Materials for
Spallation Neutron Sources

Proceedings of the Workshop held at
Los Alamos National Laboratory
February 6-10, 1995
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Materials for Spallation Neutron Sources

Compiled by
W. F. Sommer and L. L. Daemen

Abstract

The Workshop on Materials for Spallation Neutron Sources at the Los Alamos Neutron Science Center, February 6 to 10, 1995, gathered scientists from Department of Energy national laboratories, other federal institutions, universities, and industry to discuss areas in which work is needed, successful designs and use of materials, and opportunities for further studies. During the first day of the workshop, speakers presented overviews of current spallation neutron sources. During the next 3 days, seven panels allowed speakers to present information on a variety of topics ranging from experimental and theoretical considerations on radiation damage to materials safety issues. An attempt was made to identify specific problems that require attention within the context of spallation neutron sources. This proceedings is a collection of summaries from the overview sessions and the panel presentations.
Foreword

The workshop on Materials for Spallation Neutron Sources was held at Los Alamos National Laboratory, February 6 to 10, 1995. More than 100 persons registered for this workshop.

The chairpersons express their appreciation to the participants who contributed and made this a meaningful workshop. We especially thank our colleagues from Europe and Japan for their efforts in traveling to the United States and for the numerous contributions they made.

This report summarizes the workshop. It identifies areas in which work is needed, describes successful designs and use of materials, and identifies opportunities for further studies.

Addresses of the participants are listed in Appendix A. People are encouraged to correspond directly with the contributors to the workshop in areas in which additional information is desired and in which collaboration is appropriate. Visual aids from the presentations can be obtained by contacting the session chairperson or a workshop chairperson.

Luke L. Daemen, Los Alamos National Laboratory
Walter F. Sommer, Los Alamos National Laboratory
Torben O. Brun, Los Alamos National Laboratory
Lee S. Schroeder, Lawrence Berkeley National Laboratory

Chairpersons
**Workshop Goals**

- Determine the present state of knowledge on materials performance at spallation neutron sources
- Identify experimental and theoretical efforts that will produce an understanding of materials performance that will allow facilities to be constructed and operated with confidence
- Identify facilities that can and should be used for definitive experiments
- Identify programs that are able to support work in this area
General Workshop Conclusions

- 1-MW spallation neutron sources (SNSs) are within reach now; 5-MW sources will require additional development, particularly as far as materials are concerned.

- The possibility of enhanced corrosion phenomena induced by particle-water-metal interaction needs to be understood in the SNS radiation environment.

- Radiation damage effects data for SNS environments are limited; expect surprises at high power and high fluence.

- The effect of shock loading for short, high-intensity pulses on solid and liquid needs to be studied experimentally.

- Basic data on response of materials to SNS environments are absolutely necessary to qualify the operational performance of advanced SNS.

- Water chemistry and ways to mitigate the corrosion effects from SNS environments must be understood.

- In view of limited resources and facilities, collaboration among all parties is required.

- Be aware of "lessons learned" at operating facilities.
Overview of Spallation Neutron Sources

The Materials for Spallation Neutron Sources workshop began with a welcome from John Browne, Program Director for Los Alamos Neutron Science Center and Energy Research Programs. He summarized the plans for continuing the development of spallation neutron sources (SNSs) at Los Alamos. He urged the workshop participants to establish collaborative development programs on materials for target systems as well as in other areas important to SNSs.

Lee Schroeder, Lawrence Berkeley National Laboratory, summarized recent activities surrounding studies aimed at identifying the next SNS in the United States. But at this time (1995), funds from the Department of Energy (DOE) have not been available. However, discussions involving the potential user community have identified the need for a new source or sources in the 1- to 5-MW range. Such a new facility can probably not be realized (due to fiscal restraints) until the early part of the 21st century. It is also generally recognized that workshops, such as the present one, be held to determine needed research and development as a guide to funding agencies.

Unless otherwise noted, the facilities described below accelerate protons used for the production of neutrons through interactions with metal targets.

Spallation Neutron Sources in Europe

Günter Bauer, Paul Scherrer Institute

Günter Bauer summarized the present status and plans for the ISIS facility in England, the AUSTRON initiative from Austria, SINQ in Switzerland, and the studies on the European Spallation Source (ESS).

ISIS

At ISIS, a rapid-cycling synchrotron produces an 800-MeV beam at 50 Hz. The peak current density on the target is 9 μA/cm². This facility has been in operation since 1986 during which time the current has been increased steadily up to the design level of 200 μA. The facility has used a uranium target that has experienced some difficulties from radiation-induced swelling. A tantalum target has performed reasonably well. There are plans to examine a spent tantalum target for radiation damage morphology.

AUSTRON

The AUSTRON SNS is under study in Austria and will feature a 1600-MeV, 25-Hz pulsed beam of 440-ns duration. The present target design considers a W 5% Re alloy that is cooled with water on the target edges, eliminating any coolant passage through the beam. Thermal strains are relieved by splitting the target into “pie-shaped” segments. The average current density is low at 18 μA/cm².
SINQ

SINQ is a continuous source, which will operate at 590 MeV and 1.5 mA at 50 Hz. The expected maximum current density on the target will be 17 μA/cm² initially with the possibility of operation at 25 μA/cm² with advanced target designs. The initial target will comprise rods in hexagonal cans. There is a strong desire to develop a liquid target for SINQ.

SINQ experience includes the exposure of an aluminum-magnesium-silicon alloy (AC-100), used as a beam window, to 6000 hours of protons (perhaps a fluence of about 6 x 10^{24}/cm²) without failure. SINQ proposes to include a surveillance program that allows removing critical target component samples at intervals for testing to determine whether replacement is needed. SINQ staff are concerned about passing cooling water through a proton beam because of the attendant activation of the water and the strong possibility of enhanced corrosion mechanisms that may be induced and that are not yet fully understood.

ESS

The parameters for the proposed ESS include an energy of 1.35 GeV, a current of 3.7 mA, and a frequency of 50 Hz. The total beam power of 5 MW will be shared by two target stations: a 4-MW, 50-Hz station and a 1-MW, 10-Hz station. The high-power station will be designed for taking the full power of 5 MW, which is placed in a two-dimensional parabolic spot with a 10-cm base dimension resulting in a maximum current density of 94 μA/cm² at the center of the beam. The designers are determining the feasibility of both a stationary beam entrance window and stationary target for this 5-MW source. A present design considers a rod target that requires cooling on both the rod surface and on the rod centerline. These rods are packed in a hexagonal array. Additional consideration is being given to thin plate targets and liquid targets, as well as a rotating solid target that would have a diameter of 60 cm.

Spallation Neutron Sources in Japan

Michihiro Furusaka, KEK National Laboratory for High Energy Physics

A caution was offered; neutron flux of high-power spallation sources does not linearly scale with proton power because of the difficulty building a highly efficient target-moderator system for the sources, especially for those exceeding a megawatt.

The present Japanese KENS facility at KEK shares proton beam from a 500-MeV, 6.5-μA, 20-Hz booster synchrotron accelerator with muon and proton therapy facilities.

There is a planned neutron scattering facility at the Japanese Hadron Project (JHP). JHP is based on a proton accelerator complex, which consists of a 200-MeV, 400-μA linac, a 3-GeV, 200-μA, 25-Hz (0.6-MW) booster synchrotron for neutron scattering (N-arena), muon (M-arena), and exotic nuclei (E-arena) facilities, and a 50-GeV, 10-μA main ring for particle and nuclear physics (K-arena). For the second phase, the booster synchrotron will be upgraded to 1.2 MW by increasing repetition rate to 50 Hz.

There is also an Accelerator Transmutation of Waste (ATW) program in Japan. The machine is to be operated at 1.5 GeV, 10 mA. Use of a part of the beam for a spallation neutron source is under consideration.
There is also an Accelerator Transmutation of Waste (ATW) program in Japan called the Engineering Test Accelerator. The machine is to operate at 1.5 GeV and 10 mA. The major purpose initially will be to test the engineering aspects of ATW.

Operating and Proposed Spallation Neutron Sources in the United States
Jack Carpenter, Argonne National Laboratory

A 1-MW source is within reach now, based on our experiences and our ability to test some important target engineering parameters; this is not considered to be true at the present time for a 5-MW source. It is also believed that the path to higher beam energy is best through increased voltage, up to 10 GeV.

Two SNSs operate in the U.S. at present. The Intense Proton Neutron Source (IPNS) at Argonne National Laboratory operates at 450 MeV and a proton beam power of 6.8 kW. The facility uses uranium in α-phase, clad by Zircaloy. They have experienced some difficulties with cladding cracks. IPNS does have the capability for radiation damage studies by using a “thimble” that penetrates the shield. The Manuel Lujan Jr. Neutron Scattering Center (MLNSC) at Los Alamos National Laboratory (LANL) operates at 800 MeV and 70 μA (designed for 100 μA). The target is a W heavy metal alloy. Performance of the W has been good, but there have been difficulties with cracks in the LH2 moderator system.

