS now, and a complementary 1 MW pulsed spallation source in the future. The experts in the various fields speculated about what new opportunities a tenfold increase in flux, or a minimum of five times the ILL flux, would provide and what new experiments they would be able to perform. The overall conclusion is that high flux will make it possible to study the materials more completely and thoroughly, and especially to study smaller samples. Another advantage of having higher flux is the reduction in measuring times allowing more experiments to take place. The main findings and conclusions in the Oak Brook report are summarized below.

Neutron Scattering

The most important use of neutrons is to develop the understanding and technology of new materials. Examples where neutron scattering has contributed vital information are in studies of high temperature superconductors (atomic properties, oxygen position and concentration, and lattice dynamics), heavy-fermion systems (magnetic properties), quasicrystals (atomic and magnetic structure, and vibrational frequencies), and fullerenes (structure, the lattice and rotational dynamics, and phase transitions). Another area is scattering from surfaces where the roughness of the surface can be studied. Altogether, neutron scattering has played an important role in the understanding of the fundamental properties of condensed matter, and will continue to do so in the future. An increase in available flux will extrapolate what can be done with neutrons today and also make it feasible to use smaller samples to, for example, study inelastic scattering since the resolution will be improved. New fields such as ultracold neutron spectroscopy, neutron microscopy, and studies of nonequilibrium phenomena are areas that would open up primarily as a result of the new instrumentation that will be used at the ANS.

Neutrons (in contrast to x-rays) are sensitive to light atoms such as hydrogen and oxygen, and therefore neutron scattering has become an important tool for the determination of the structure of biological and chemical molecules and compounds which often have large contents of hydrogen. The placement of hydrogen atoms in molecules can also be visualized, as well as the hydrogen bonds in, for example, enzymes which commonly involve complex hydrogen-bonded networks. The differences in scattering length between hydrogen and deuterium allow sophisticated labeling studies which can reflect the relative abundances of hydrogen in the substances. This has been practised in the science of polymers where the scientists have been able to determine the shapes and movements of polymers in solutions, melts, gels, and crystals (Stein, 1985). In chemistry, diffraction methods are used to determine the structure of molecules and of complex molecular assemblies, and the dynamics of the molecules can be determined by using inelastic scattering. Studies of zeolite structures, diffusive motions of deuterium atoms in chemical compounds, and the structural and dynamical details of hydrogen bonds are some areas where neutron methods have made and will make important contributions to the general understanding.

Materials Irradiation

Irradiating materials with fast neutrons may change the atomic structure of the targets. Fast neutrons can, for example, create vacancies which combine together forming voids. These can grow in size and cause distortion and embrittlement of the materials (Skold, 1986). This is of large interest to the nuclear scientists who are studying the effects of intense irradiation on reactor wall materials and fuel cladding. In the ANS, irradiation facilities will be provided near the core and will allow simulation of the radiation damage that would be encountered in the first wall of a fusion reactor. Production of isotopes for medical, industrial, and military applications are also intended to be produced in the ANS (ORNL, 1992).

Materials Analysis

Materials analysis comprise the use of neutron reactions (as opposed to neutron scattering) in methods such as neutron activation analysis, neutron depth profiling, prompt-gamma activation analysis, and neutron radiography. These methods make it possible to detect trace amounts of elements in, for example, silicon for semiconductor applications, or biological samples such as human tissue. A depth profiling station will allow the mapping of near-surface impurities in semiconductor device materials. In industry, neutrons are used in imaging and tomography. Stress changes the lattice constant and so defects in, for example, plane wings can be revealed by imaging. Defects of sizes 0.1-1 mm are detected with existing facilities, but with the ANS defects down to µm can be revealed since the spatial resolution is proportional to the flux.

The Importance Of High Flux

Higher flux means more neutrons per unit area and time, and thus more neutrons that hit the target. More neutrons are therefore scattered by the target, resulting in an enhanced signal at the detector.

From a qualitative point of view, an increase in flux from the source is always welcome to experimentalists because increased intensity improves the resolution for the same measuring time. The quality of the measurements can thus be better which allow scientists to extend the experimental conditions so that, for example, smaller samples can be measured.