The existing experience base for SNSs is as follows:

<table>
<thead>
<tr>
<th>Facility</th>
<th>Power</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISIS</td>
<td>160 kW</td>
<td>Since 1986</td>
</tr>
<tr>
<td>MLNSC</td>
<td>80 kW</td>
<td>Since 1989</td>
</tr>
<tr>
<td>IPNS</td>
<td>6.8 kW</td>
<td></td>
</tr>
<tr>
<td>KENS</td>
<td>3.5 kW</td>
<td></td>
</tr>
<tr>
<td>In the near future</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SINQ</td>
<td>780 kW</td>
<td>to be demonstrated</td>
</tr>
</tbody>
</table>

Accelerator Production of Tritium Neutron Source: Design Overview and Expected Operating Environment
Mike Cappiello, Los Alamos National Laboratory

The Accelerator Production of Tritium (APT) facility is to operate at 1 GeV and a current of 100 to 200 mA. This is to be a continuous-wave machine. The current density will be around 50 μA/cm². Neutrons will be produced in a target made of pure W rods. Neutron multiplication is accomplished in lead, and moderation is accomplished in D2O. Tritium is produced by neutron capture in He-3 or Li-6. Some areas of the blanket receive a neutron flux > 10²⁰/cm²-s.

The target and blanket designs are largely based on experience at the Los Alamos Meson Physics Facility (LAMPF). Inconel 718 has been used successfully at LAMPF and is the candidate material for the beam entry window at APT. Radiation damage effects data from LAMPF experience and from dedicated experiments have been effectual in guiding the design. An extensive materials qualification program using the LAMPF/Los Alamos Neutron Science Center (LANSCE) irradiation facility and the development of a surveillance program are
planned. The goals of this work are collecting basic radiation damage effects data, observing the performance of components and weldments, and determining and mitigating corrosion-related phenomena.

Overview of Accelerator-Driven Transmutation Technology

*Ed Arthur, Los Alamos National Laboratory*

Los Alamos has considered several concepts for accelerator-driven neutron sources suitable to transmute fission products and actinides from spent reactor fuel to shorter-lived isotopes. The possibility for using plutonium as a fuel and also producing power in these systems is under study.

Both solid (W) and liquid (Pb) targets have been considered. At present, a liquid Pb target and a blanket of molten salt containing coolant and fuel as well a slurry stream of isotopes for transmutation is being considered. A demonstration of the target and blanket is under consideration and would be housed in the LAMPF/LANSCE experimental area.

Beam power at accelerator-driven transmutation technology complexes could be in the 100- to 200-MW range. The beam would be spread to keep current densities at an acceptable level.

Experience with Radiation Effects to Materials at Spallation Neutron Sources

*Walt Sommer, Los Alamos National Laboratory*

Two facilities have provided the bulk of the radiation damage effects data for high-energy proton and spallation neutron environments: the Proton Irradiation Experiment (PIREX) at the SIN accelerator in Switzerland and the Los Alamos Spallation Radiation Effects Facility (LASREF) at LAMPF/LANSCE. Both facilities were initiated through the efforts of Walter Green. PIREX began operation in 1980 and was later upgraded. LASREF was initiated in 1975 and upgraded in 1985. Both facilities are still operational. Their characteristics are described later in this report.

It is now possible to determine radiation damage parameters for SNS environments through use on high-energy transport codes such as the Los Alamos High-Energy Transport (LAHET) Code System. Displacement energy cross sections and transmutation production cross sections as well as details of atom recoil energy spectra and distribution functions are the usual result of these calculations. Monroe Wechsler has been largely responsible for the work in this area at Los Alamos.

A limited number of reports on the results of materials exposure to SNS environments are available. There is an indication that the higher He production rate in SNS environments, relative to the fission reactor environment, is effective in stabilizing void embryo and beginning bubble formation in pure aluminum.

Low-dose irradiations on pure copper indicate that the defect cluster morphology found after equivalent displacement per atom levels from exposure to fission, 14 MeV, and spallation neutrons is nearly identical. This result suggests that even as the higher energy recoils from the higher energy neutrons create larger displacement cascades than for the fission case, these break into subcascades, the largest of which imply an effective recoil energy of 20 keV or so.
Experience at LAMPF indicates that nickel alloy Inconel 718 can perform to a dose of at least $7 \times 10^{21}$ protons/cm$^2$. A collaboration among MLNSC, ESS, and the Paul Scherrer Institute (PSI) will investigate mechanical property changes to beam entry windows actually used at LAMPF or especially irradiated LAMPF. Materials include alloy 304L stainless steel, Inconel 718, and a Fe-10.5% Cr alloy.

LASREF will again be used to study materials for the APT and MLNSC programs. Collaborators from around the world are encouraged to participate in this work. The irradiations are planned to begin in August 1996.
Panel I

Applicability of Fission/Fusion Materials Data

Session Chairperson: Frank Garner, Pacific Northwest Laboratory

Presentations

The following presentations were made during this panel session:


2) “Corrosion Problems in Nuclear Environments,” M. R. Louthan et al., Westinghouse Savannah River Company

3) “Fission and Spallation Radiation Environments,” L. L. Daemen, Los Alamos National Laboratory

4) “Radiation Effects in Materials and New Irradiation Environments,” L. K. Mansur, Oak Ridge National Laboratory

Summary

The successful design and construction of a SNS will strongly depend on the properties of the materials that compose the source and its supporting structures. It is well known, however, that the properties of all materials change to some degree upon exposure to radiation that displaces and ionizes, and that the evolution of such properties frequently becomes the life-limiting criterion for any given material or component.

The confident prediction of component lifetimes requires that data be available on the response to radiation of the materials and properties of interest. In the best of situations, this in turn requires that performance data be collected from an environment in which the damaging species, their energy spectra, and their particle fluxes are completely prototypic of the environment anticipated in the neutron source. In most cases, however, such data are currently not available or were generated in environments with different flux and spectra, and sometimes even different damaging species.

This situation has been faced previously by other segments of the radiation damage community, most recently in the fusion materials area. The use of “surrogate” spectra and “fission-fusion” correlations is a well-established subspecialty of the radiation damage community. Similar correlation efforts can therefore be applied to the neutron source situation, providing that all important differences in environment between the source and the surrogate spectra are identified and their impact on the correlation assessed.

Luke Daemen described in detail the differences between the spallation neutron environment and the environment found in typical fission-based devices. The most important differences with respect to materials behavior are as follows:
1) Whereas neutron-induced transmutation can exert a large influence on property evolution in fission-based sources, there will be a very much wider range of elemental species induced by the spallation process. The impact of such alteration is not yet known.

2) Per unit of displacement damage, many of the materials of interest to spallation devices will have a larger level of induced radioactivity than that induced by typical fission spectra. This represents additional challenges in the testing of spallation-damaged components.

3) The spallation process also creates highly energetic charged particles which can contribute to the damage process. This complicates the prediction of component behavior.

Frank Garner presented a review of those factors thought to be relevant to spallation-surrogate correlations. He noted that high-flux irradiation, especially at elevated temperatures, places all materials of interest in an environment that is unprecedented in its ability to modify phase stability, dimensional stability, mechanical properties, and most physical properties.

In particular, the following major points were stressed:

1) For many materials of interest to spallation sources, transmutation processes have been found to be a dominant contributor to the damage process. Unfortunately, variations in transmutation rates that arise from spectral variations in a given reactor are usually accompanied by variations in damage rate. It has also been observed in many systems that the strongly coupled influence of damage rate and temperature determine many important features of the irradiation response. Therefore, the influence of simultaneous variations of both transmutation rate and displacement rate are sometimes difficult to separate in surrogate spectra. This in turn presents problems in the “translation” of such data from surrogate tests to the new environment. It was also shown in this presentation, however, that procedures developed in the fusion materials program to help isolate the separate effects of transmutation and displacement rate could also be used for spallation sources.

2) Many materials of current interest to the fusion materials community were “low-activation” in nature and therefore perceived as being inherently more safe. Unfortunately, however, “low activation” does not necessarily imply “low transmutation,” but only that the transmutation products themselves are not radioactive. Of the various examples shown to be relevant to the fusion community, the element tungsten was singled out to be especially high transmutation in nature. Tungsten is a proposed spallation source material.

3) The perversity of nature expressed itself in that most materials chosen in the fusion program primarily for their neutronic qualities seemed to be uniquely prone to either transmutation or embrittlement. Several of the materials being considered for spallation sources also fall into this category.

4) The identification and separation of all relevant variables and damage processes for a given material and property change are essential in order that the data derived in a surrogate environment be successfully applied to another environment.

The latter point was not only illustrated by several examples in Garner’s talk but was especially highlighted in Lou Mansur’s presentation. In one particular example, it was shown that two fission environments, thought previously to be quite comparable, differed strongly...
in one unrecognized aspect, that of the relative gamma ray/neutron flux. Whereas the gamma-induced component of the damage was relatively small in most of the surrogate spectra, it was unexpectedly dominant in the case of embrittlement of the High Flux Isotope Reactor (HFIR) pressure vessel. The vessel appeared to be embrittling at a rate that was strongly accelerated relative to that predicted by the embrittlement equation developed in more typical fission spectra. The successful resolution of this apparent discrepancy has led to rethinking the relative rates of gamma and neutron damage for other applications as well.

Whereas the presentations of Garner and Mansur focused on single properties of single materials, the presentation of Mac Louthan focused on the sometimes strongly interactive nature of multiple materials existing in a shared and interactive environment, especially for corrosion-related phenomena. The major conclusions from Louthan’s presentation that were considered relevant for spallation sources are as follows:

1) The conditions necessary to protect one material in a system can compromise the integrity of other materials in the system. The system must be considered in its entirety and a balance sought to maintain all components.

2) The influence of evolving (i.e., radiation-induced) or deliberately changed operating conditions was strongly emphasized.

3) Echoing a theme from Garner’s talk, the influence of synergistic effects was also stressed.

All of the presentations expressed the following certain themes:

1) There is always a strong possibility of unexpected phenomena arising from radiation.

2) Each radiation-induced damage process has the potential to limit the lifetime of individual components or the entire system.

3) Radiation-induced changes must be evaluated not only for their single effect but also for their synergistic effects.

4) It is necessary to maintain an active materials surveillance program throughout the lifetime of the system.

5) The experience of lessons learned in other radiation environments should be studied in order to avoid repeating previously encountered problems in new environments.

Two major choices evolved from the various discussions that followed the formal presentations:

1) Where possible, the required data should be acquired in the appropriate spectra at the correct damage rate. At this time, LASREF at LAMPF provides the best fit to this criteria, although the neutron damage rate is lower than anticipated for most spallation applications. The achievable damage rate in the proton beam at LASREF is prototypic for planned SNSs.

2) Either obtain new data or use existing data from whatever spectra are available, and then use guidelines developed in other programs to help “translate” the data for predicting the response in the spallation case.
Panel II
Materials for Liquid-Metal Targets
and Molten-Salt Technologies

Session Chairman: James R. DiStefano, Oak Ridge National Laboratory

Presentations

The following presentations were made during this panel session:

1) “Compatibility of Structural Materials with Molten Fluoride Salts and Liquid Lead,” J. Keiser, Oak Ridge National Laboratory

2) “Materials Problems Associated with Liquid Metal Targets,” G. Bauer, Paul Scherrer Institute

3) “Radiation Damage Considerations for Accelerator-driven Transmutation Technology Using Molten Salt and Liquid Metal,” R. Klueh, Oak Ridge National Laboratory


5) “Preliminary Lifetime Considerations for 304 Stainless Steel as LANL ABC/ATW Blanket Material,” J. Park, Los Alamos National Laboratory

Summary

The objective of the presentations for Panel II was to review existing data relative to materials that might be used in pulsed accelerator-driven systems with a liquid-metal target and a molten fluoride blanket system. Information was presented relative to

- properties of liquid-metal targets
- corrosion problems relative to container materials for liquid Pb or Pb-Bi target systems and molten fluoride salt blanket systems
- radiation effects on these container materials

Liquid-metal targets can eliminate or reduce problems that have been experienced with solid targets, such as thermal stress and fatigue, degradation resulting from spallation reactions, heat transport, and radioactivity transport, and, thus, have the potential to allow higher-power levels with high-neutron densities. Based on desirable target properties, such as high density, low-melting point, low corrosivity, and good neutronic properties such as a low-neutron-absorption cross section, the following candidates were suggested: Hg, Pb, Bi, Pb-Bi, and Pb-Mg. Liquid mercury was a particularly interesting recommendation because it is liquid at room temperature, is generally less corrosive compared with other candidates, and is chemically inert. Further evaluation of mercury as a spallation target material appears warranted. Resistance to corrosion, radiation damage, wettability by the liquid metal, and thermal shock resistance are important properties of container materials that must be addressed.
Because of their higher solubilities and susceptibility to corrosion from mass transfer in Pb, Bi, or Pb-Bi systems with a temperature gradient, nickel-based alloys are generally excluded from consideration as container materials. For Pb, or Pb-Bi, low-alloy steels, e.g., 2 1/4 Cr-Mo steel, 9 Cr-Mo steel, and HT-9, have suitable resistance to mass transfer at temperatures to 400°C, and in an inhibited system (Zr, Mg) that temperature may extend to perhaps 550°C. Inhibitors can reduce the corrosion of these alloys by forming a protective surface film (e.g., ZrN) and removing oxygen from the liquid metal (MgO). However, maintaining the inhibitor in solution can sometimes be difficult thereby making an inhibited system somewhat unreliable without continuous monitoring. Although these BCC alloys exhibit increases in their ductile-to-brittle transition temperature (DBTT) when irradiated, they are more resistant to radiation damage from helium embrittlement than Ni-containing alloys, an important consideration if the container material is to retain its properties. At higher temperatures, refractory metals are the likely candidates because of their mechanical strength and much better corrosion resistance to Pb or Pb-Bi. However, niobium and tantalum (or their alloys) present special problems because of their reactivity with system impurities such as oxygen. Very high-purity systems (oxygen partial pressure < $10^{-7}$ Torr) are required to prevent their rapid embrittlement. Furthermore, data on the effects of radiation on refractory metals are quite limited. Molybdenum would be an excellent choice as a high-temperature container material for liquid Pb or Pb-Bi targets, but some data has been reported that indicates it rapidly loses ductility when it is irradiated (Figure 1).

A Molten-Salt Reactor Program (MSRP) for civilian power applications was initiated at Oak Ridge National Laboratory (ORNL) in 1956. In 1965, the Molten-Salt Reactor Experiment (MSRE) went critical and was successfully operated for several years. The MSRE was constructed of the nickel-based alloy Hastelloy N (see Table), a material that was specifically developed for this application on the basis of multiyear investigations of mechanical and corrosion properties imparted by various alloying additions.

### Normal Composition of Hastelloy N (wt %)

<table>
<thead>
<tr>
<th>Element</th>
<th>Standard</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>Balance</td>
<td>Balance</td>
</tr>
<tr>
<td>Mo</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Cr</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Fe</td>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>Mn</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Si</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>C</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Ti + Nb</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>Rare Earths</td>
<td>—</td>
<td>0.01</td>
</tr>
</tbody>
</table>

However, the MSRE did reveal two potential areas of concern if Hastelloy N was to be used in more advanced applications where greater neutron fluences and concentrations of fission products would be encountered:

- radiation damage at high temperatures due to helium embrittlement
- grain-boundary cracking that was associated with the presence of the fission product tellurium

An improved Hastelloy N composition was subsequently developed by the MSRP that had better resistance to both of these problems. Molten-salt corrosion and fission-product cracking can also be decreased by reducing the oxidation or redox potential of the salt. In a
molten-salt reactor with uranium fluoride fuel, the redox potential can be adjusted to make the salt less oxidizing (e.g., by exposing the salt to Be metal); however, the activity of UF₃ must be high enough to avoid its disproportionation to metallic uranium and subsequent alloying with the container. As shown in Figure 2, the oxidation potential at which the plutonium activity associated with PuF₃ becomes unity is lower than that compared with UF₃. Accordingly, it may be possible to maintain a lower oxidation potential in a PuF₃ system compared with the UF₄/UF₃ system and the corrosion rate of austenitic or ferritic steels could be sufficiently reduced so as to be acceptable. Furthermore, these materials also possess better resistance to tellurium cracking and radiation damage from helium embrittlement.

In summary, materials data do exist relative to SNS applications. Careful design considerations must factor the strengths and limits of the potential materials both as related to corrosion and radiation resistance. Finally, when system parameters can be specified it is likely that some testing will be required to provide design and materials selection guidance.

Figure 1. Stress-strain curves for Mo and Ta, both unirradiated and irradiated, to fluences of 1.3 × 10¹⁹ and 1.5 × 10²⁰ p/cm² (Brown and Cost).
Figure 2. Oxidation states of actinides in LiF - BeF$_2$ - ThF$_4$ - UF$_4$.
Panel III
Computer Simulation and Modeling of Radiation Damage

Session Chairpersons: Michael W. Guinan, Lawrence Livermore National Laboratory
Luke L. Daemen, Los Alamos National Laboratory

Presentations

The following presentations were made during this panel session:

1) “Molecular Dynamics Studies of Radiation Effects,” M. W. Guinan, Lawrence Livermore National Laboratory
2) “Molecular Dynamics Simulation of Radiation Damage in Metals,” R. Devanathan, Los Alamos National Laboratory
3) “Codes and Data Bases for the Design and Optimization of Spallation Targets,” T. Gabriel, Oak Ridge National Laboratory
4) “Spallation Radiation Damage Calculations Using LAHET,” M. Wechsler, North Carolina State University
5) “Status and Perspectives of Theoretical Predictions for Materials Damage and Gas Production of Spallation Relevant Materials,” D. Filges, Jülich
6) “The Electric Field due to a Charged Particle Beam Passing through a Conductor,” M. Plum, Los Alamos National Laboratory

Summary

Two distinct families of codes are necessary to model radiation damage to materials. First, we need computer codes to characterize the radiation environment present at spallation sources. Second, given a radiation environment, we need computer codes to determine the effect of the radiation field on materials. Several examples of codes belonging to these two broad classes were described during the workshop. A brief overview follows.

Radiation Transport Codes

The radiation transport codes have been developed extensively over the past 30 years, and have reached a high degree of sophistication. These codes fall within two broad classes: deterministic (e.g., discrete ordinates) and Monte Carlo. The former are typically faster, but more limited in terms of modeling capabilities while the latter are slower but, generally, allow for arbitrarily complex geometry modeling. The codes typically use experimental cross-section data (multigroup or continuous). The codes are typically not monolithic. Many consist of groups of specialized programs exchanging information with each other.