The signal-to-noise ratio is usually proportional to the square root of the intensity, so that a quadrupling in intensity means a doubling in signal-to-noise ratio. In some experiments carried out at a steady-state reactor, however, the signal-to-noise ratio may not be improved this much with higher intensity because the neutron beams themselves act as background. A pulsed spallation source gives a better signal-to-noise ratio since the signal from the sample is detected when the neutron beam is off.

According to the Oak Brook report (DOE, 1994) one advantage of having higher neutron flux is the reduction in measuring times. The measuring time is inversely proportional to the neutron flux, so an increase in flux with a factor of two results in half the measuring time.

5. ALTERNATIVES

The scientific community has demanded a neutron flux at least five times that at ILL in France, which necessitates the use of HEU as fuel. Motivated by the U.S. non-proliferation policy there is an interest in using the ANS with LEU, which will be at the cost of lower flux. A key question is whether reduced fluxes can be compensated somehow.

Instrumentation

Improving instrumentation and methods are as vital as having high flux in order to improve the performance as well as conducting new experiments. The setup and the quality of the instruments is of major importance for the performance of the ANS.

The scientists involved in the Oak Brook report wanted in the shorter term easier access to the DOE facilities, and supported a major program of instrument building at all existing DOE facilities. Incorporating new developments in the instrumentation would improve the intensity at the sample and provide greater experimental flexibility. This would upgrade the quality of the facilities in the short term and at the same time establish a competence for instrument building (DOE, 1994).

Spallation Source

Another issue is to what extent a spallation source could complement the ANS covering those experiments requiring the highest fluxes. Spallation sources (most effectively operated in a pulsed mode) produce the neutrons by sending a charged beam of accelerated protons or electrons into a heavy metal target, resulting in emission of neutrons. These sources have high peak neutron fluxes, but the time-averaged flux is lower than in reactor sources. The pulsed nature of spallation sources yields great signal-to-noise ratio, and good resolution. The neutrons are slowed down to the energies required in different experiments, by an appropriate moderator. With proper instrumentation adapted to the specific beam characteristics, many experiments can just as well be performed at reactor sources or spallation sources. Although there is considerable overlap in capabilities between the two sources, there are domains in which one is preferable.

Reactors typically produce high fluxes of cold and thermal neutrons, which make them preferable for experiments in the lower energy regime. Spallation sources also produce cold and thermal neutrons but have a larger component of high-energy neutrons, desirable for applications at the more energetic regime (Price, 1985; Skold, 1986).

The users requested, in addition to the ANS, the construction of a 1 MW pulsed spallation source (PSS) in the future, to complement the ANS. The laboratories at Los Alamos and Argonne which have spallation sources with beam powers of 60 kW and 7 kW, respectively, have been involved in the development of a new 1 MW PSS. The Oak Brook report (DOE, 1994) included a comparison between spallation and reactor sources with the conclusion that with proper instrumentation adapted to beam characteristics, either source can be used for many experiments. Their recommendation, however, was to start with the construction of the ANS. According to the report, a 1 MW PSS could be built at a total estimated cost of $0.5 billion. It would be a critical input to DOE and the decision making process to know to what extent a 1 MW spallation source could cover the experiments that require the highest fluxes, while the majority of the research could be performed at the ANS with a lower flux from LEU fuel.

A major disadvantage with spallation sources in the past has been the relatively low time-averaged neutron flux. However, approximately the same time-averaged thermal neutron flux as from the ANS could be produced by increasing the power of the spallation source to 5 MW (DOE, 1993). With proper instrumentation adapted to the specific beam characteristics, a 5 MW PSS could be an alternative to the ANS. According to the experts, an upgrade of a 1 MW source to a 5 MW facility can be done for an additional $0.5 billion, if it is properly planned for in the beginning. According to the Oak brook report, this facility would require further research and development since the major problem with this high-power source lie in the areas of heat removal from the target and radiation damage to materials. In Europe, however, a new 5 MW spallation source is now under consideration. This will yield approximately the same time-average flux as the ILL, but with a peak flux 40 times higher (DOE, 1994; Aeppli, 1994).