Tony Gabriel, gave a very detailed description of the capabilities of a Monte Carlo code developed at ORNL, namely CALOR’95=HETC94+SPECT95+EGS4-95/PEGS95+MORSE+MICAP. By and large this package is very similar to the LANL equivalent (LAHET+MCNP)
and to other packages used elsewhere for radiation transport calculations such as the HERMES package at the Kernforschungszentrum in Juelich. Therefore, the following summary applies to many of these codes.

Most Monte Carlo radiation transport codes have at least two components. Codes such as LAHET or HETC rely on simple nuclear physics models to describe the interaction of incident, high-energy particles (e.g., protons) with target nuclei. LAHET is an extension of the ORNL code HETC for the transport and interaction at high energies (20 MeV < E < 10 GeV) of nucleons, pions, and muons. It uses the Bertini or the ISABEL model to describe the physics of the intranuclear cascade, and the well-known evaporation model for the last phase of the nuclear interaction. A pre-equilibrium model was added recently as an intermediate stage between the intranuclear phase and the evaporation phase. Two fission models (Rutherford Appleton or ORNL) complement the set of physics models used by LAHET. Particles transport is based on the Monte Carlo technique. Although LAHET is capable of transporting a great variety of charged and uncharged particles, only neutron transport is of interest here. Neutrons with energies above 20 MeV are transported by LAHET. They can participate in nuclear reactions and produce additional particles. Neutrons with energies below 20 MeV are written to a source file, later to be read by MCNP. During a LAHET calculation, a large quantity of information is recorded on a separate file which can subsequently be analyzed by another piece of code, PHT—a photon source generating code, to produce a source for MCNP. The MCNP phase of the calculation can then be executed as a coupled neutron/photon transport problem. The photons originate either by the decay of neutral pions produced in the intranuclear cascade phase or by the deexcitation of residual nuclei after the evaporation phase.

A second piece of computer code usually completes the transport by dealing with lower energy neutrons (E < 20 MeV). Examples of such codes are MCNP and MORSE. They make use of ENDF/B cross sections for neutron and photon reactions. Thermal neutrons are described by the free gas model, or when available, by a detailed scattering kernel. For photons, the code takes into account coherent and incoherent scattering, fluorescent emission after photoelectric absorption, as well as various other physical processes of no direct interest here. Contrary to multigroup codes, MCNP is a general-purpose, continuous-energy, time-dependent Monte-Carlo transport code. It is capable of handling arbitrarily complex three-dimensional geometries. One of its standard features is the capability of performing detailed criticality calculations. MCNP provides a wealth of information which cannot possibly be described in detail here. The output produced by MCNP ranges from neutron fluxes and current to energy deposition, from energy fluxes to gas production, from radiation doses to criticality eigenvalues, etc. MORSE has very similar capabilities but relies essentially on a multigroup representation of the neutron scattering cross sections.

The history tape produced by high-energy transport codes such as HETC or LAHET can be analyzed to extract primary radionuclide yields and recoil momenta. This information can be processed by nuclide burnup/transmutation codes such as ORIGEN or CINDER’90 to produce radionuclide inventories. Of particular importance from a materials standpoint is the production of hydrogen and helium isotopes. Production rates and the spatial distribution of the H and He in the irradiated material are important, basic pieces of information that are needed to predict the impact of gas production in the irradiated material.

Equally important for radiation damage calculations is information such as the recoil energy of nuclei involved in nuclear reactions or scattering events. This type of information is of crucial importance for many radiation damage codes and constitutes the essential link between radiation transport codes and these codes. Nuclide recoil information could potentially be provided in two different ways. Average recoil energy and recoil angular distributions can be calculated by the radiation transport codes. These statistical distribution
can then be convoluted with flux information to produce macroscopic quantities such as displacement cross sections, displacement rates, damage energy, etc. Or they can be used in conjunction with Monte Carlo or molecular dynamics codes by sampling these distributions to produce single “source” events for the microscopic radiation damage codes. Alternatively, one can avoid producing statistical distributions and simply save the recoil information associated with relevant microscopic nuclear events as calculated directly by the high- and low-energy transport codes.

Radiation transport codes have been benchmarked extensively over the years, especially low-energy neutron transport codes. However, much benchmarking remains to be done of the high-energy transport codes. This is particularly true with regard to gas (H and He) production and nuclide recoil spectra. Virtually no experimental data exists as far as the latter problem is concerned. Current physics models should be reviewed in the light of more recent developments in nuclear physics. A first step toward assessing the present state of affairs would be to perform a systematic comparison between codes regarding radionuclide production and recoil information calculation. Comparison with experimental data and with the results of controlled, validation experiments is another essential step to establish the validity of today’s radiation transport codes. Clearly, a collaborative effort between various institutions will be necessary for progress to be made with such an ambitious program.

Many radiation transport codes were modified to take advantage of recent developments in parallel computing. In particular, parallel versions of codes such as CALOR95 and MCNP are now available to run on large multiprocessor machines such as the T3D or on workstation clusters. The increase in computational power afforded by these new developments not only should increase the turnaround time for Monte Carlo simulations, but also will help the material scientist obtain statistically significant, detailed, local information regarding recoil events and radionuclide production. This increase in computer power is also likely to be useful if more sophisticated nuclear physics models are to be added to the existing codes in the near future.

From the point of view of ease of use, some attention should be paid to issues such as code integration, flow of information between codes, ease of information retrieval and processing, and interfacing with the code user.

Radiation Damage

Several broad classes of radiation damage codes can be distinguished.

Phenomenological models

Phenomenological models have been used for a long time. They are typified by the work of Lindhard et al. and rely on simple analytic approximations and semi-empirical data to convert particle fluxes into macroscopic quantities such as displacements per atom (DPA), DPA rates, damage energies, etc. While the physical interpretation of these quantities has often been questioned, they are used routinely in the nuclear industry to characterize radiation damage to materials. The main advantage of this method is its simplicity. One of the main limitations of this approach is that it assumes that the material is amorphous and defect-free. The information provided (e.g., DPA) can often be related to familiar experience to draw broad conclusions as to the potential for radiation damage in the irradiated material. Unfortunately, our present experience database is largely limited to nuclear reactor data, and information regarding materials irradiated in the spallation radiation environment is scarce.
The most prominent code based on this approach is SID (Spallation-Induced Damage) developed at the Kernforschungszentrum Juelich.

Monte Carlo codes and the binary collision approximation

Monte Carlo codes and the binary collision approximation go one step beyond the Lindhard model in that they attempt to model particle transport explicitly in the material, albeit in a simplified fashion to keep the time required for the simulation down to an acceptable level. Particle transport is repeated for many source particles, basic quantities such as vacancy numbers are calculated, and an average over all histories is taken at the end of the calculation in the spirit on Monte Carlo calculations. MARLOWE is probably the best example of such codes, but there are many others. MARLOWE was developed at ORNL by M. T. Robinson, “The MARLOWE program simulates atomic collisions in crystalline targets using the binary collision approximation. It follows out the consequences of launching an energetic atomic projectile, either from an external beam or from an interior site, into a target. The targets may have many material regions, each with its own arbitrary (triclinic) crystal structure and with many kinds of atoms. The program follows the slowing-down of the primary particle and (if desired) of all target particles which are displaced from their lattice sites. The particle trajectories are constructed as series of binary encounters between the projectiles and the initially stationary target atoms. Elastic scattering is governed by one of several different repulsive interatomic potentials. Inelastic (electron excitation) effects are included in a low-energy (< ~25 keV/AMU) approximation. Several analyses of the calculated results are supplied, including primary recoil range and time distributions; time and energy distributions of sputtered atoms, adatoms, redisplaced atoms, and various types of defects; replacement sequence directions and length distributions; distributions of pair separations; and various detailed cascade reports. Users may supply other analyses of developing cascades and of assemblies of completed ones.” MARLOWE and other codes like it have been benchmarked rather extensively mostly with materials irradiated by low-energy ion beams or in the radiation environment of nuclear reactors. Recently, an interface between LAHET and MARLOWE has been built at LANL, but, to the best of our knowledge, MARLOWE has never been applied to the spallation radiation environment regime. The TRIM code is another popular Monte Carlo code for atomic transport in solids. Its capabilities are somewhat similar to that of MARLOWE, but the physics models are much less sophisticated. One of the main limitations of these codes is that they are limited to rather high-energy projectiles.

Molecular dynamics

The molecular dynamics class of computer codes attempts to perform very detailed atomic transport calculations at the microscopic level. No approximations are made in solving the equations of motion of all particles involved. Ab initio interatomic potentials are often used to model interaction between atoms, and many-body effects are taken into account. Because molecular dynamics codes solve the equation of motion for every single particle involved—including target particles—it is limited in the number of target material atoms it can model (typically millions of target particles with present day computers). Although these techniques have come a long way, mostly thanks to developments in computer technology, their application remains time-consuming. They can model cascades very accurately, but only over a limited time and spatial scale, and, hence, are limited to fairly low recoil energies (tens of keV). Within these limitations, however, the information provided is invaluable, and molecular dynamics is an essential tool for fundamental radiation damage studies. Their limitation to low-energy projectiles is not necessarily a disadvantage, and they complement quite nicely higher energy codes such as MARLOWE. Several schemes have already been
developed to "finish" the calculation of high-energy cascades initiated with MARLOWE with molecular dynamics codes when the energy of recoiling atoms falls below a certain threshold.

In the end, these computer codes produce very basic information: concentration and spatial distribution of vacancies, interstitials, and other types of defects, replacement sequence directions, sputtered atoms, etc. The daunting task remains of predicting basic macroscopic mechanical properties from this basic information. Limited work has been done regarding defect kinetics and the calculation of materials properties from basic radiation damage information, and more work is necessary in this respect to reach a point where microscopic radiation damage information can be related to quantities of interest to the engineers designing spallation sources.

Other Radiation Effects

For the sake of completeness, we should mention that many other radiation effects take place that affect the physical and chemical properties of the materials exposed to a radiation field: galvanic corrosion, radiation-enhanced corrosion, water radiolysis, chemisorption and physisorption, sputtering, nuclear transmutation leading to chemical impurities, and many others. They may affect the surface or the bulk of a material, or the interface between two materials. An example of such an effect was described by M. Plum.

The electric field at the surface of a conductor can be surprisingly intense when a charged particle beam passes through it. This is important because intense electric fields may strongly affect processes that can alter the surfaces of critical assemblies. For example, in water-cooled vacuum windows, the electric fields may cause the water molecules to disassociate, and the hydrogen ions thereby created may be adsorbed into the vacuum window, thus mechanically weakening the window, causing premature failure of the window. An electrostatic analysis of a water-cooled vacuum window showed that, for the case of the beams at LANSCE, assuming a peak beam current of 32 A, a cylindrical beam radius of 5 mm, and a water-cooled channel width of 2 mm, the electric field is $1.8 \times 10^5$ V/m, with nothing in the water-cooling channel. When we add the water, the dielectric constant ($\varepsilon = 78$) of the water reduces the electric field to 2,300 V/m. Note that this result scales proportionally with beam current. Assuming for water a mobility of 1.1 cm²/s/V/cm, and an electric field of duration 250 ns, ions created within 55 nm will be collected by the vacuum window. Assuming an electric field of 2,000 V/m, and an energy loss of 1.8 MeV/g/cm² per proton, 9.9 eV per proton will be dissipated in the 55 nm distance. Since the ionization energy of water is about 30 eV per ion pair, less than one hydrogen ion will be created per incident proton. We may therefore conclude that preliminary calculations indicate that less than one hydrogen ion will be collected by the vacuum window for each proton incident on the window. We may also conclude that this effect can be minimized by maximizing the beam cross section, and minimizing the distance between the water-cooled vacuum windows.
Open Discussion

Discussion Chairperson: Monroe Wechsler, North Carolina State University

Summary

The Open Discussion Session focused on the pulsed nature of the proton beam in SNSs for neutron scattering facilities. For example, the average current incident on the present LANSCE target after bunching and storing is 100 μA. But the instantaneous current for the stored pulse is 22.1 A, which lasts 250 ns, whereas the period of pulsing is 50 ms. This means that if the average DPA rate is $10^{-6}$ DPA/s, the instantaneous DPA rate is $(50 \times 10^3 s/250 \times 10^{-9} s)(10^{-6}) = 0.2$ DPA/s. This raises two questions concerning possible differences between radiation damage because of pulsed sources as compared with that from steady sources:

1) Is there a dose rate effect? In other words, is the radiation-produced defect structure different when the same DPA is produced at a rate of $0.2$ DPA/s instead of $10^{-6}$ DPA/s?

2) Are there significant defect rearrangements during the wait time of almost 50 ms between pulses for the pulsed irradiation cases?

Louis Mansur, ORNL, made the first contribution to the analysis of the nature of radiation damage due to pulsed irradiations. He maintained that a local picture of defect arrangements and interactions indicates that there is an upper limit in pulse frequency at which the materials can detect that the radiation source is pulsed. Furthermore, the material is always "pulsed" locally even during steady irradiation. In calculations typical of steels at 500°C in a steady-state fission reactor, Mansur and collaborators found that local bursts of interstitials are separated by about $10^3$ s in pulses of $10^4$ s duration. Thus, a pulsed source operating at frequencies much greater than $10^3$ Hz would produce effects indistinguishable from steady irradiations. These theoretically predicted trends were confirmed experimentally by means of pulsed dual ion irradiations.

Heinrich Wollenberger, Hahn-Meitner Institute, called attention to the work of Kishimoto at the National Institute of Metals in Tsukuba, Japan. Kishimoto studied in-beam creep behavior of type 316 stainless steel around 400°C for 10-MeV proton irradiation. After about 10 hours of steady irradiation, the strain rate was negligibly small. But, upon pulsed irradiation with equal on and off times, the creep restarted, approaching a total amount of about $10^{-4}$. Wollenberger stated that he does not think radiation-induced creep will play a major role for SNS targets. However, he feels that SNSs are well-suited for studies of point defect behavior during pulsed irradiation.

Hans Ullmaier, Forschungszentrum Jülich, discussed the mechanisms by which pulsed production of interstitials and vacancies may enhance creep. He stated, however, that theoretical modeling suggests that radiation-enhanced creep occurs only for ranges of temperature and displacement rate not experienced in fission and fusion reactor conditions. In addition, he referred to work by P. Jung et al. on type 316 stainless steel that showed no enhancement of creep rate for a wide range of pulsing frequencies and temperatures. The reasons for the discrepancy between the findings of Jung and Kishimoto have not been identified.
Panel IV

Materials-Related Safety Issues
and Radiological Considerations

Session Chairpersons: Allen Goland, Brookhaven National Laboratory
Torben Brun, Los Alamos National Laboratory

Presentations

The following presentations were made during this panel session:

1) “Operational Experience at LAMPF,” R. Brown, Los Alamos National Laboratory

2) “Some Operational Consequences of Induced Activity in Materials,” T. Broome, Rutherford Appleton Laboratory

3) “Isotope Analysis of Spent ISIS Target Materials,” H. Wollenberger, Hahn-Meitner Institute

4) “Potential Coatings for Tungsten Spallation Neutron Sources,” J. Park, Los Alamos National Laboratory

5) “Examination of Zircaloy-Clad Alpha-Uranium Discs from ISIS,” J. Carpenter, Argonne National Laboratory

Summary

A great deal of experience has been gained at or near the beam stop at LAMPF where for many years proton irradiations and spallation neutron irradiations have been conducted. Bob Brown discussed LASREF (Mike Borden presented a detailed description of LASREF in Panel V) that can provide a proton beam of about 1 mA at 800 MeV and a spallation neutron spectrum in proton irradiation capsules or in separate neutron irradiation capsules, respectively. The target cell includes vacuum-to-air windows, an isotope production where the targets produce neutrons, and a copper beam stop. The original target cell installed in 1970 was rebuilt in 1984 and 1985.

As expected, access to the target cell must be accomplished remotely and all in situ repairs must be performed in the same manner. The target cell environment includes provisions for water cooling of windows, targets, magnets, and any other components that may be exposed to the proton beam. Magnet cooling is essential because currents are high and air cooling would not be sufficient. Moreover, radiation in the cell activates all components and dissociates cooling water leading to corrosion, and activated air leads to emission of radioactive isotopes. Activated components can attain a level of ~103 R/h and must be handled and repaired by a crew using manipulators and a crane while being stationed in a remote trailer equipped with controls and video monitors.

Many lessons have been learned in the process of repairing water connections, replacing unreliable materials, and redesigning cooling-water lines. These lessons can be summarized as follows:
1) Use standard fittings where water lines are joined and design with access for repair in mind. That is, allow ample clearance for remotely operated tools where necessary.

2) Use welded 304-L stainless-steel water lines and fittings in the radiation environment of the target cell. This material has not shown any corrosion problems to date. Target encapsulation in stainless steel or Inconel should be used.

3) Whenever possible, install connectors outside of the target cell.

4) Avoid the use of brass in target cells, and keep the use of copper to an absolute minimum.

5) Use hemispherical windows to accommodate beam-induced thermal stresses. Inconel 718 has worked well for these applications. Windows have been exposed to 2000 to 6500 mA-h without failure.

6) For the as low as reasonably achievable (ALARA) principle to be observed, design all remote handling with great care to avoid spills and optimize handling of disposable components. Remote maintenance requires simple designs.

7) Overdesign and overcool to minimize stresses, static and cyclic.

8) Keep the number of connections of all kinds to a minimum.

9) Finally, give serious attention to the choice of target cell materials—use only inorganics and stainless steel or Inconel 718.

Tim Broome described the operation of the ISIS facility of the Rutherford Appleton Laboratory, which illustrated the need for understanding how to deal with the induced activity that naturally arises during operation of a SNS. It must be recognized that the induced activity results in varying levels of radiation exposure to the staff and visiting scientists, in radioactive discharges to the environment, and ultimately in the necessity for disposing of radioactive waste, usually a costly process that can expose staff to radiation.

The ALARA principle guides the managers of Rutherford Appleton Laboratory in establishing radiation dose limits and produces constant pressure to do better. Operating experience suggests where improvements can be made by retrofitting and, certainly, by designing the next generation of SNSs with the ALARA principle foremost.