6. DISCUSSION AND CONCLUSION

The latest core design of the ANS is an 82.6 L core volume with the incorporation of a third fuel element to ensure greater safety margins and the use of lower enriched fuels. From the enrichment study by Brookhaven National Laboratory (Bari, 1994) it was concluded that the use of high enriched uranium would give a neutron flux of around six times that at ILL. The minimum flux of five times the ILL flux which was demanded by the scientific community, can be satisfied with 35% enriched uranium but requires some further fuel development. The use of HEU as fuel is, however, incompatible with the Reduced Enrichment for Research and Test

Reactors (RERTR) program, and would most likely establish a double standard for domestic and foreign research reactors, as would the use of any fuel with uranium enriched above 20%. Using high density LEU fuel, when developed by Argonne National Laboratory, would give a neutron flux at least twice that at ILL in France, and would thus be the highest in the world.

Who Needs The High Fluxes?

Following on the results from the Brookhaven study, an important issue is what impact various neutron fluxes would have on research. This issue has not been evaluated by DOE, but it is of major importance in order to make an informed decision concerning the choice of fuel and reactor design. Non-violation of the RERTR program demands the use of LEU. With a high density LEU fuel this would still result in a flux of at least twice that at ILL. None of the questions DOE has posed to the scientific community cover the concern of what impact a flux twice that of ILL would have on the applications using neutron beams. It is important to evaluate what experiments can be done with the lower neutron flux, and to what extent a flux five times the flux at ILL is more useful than a flux twice that at ILL. The lower flux would of course mean somewhat longer measuring times, but would still allow much faster measurements than today. The issue whether a flux twice that of ILL would imply significant losses in scientific valuable information in all applications using neutron beams, or if the flux would be sufficient to the majority of the users, has not been addressed. What specific experiments need the highest fluxes, and what experiments can be performed with the lower fluxes? For example, if a small fraction of the irradiation systems experiments need very high fluxes, a natural question to be asked is whether these few experiments are so valuable that they justify having a high flux neutron source at the cost of violating the RERTR program.

Technology Development

Another question is if those experiments that require the highest fluxes could be performed at a spallation source. A reactor source and a spallation source are often considered complementary, but according to the scientists in the Oak Brook report, many experiments can be performed with either source if only the proper instrumentation exists. Their recommendation was to start the immediate construction of the ANS, and design a 1 MW pulsed spallation source for the future. The reactor source technology is well-known and established, whereas the pulsed high-power spallation source technology is newer and constantly developing. The ANS has seen ten years of development, during which time the technology of spallation sources has made progress with new sources under consideration (DOE, 1994). According to the Oak Brook report, 5 MW is not an upper limit of beam power for a PSS. Reportedly nobody yet sees a limit to the potential of spallation sources, while reactor neutron sources cannot get much more powerful than the original ANS design (Goldstone, 1993). Considering the differences between the ANS and the PSS in total costs, and overall opportunities, it seems that it would be more cost effective to carry out research and development of a high power PSS than on the ANS. The latter well established technology has, however, been given preference by the scientists initially involved in the Seitz report by the National Research Council (Seitz, 1984), and those represented in the science advisory committees to DOE.

In sciences with a relatively short history in neutron research, there is not enough experience to say what new experiments can be performed at a spallation source since this technology is newer than the reactor technology. In biology, pilot experiments are planned at Los Alamos Neutron Scattering Center (LANSCE), and ISIS (a pulsed spallation source in the U.K.) which will provide data for quantitative comparisons between measurements at a reactor and a spallation source, in the next coming years. Until detailed questions related to the value of having high fluxes at the cost of violating the RERTR program, and the promise of spallation source technology has been evaluated, the case for moving ahead with an ANS that might have to use HEU appears to be weak.

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8. REFERENCES

Aeppli, G., private communication, 1994.