At the ISIS Facility, the water-cooling plant is complex and requires regular maintenance. However, the dose rate around the piping is 20 to 50 mrem/h and is caused by the deposition of $^7$Be (from spallation of oxygen in the cooling water) on the inside of the pipes. If this process scales with beam power, then it would be impossible to perform “hands-on” maintenance of water-cooling pipe at a 5-MW source because the dose rate would be 0.6 to 1.5 rem/h. Because the activity of the target coolant, the commercial sensors of flow, pressure, temperature, etc., will have to operate in high radiation fields. At ISIS, the dose rate on the pipework is ~500 R/h. Consequently, pressure and conductivity sensors have a life of 1 to 2 years. At 5-MW beam power, this means replacing sensors every few weeks. But the $^7$Be introduces an exposure problem for this work.

The conclusion is that the $^7$Be problem needs to be addressed if “hands-on” operation and maintenance of a water-cooling plant is to be practical.

As in the case of LAMPF, years of successful operation at ISIS have produced valuable insights into the design criteria for a future high-power source. Some of them follow:
1) Recovery from equipment failures always results in increased radiation exposure to staff.

2) To minimize exposure, develop a means of quantitatively predicting effects of radiation on materials, defining component lifetime, and quantitatively measuring the condition of a component.

3) Development of a leak-tight, radiation-hardened connector which is easy to handle remotely is required because remote handling will be a significant activity at any high-power source. This observation is consistent with that made by Brown of LAMPF who argued for minimizing connections within a target cell.

4) It is obvious from the foregoing that the design of a high-power neutron source must incorporate low-activity materials with short half-lives, and should pay attention to minimize handling of active materials.

5) Problems of handling tritium should be anticipated in the facility design because it is a particular problem in water systems and irradiated targets. Tritium handling has been addressed in great detail in many laboratories, and this collective experience should be harvested for use in the design of a new SNS.

Heinrich Wollenberger raised an interesting question in his assessment of the atom probe as a sensitive instrument for isotope analysis of a long-term irradiated target material. He explained the principle of the instrument and showed its typical features. Through a combination of mass spectrometry and pulsing techniques, it is possible for this instrument to detect isotopes with unit mass resolution when they are present even in a concentration less than 1%. This can be accomplished by Ar-ion sputtering of target atoms onto a W atom-probe tip, and then carrying out pulsed-field desorption of the atoms on the tip. Such instruments are available in many institutions and could become valuable tools in the analysis of spallation neutron targets. The information they provide could be helpful to target designers and those who strive to quantify high-energy proton interaction with materials. Wollenberger poses the following question: Does the SNS community regard the atom probe as a useful tool for this purpose? The answer presumably will be forthcoming as funding to develop a spallation source is made available.

John Park continued the discussion by reporting on a literature survey that he and his colleagues conducted of potential coatings for a tungsten spallation neutron target. Tungsten has several attractive features including its high melting point, high neutron yield per proton, and relative ease of disposal after activation. However, its high-thermal neutron-absorption cross section may be a serious disadvantage. The point was made that the deposition of spallation products from the tungsten onto the walls of the coolant system might be suppressed by coating the tungsten.

Several problems arise in choosing an appropriate coating. It must have high corrosion resistance, good adhesion properties, and the ability to remain bonded to the target under rapid thermal cycling. From a practical point of view, not much information is available and a research effort would be required to select the appropriate combination of coating and tungsten target. The literature suggests that the choice may lie between metallic and refractory-oxide coatings. The coating method of choice in either case seems to be electroplating with plasma spraying as a possible alternative. The primary obstacle to overcome in applying an adherent deposit to tungsten is the naturally forming oxide that is difficult to remove and that reforms rapidly in air or water. Newer methods of coating that combine ion plating and electroplating or combine an ion beam and evaporation-deposition would seem worthy of further study for this application. Ring shear tests have shown that ion plating and electroplating can create a strongly bonded coating of copper on tungsten. But much work needs to be done if target coatings are to be used with confidence.
Fortunately, there is now some target operating experience at an existing, albeit low-power, SNS. Jack Carpenter provided an example of what can be discovered by installing targets with finite expected service lifetimes followed by analysis of failure mechanisms. He reported on examinations of an IPNS depleted uranium target. The target was a cast uranium alloy that was machined to an appropriate size and housed in machined Zircaloy cups that were assembled by electron-beam welding. Final machining of the target is performed after heat treatments that determine the final crystallographic phase of the uranium.

A comparison of the ISIS and IPNS target failure data reveals that burnup seems to be the variable that best correlates with time of failure. Anisotropic growth arising from a combination of thermal cycling and irradiation is the underlying process. Therefore, the conclusion is that fine-grained and randomly oriented grains are best for target fabrication. It should also be noted that the $\gamma$ phase of uranium is cubic and has isotropic properties; these attributes should be considered in developing new uranium target fabrication techniques. However, difficulties are anticipated because the $\gamma$ phase is metastable.

Examination of the fractures of the Zircaloy-clad uranium target revealed cracks containing gray-colored material and debonding of the cladding. Corrosion products from the failed target were examined and identified by analysis of diffraction patterns as expected products of uranium corrosion in water. The complete story has been prepared for publication and is available upon request.

The presentations in the session emphasized the need to include serious attention to personnel safety issues in the design of new SNSs at the earliest stages. Although this may seem to be an added burden to designers who already face a difficult task in dealing with a high-power source, attention to safety issues can have a profound effect upon selecting a material. This failure to address both questions simultaneously could lead to costly design errors and the inability to obtain regulatory clearance to operate a very expensive facility.
Panel V
Review of Irradiation Facilities

Session Chairperson: Jim Stubbins, University of Illinois

Presentations

The following presentations were made during this panel session:

1) “Materials Irradiation Facilities at Brookhaven National Laboratory,” L. Snead, Brookhaven National Laboratory
2) “The HFIR Irradiation Facility at Oak Ridge National Laboratory,” L. Mansur, Oak Ridge National Laboratory
4) “Spallation Neutron Irradiation Facilities at the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory,” R. C. Birtcher, Argonne National Laboratory
5) “Irradiation Experiment Capabilities with the Los Alamos 800-MeV Proton Beam,” M. Borden, Los Alamos National Laboratory

Summary

Six presentations described a number of irradiation facilities that could be useful for studying irradiation effects in materials of interest for accelerator-driven neutron sources. Several categories of facilities and expertise were discussed, and need for future work identified.

Irradiation Sources

Irradiation sources can be broken down in three broad categories as shown in Table 1.

Post-Irradiation Examination Facilities

Post-irradiation examination facilities are extensive (PNL, ORNL, ANL, BNL, PSI, EEC countries, LANL, and so forth). These facilities are presently underused and becoming increasingly expensive to operate. Nevertheless, the experience in using these facilities for post-irradiation examination is high.
Table 1: Present and Planned Irradiation Facilities

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Location</th>
<th>Status</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission Reactor</td>
<td>HFIR</td>
<td>ORNL</td>
<td>Operating</td>
<td>Fast/Mixed Fission Neutron Spectra, Gamma Heating</td>
</tr>
<tr>
<td></td>
<td>HFBR</td>
<td>BNL</td>
<td>Operating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ATR</td>
<td>INEL</td>
<td>Operating</td>
<td></td>
</tr>
<tr>
<td>Proton/Spallation Neutron</td>
<td>PIREX</td>
<td>PSI &amp; BNL</td>
<td>Operating</td>
<td>Prototypical, but must watch pulse structure and current</td>
</tr>
<tr>
<td></td>
<td>IPS</td>
<td>ANL</td>
<td>Operating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LASREI</td>
<td>LANL</td>
<td>Operating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SINQ</td>
<td>PSI</td>
<td>1996</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>BNL</td>
<td>etc.</td>
<td>Proposed</td>
<td></td>
</tr>
<tr>
<td>Ions/Electrons</td>
<td>3-beam</td>
<td>ORNL</td>
<td>Operating</td>
<td>Highly controllable: fast non-activating irradiations; significant issues for correlating data with desired irradiation spectrum.</td>
</tr>
<tr>
<td></td>
<td>various</td>
<td>ANL &amp; LANL</td>
<td>Operating</td>
<td></td>
</tr>
</tbody>
</table>

Experience Base

Materials selection, characterization, and development for energetic proton and spallation neutron environments can take advantage of considerable work that has been performed over the past 50 years to characterize and select materials for radiation environments. The experience base is extensive and includes the following:

- Materials selection, development and application experience in a variety of nuclear reactor environments: light-water fission reactors (LWRs), heavy-water fission reactors (HWRs), gas-cooled reactors (GCRs) including high-temperature versions, fast-fission breeder reactors (FBRs), research and experimental reactors, space reactors, fusion systems, military reactors, accelerators.
- Large body of technical experts that has been working on materials issues related to existing reactors and new reactor concepts.
- Development of "small specimen" technology to allow for the examination of materials bulk properties irradiation performance with small quantities of materials (including mechanical properties and microstructural examination).
- Extensive capabilities for experiment design (irradiation capsules, instrumentation, etc.) and computational support (neutron, gamma, transmutation spectra, irradiation damage modeling, etc.).
- Materials-specific design codes, corrosion control methods, remote handling capabilities, nondestructive examination techniques, and so forth.

Needs

Materials testing and selection validation programs will require access to certain experimental facilities with the capability of controlling and monitoring experimental variables on-line. These facilities will require access to irradiation environments with prototypical neutron and proton fluxes, large experimental volumes, control of mechanical and thermal loading, and...
extended irradiation times. These are required to address the following list of materials and component issues that need to be resolved in the materials selection and validation process, and in the component design and fabrication:

- Component life cycle analysis (under prototypic conditions)
- In situ monitoring and control of component performance variables
- Nondestructive examination
- Component handling, repair, and replacement
- Corrosion (under prototypic conditions)
- Role of gases and other transmutants on materials/component performance
Panel VI
Critical Materials Issues for Spallation Neutron Sources

Session Chairpersons: Hans Ullmaier, Forschungszentrum Jülich
Günter Bauer, Paul Scherrer Institute

Presentations

The following presentations were made during this panel session:

1) “Radiation Damage in Spallation Targets,” H. Ullmaier, Forschungszentrum Jülich
2) “Microstructural Evolution of Target Candidate Materials under Simulation Irradiation,”
   H. Wollenberger, Hahn-Meitner Institute
3) “Microstructure and Hardening of Copper Single Crystals Irradiated with 590-MeV
   Protons,” Y. Dai, Paul Scherrer Institute
4) “Helium Embrittlement,” H. Schroeder, Forschungszentrum Jülich
6) “Thermal Impulse Stress Analysis,” R. Davidson, Los Alamos National Laboratory
7) “Effective Radionuclides Production Cross-Section Measurements in 600-MeV Proton-
   Irradiated Materials,” D. Gavillet, Ecole Polytechnique, Lausanne, and Paul Scherrer
   Institute
8) “Target and Moderator Concept for a 5-MW Pulsed Spallation Source,” H. Ludewig,
   Brookhaven National Laboratory
9) “The Prospects for Liquid Methane Moderators at High-Power Spallation Sources.”
   T. Broome, Rutherford Appleton Laboratory
10) “The AUSTRON Target,” M. Schuster, AUSTRON

Summary—Part I

In his opening remarks, Hans Ullmaier gave a list of qualification criteria for materials in
targets and structural components (Table 1). He pointed out that proper design can keep the
conventional thermomechanical stresses in these materials (even for stationary solid targets
in pulsed sources in the MW power range) low enough that they should not be a lifetime
determining factor (see also Part II of this panel). However, this statement holds only if the
materials properties are not degraded during the service time of the target. There is ample
evidence from fission and fusion materials research that radiation damage will strongly
deteriorate the mechanical properties of spallation materials. It is further suspected that the
stress waves induced by the deposited energy densities on some kW/cm² in sources with µs-
pulses could be another severe problem, especially in materials embrittled by H or He,
elements which are produced by the protons and neutron with high rates.
As an introduction to the following contributions on radiation effects, Ullmaier gave a brief summary of the sequence of events leading to radiation damage: atomic displacements and nuclear transmutations → point defects and foreign elements → changes in microstructure → "macroscopic" effects and the temperature ranges in which they occur (Figure 1). Finally, to illustrate the extent of radiation damage in target materials of existing and future spallation sources, he gave estimated DPA numbers and helium concentrations for ISIS, SINQ, and ESS as a function of service time (Figure 2). He pointed out that the presently available specimens irradiated under spallation-typical conditions (spent target of ISIS and beam windows irradiated in LAMPF) have reached doses of at most 10 DPA, corresponding to an anticipated service time on only a few weeks in ESS. It is hoped that this level can be pushed to higher values after SINQ becomes operational in 1996.

Heinrich Wollenberger proposed to use the heavy-ion simulation technique to acquire high-dose data in short times (e.g., with a typical dose rate of $10^3$ DPA/s, 100 DPA are obtained in about one day). By using dual-beam (heavy ions plus helium ions) facilities, both the displacement damage and the gas production can be simulated in the correct ratio. The somewhat softer recoil spectra of the heavy ions as compared with GeV protons (Figure 3) is not considered critical because of subcascade production at $T >$ some 10 keV. It should, however, be mentioned that because of the small range of the bombarding particles ($\sim 1 \mu m$), specimens suitable for mechanical tests cannot be produced. The post-irradiation examination will concentrate on transmission electron microscopy and field-ion microscopy. The experimental facilities available at the Hahn-Meitner Institute (accelerators, irradiation chambers, accessible parameter ranges, etc.) were described.

Yong Dai presented results on the fluence of 600-MeV proton irradiations at room temperature upon microstructure and hardening of copper, palladium, and gold single crystals. An increase in the critical resolved shear stress with the square root of the displacement dose was found up to some $10^2$ DPA, with a tendency to saturate at higher doses (Figure 4a). This hardening is attributed to the formation of stacking fault tetrahedra whose density was found to increase about linearly with dose up to some $10^2$ DPA and then saturates (Figure 4b). Comparison of the proton data with results from irradiations with fission and fusion neutrons on a DPA-basis showed reasonable agreement of the observed hardening. Furthermore, results on defect formation in deformed specimens were reported that could lead to a better insight in the description of work hardening.

Herbert Schroeder gave a brief but comprehensive review on the phenomenon of high-temperature helium embrittlement (HTHE) by discussing the parameter ranges of its occurrence (most important: temperature $> 0.45 \ T_{\text{melt}}$) and its consequences on mechanical properties such as reduced lifetime under creep or fatigue loads and loss in ductility (Figure 5) due to intergranular failure induced by helium bubbles at grain boundaries. He then showed that under conditions prevailing for spallation target materials, HTHE should be a critical issue mainly for aluminum and its alloys (Figure 1). For these materials practically no HTHE-data exist.

For tantalum and tungsten and, to a lesser extent, for steels, helium should lead to hardening and low-temperature embrittlement. He pointed out that the contribution of helium bubbles to hardening is discussed controversially and more experimental data are needed to clarify the situation. A further open question concerns synergistic effects of helium and hydrogen that are produced under spallation irradiation conditions in even larger amounts.

The last two contributions to Part I of Panel VI concerned stress waves in target materials induced by the heat shocks deposited by the proton beam of pulsed sources.
Harald Conrad gave an introduction to the problem and illustrated, using a simple one-dimensional case, the origin of tensile stresses in materials initially compressed by a short (~μs) heat pulse. Using calculations by Sievers he then showed that for a disk geometry foreseen in various target designs there is a tensile stress singularity in the center of the disk that could in principle lead to loads exceeding the strength of the material (Figure 6). He finally stressed the urgent need of experiments in this area and proposed pulsed electron beams of some 10-MeV energy as a suitable simulation technique. Such beams with sufficient intensity are available at a few laboratories and discussions are under way to initiate first tests.

Rich Davidson confirmed the qualitative statements of the previous contribution and corroborated the importance of stress waves in pulsed systems by showing SPR II Fuel Elements with large cracks originating from the hole in the center of the rod. He then presented results of calculated stresses in SPR II Fuel Elements (Figure 7) and described the features of computer codes suitable to treat the problem. In his conclusions he pointed out that, although the fundamentals are simple, thermal impulse stress analysis is in general a complicated task because subtle details concerning stress state, thermal and inertial dynamics, and geometry (especially for round shapes) must be taken into account.

Summary—PART II

Didier Gavillet presented results of effective radionuclides production cross-section measurements in 600-MeV proton-irradiated materials. After explaining the meaning of “effective” cross sections, he described the experimental conditions (beam parameters, specimens, γ-spectroscopy, dose determination) and the evaluation of the data. He then gave results from the production cross sections of different isotopes in four typical elements: iron, copper, zirconium, and gold. Whereas for iron and copper good agreement between measured and calculated (HETC code) values were found, large discrepancies were observed for the heavy elements (Figure 8). The reasons for these differences were discussed and attributed mainly

- to the increase in the number of precursors for each isotope with increasing atomic mass of the target
- to problems of the HETC code to model high Z target atoms

Conceptual designs for targets and moderators in future pulsed spallation sources were presented in the following three contributions.

Hans Ludewig reported the results of a detailed feasibility study of compact high-power-density targets for a 5-MW pulsed spallation source (3.6-MeV protons, pulse repetition rate of 10 to 60 Hz). After a general analysis of the overall feasibility, two target concepts were considered in detail. They employ particulate beds of tungsten and heavy-water cooling (Figure 9). Many results of calculations concerning power deposition, neutron fluxes for a variety of moderator configurations, temperature distributions, etc. were given. As critical materials issues, mechanical shocks, fatigue, oxidation, and radiation damage were mentioned.

Timothy Broome advocated the use of liquid methane as an excellent moderator substance for spallation sources. The high-hydrogen density and low-energy vibrational modes of methane lead to a neutron energy spectrum (Figure 10) that matches the requirements of a large fraction of neutron scattering instruments. Based on experience from the ISIS PANS-II methane moderator, radiation effects have been identified as the main cause for operational problems, such as induced activity, hydrogen production, and formation of high molecular weight hydrocarbons. Measures to overcome these problems were discussed and the methane moderator development program at ISIS was described. It was concluded that for beam powers
from 0.4 to 1.2 MW methane is already a practical candidate moderator material and that there are good prospects that it will also be viable for 5-MW sources.