Alston, E. E. et al., *Fuel Density, Uranium Enrichment, and Performance Studies for the Advanced Neutron Source Reactor*, ORNL/TM-12775, Oak Ridge Natl. Lab., June 1994.

Appleton, B. R., private communication, 1994.

Bari, R. A. et al., *Advanced Neutron Source Enrichment Study*, Brookhaven Natl. Lab., January 1994.

DOE, *Neutron Sources for America's Future*, Report of the Basic Energy Sciences Advisory Committee Panel on Neutron Sources, DOE/ER-0576P, January 1993.

DOE, *Neutron Sources and Applications*, Report of a Review Held at Oak Brook, Illinois, September 1992, DOE/ER-0607P, January 1994.

Goldstone, J., quoted by Flam, F., Science, Vol. 261, July 1993.

ILL, *Guide to Neutron Research Facilities at the ILL*, 1988.

ORNL, *Conceptual Design Summary*, ORNL/TM-12184, Oak Ridge Natl. Lab., September 1992.
Price, D. L., Physics Today, January 1985.
Seitz, F., Eastman, D., *Major Facilities for Materials Research and Related Disciplines*, National Research Council Major Materials Committee, National Academy Press, Washington 1984.
Skold, K., Price, D. L., *Neutron Scattering*, Orlando: Academic Press, 1986.
Stein, R. S., Han, C. C., Physics Today, January 1985.
West, C. D., private communication, 1994.

Discussions with: Dr. William Happer, former director of Office of Energy Research; Dr. Sunil Sinha, Exxon; Professor Richard Register, Princeton University; Dr. Andre' Michaudon, LANL; Professor Eric Kaler, University of Delaware; Dr. Colin West, project leader, ORNL; Dr. Ron Fleming, University of Michigan; Dr. James Lake, INEL; Dr. Frank Bates, University of Minnesota; Dr. Gabriel Aeppli, AT&T Bell Laboratories; Dr. Bill R. Appleton, associate director, ORNL; Dr. Alan Mills, AT&T Bell Laboratories; Dr. Doug Selby, ORNL.

APPENDIX: NEUTRON PHYSICS

Neutrons are subatomic particles with zero charge and a magnetic moment. The zero charge means that the interactions with matter are confined to the short-ranged nuclear and magnetic interactions. This results in a small interaction probability with the material, and so the neutrons can penetrate deep into matter. The value of the neutron mass is such that for room temperature (T=300K) the wavelength ($\lambda \approx 2$Å) is comparable to the atomic separation in a solid or dense fluid. This make neutrons very well suited to studies of the atomic structure of condensed matter in scattering experiments. Since neutrons only interact with the components of the nucleus, the neutron scattering cross section for a nucleus changes in an irregular fashion with the atomic number, in contrast to x-ray scattering. Neutrons are thus sensitive to light atoms such as hydrogen and oxygen, as opposed of x-rays.

In a scattering experiment a beam of neutrons falls on to a sample. Most of the neutrons are transmitted without any interaction with the sample, but some will be scattered and are measured with a detector placed in a certain direction. By examining the angles and speeds at which neutrons are scattered, information about the arrangement of the atoms in materials and, how the atoms diffuse can be gained. In crystalline materials, intensity maxima in the diffraction pattern are obtained when waves scattered from successive planes interfere constructively.

In addition, the neutron has a magnetic moment. Diffraction experiments in which neutrons are scattered through the magnetic interaction provide information about magnetism as well as the electronic structure of the material. This pattern contain detailed information about the spatial configuration and correlations of atoms and spins in the target. Length scales between 1Å and 1000Å can be readily probed but with certain techniques these limits can be extended. The intensity of the scattered neutrons are measured with suitable detectors. In structural determinations neutron scattering gives information directly as to positions of the nuclei in the crystal whereas with x-rays this information is convoluted with the electron positions. The magnetic moment of the neutron makes it a unique probe of magnetism on an atomic scale. The neutrons may be scattered from the magnetic moments associated with unpaired electron spins in magnetic samples. In a scattering experiment both the magnetic structure and the dynamics of the spin system can be studied (Skold, 1986).