After briefly introducing the general features of the planned AUSTRON Spallation Source (1.6 GeV - 205 kW pulsed proton beam [25 Hz]), Martin Schuster described the split-target concept (Figure 11). The target sections consist of cylindrical quasi-monoblocks of W-5% Re alloy cooled only at their circumferences (i.e., no water is present in volumes penetrated by the proton beam). Finite element calculations of temperature and stress distributions were presented. Finally, an advanced design ("flat target") for higher beam powers (400 kW) was discussed.
QUALIFICATION CRITERIA FOR MATERIALS IN TARGETS AND STRUCTURAL COMPONENTS OF MW-POWER SPALLATION SOURCES

thermomechanical stresses
stress waves
radioactivity, afterheat
corrosion
radiolysis
radiation damage
machinability
weldability
availability
costs

Table I

Thermomechanical stresses
μs-pulses, ≈ 50 Hz
ms-pulses, ≤ 10 Hz

Corrosion
Radiolysis
Radiation damage
Machinability
Weldability
Availability
Costs

Fig. 1

Ullmaier
Fig. 2
Ullmaier

Materials For Spallation Neutron Sources February 6-10, 1995

Fig. 3
Wollenberger

Distribution of Recoil Energies in Ta and W, respectively, for the Particle Indicated.
Fig. 6
Conrad

Fig. 7
Davidson
Calculated Stresses on Inside Surface of SPR II Fuel Element
Graphic presentation of the production x-section

Fig. 8

Fig. 9

Tungsten Particle Target
TITLE: Vanadium 10mm rod

Fig. 10
Broome

Methane (100 K)

H₂O

WAVELENGTH, (Angstrom)

Fig. 11
Schuster

Split-Target with Moderators
(Cross-Section in front view - Reflector is not shown)
Panel VII
Outline of a Materials Selection and Qualification Program

Session Chairpersons: Frank Garner, Pacific Northwest Laboratories
Walt Sommer, Los Alamos National Laboratory

Presentations

The following presentations were made during this panel session:

1) “Considerations for the Selection of Structural Materials for Application in Accelerator-Driven Systems,” J. Stubbins, University of Illinois—Urbana-Champaign


Summary

Jim Stubbins summarized the present state of knowledge on materials performance in spallation neutron and high-energy proton environments. Low-dose exposures of aluminum alloys to a spallation neutron flux, $\sim 4 \times 10^{20}/\text{cm}^2$, show little change in mechanical properties.

A number of materials are available that have shown adequate performance in fission reactor applications and as candidates for fusion reactor structures. To be viable qualified candidates for SNSs, especially if they are to be taken to high dose, irradiations in prototypic spectra are needed. These tests are necessary to determine the synergetic effects of high-energy atom displacements accompanied by a relatively large impurity atom production from transmutation reactions.

Flavio Carsughi outlined the materials investigation plan at the ESS project. The ISIS tantalum target and associated beam entry windows and structure will be studied at KFA Jülich. Beam entry windows made of nickel alloy Inconel 718, stainless-steel alloy 304L, and an Fe-10.5% Ni alloy, all of which have been irradiated at LAMPF, will also be studied at KFA. Other proton-irradiated materials from the LAMPF/LASREF activities may also be studied.

Carsughi presented arguments for standardizing radiation damage parameters to allow comparison among various radiation spectra on a displacement level basis. He also stressed the need to quantify parameters such as cross sections for transmutation yield, citing especially the need to understand helium production from spallation reactions.

Max Zaslawsky reported on the DOE’s position on the APT project. No decision on a preferred technology has been made at this point. A materials risk-reduction program is considered to be an integral part of the APT. The DOE encourages researchers in the United States and abroad to collaborate on the study of materials for SNSs.
Walt Sommer and Stuart Maloy outlined the APT materials qualification program at LANL. Tungsten target material, candidate materials for beam entry and structural components, and aluminum alloys and lead multiplier components will be exposed to prototypic environments at LASREF. The plan calls for exposure of a variety of samples for determining strength, ductility, and toughness to a proton fluence approaching $10^{22}$/cm$^2$ and a spallation neutron fluence approaching $10^{21}$/cm$^2$.

The APT irradiations at LASREF will also feature a heavily instrumented closed-loop water-cooling system. Candidate materials and coolant will be exposed to the proton beam. Water chemistry will be monitored as well as corrosion rates on a variety on samples. Stress-corrosion cracking will also be studied. The goals of these measurements are to determine the synergetic effects of irradiating water and metal simultaneously while they are in contact, to determine means of mitigating any undesired corrosion-related effects, and to qualify instrumentation suitable for use in an operating facility.
Open Forum

Session Chairperson: Heinrich Wollenberger, Hahn-Meitner Institute

Tim Broome, Rutherford Appleton Laboratory, related that the ISIS reflector has Be directly in water coolant and observes no corrosion effects. They maintain their water at a conductivity of $< 0.5 \, \mu\text{mho}$. 

Substantial interest remains in quantifying the effect of short (100-ns) pulses of protons on windows and targets. It appears an experiment is needed to determine whether this concern is real. Exposure of materials to a pulsed beam from the LANSCE complex Proton Storage Ring is possible and should be pursued. Harald Conrad, Forschungszentrum Jülich, also believes that these experiments can be done with pulsed electron beams at Lawrence Livermore National Laboratory and will pursue them there.

Günter Bauer, Paul Scherrer Institute, explained that SINQ plans to implement a surveillance program that allows removal of target rods at specified intervals. These materials would be studied for mechanical property changes in conventional ways and also studied with small-angle neutron scattering to determine radiation-induced strains and phase changes. It was agreed that a surveillance program and a means for using existing spallation targets as a tests bed was a sensible and needed means for obtaining relevant data. New spallation target systems should be built with this testing capability in mind.

Dick Werbeck, LANL, summarized his experience at LAMPF in dealing with high-power target stations. His remarks follow:

- Consider remote handling needs from the beginning
- Overdesign
- Minimize temperature cycles
- Simple is always better
- Use no organic materials in target cells
- Use stainless steel, avoid brass and copper
- Avoid electrical devices in the target cells
- Design for the worse case
- Consider storage of radioactive materials on-site
- Consider access to the target cell from the beginning
- Place the target cell in a vacuum, if possible
- Isolate maintenance and experiment activities

Bauer stressed that the synergetic effects of displacement damage and helium production will likely shift the regimes of swelling, creep, and creep rupture relative to our experience with materials used at fission reactors. Herbert Schroeder shared his data from H, H-He, and He implantation studies where he found that He was the most effective agent for increasing the yield strength. This is certainly a rich area for further study.

Gary Russell, LANL, asked that a study be conducted that would trade-off all the advantages and disadvantages of using W or Ta.

Frank Garner, Pacific Northwest Laboratory, reminded us that small-scale sample testing was well-developed and was continuing to be developed. This development allows information to be obtained with a minimum of radioactive materials.
Appendix A
Program

MATERIALS FOR SPALLATION NEUTRON SOURCES
Los Alamos National Laboratory
February 6–10, 1995

Monday, February 6, 1995

8:00–9:00  Badging and registration—Coffee
9:00–9:10  Welcome (Browne, LANL)
9:10–9:20  Workshop structure and goals (Sommer, LANL)

Session Chairman: J. Carpenter (Argonne National Laboratory)

9:20–9:35  The Berkeley Pulsed Source Study—Present Activities/Future Directions
           (Schroeder, LBL)
9:35–10:35 Spallation Neutron Sources in Europe (Bauer, PSI)
10:35–11:00 Coffee break
11:00–12:00 Spallation Neutron Sources in Japan (Furusaka, KEK)
12:00–13:30 Lunch

Session Chairman: L. Schroeder (Lawrence Berkeley National Laboratory)

13:30–14:30 Operating and Proposed Spallation Neutron Sources in the U.S. (Carpenter,
             ANL)
14:30–15:00 APT Neutron Source: Design Overview and Expected Operating
             Environment (Cappiello, LANL)
15:00–15:30 Coffee break
15:30–16:00 Overview of Accelerator-Driven Transmutation Technology (Arthur,
             LANL)
16:00–16:30 Experience with Radiation Effects to Materials at Spallation Neutron
             Sources—Experimental and Phenomenological (Sommer, LANL)
18:00      Director-hosted reception (Bradbury Science Museum)

Tuesday, February 7, 1995

PANEL I: Applicability of Fission/Fusion Materials Data

Session Chairman: F. Garner (Pacific Northwest Laboratory)

8:00–8:45  Radiation Effects Correlations among Facilities with Different Neutron
           Spectra (Garner, PNL)
8:45–9:30  Overview of Corrosion Problems in Various Nuclear Environments  
(Louthan, Savannah River)
9:30–9:50  Fission and Spallation Radiation Environments (Daemen, LANL)
10:00–10:30  Coffee break

PANEL II: Materials for Liquid Metal Targets and Molten Salt Technologies
Session Chairman: J. DiStefano (Oak Ridge National Laboratory)

10:30–11:00  Compatibility of Structural Materials with Molten Fluoride Salts and Liquid Lead (Keiser, ORNL)
11:00–11:30  Materials Problems Associated with Liquid Metal Targets (Bauer, PSI)
11:30–12:00  Radiation Damage Considerations for Accelerator-Driven Transmutation Technology Using Molten Salt and Liquid Metal (Klueh, ORNL)
12:00–12:15  Candidate Containment Materials for Lead and Lead-Bismuth Eutectic Targets (Park, LANL)
12:15–12:30  Preliminary Lifetime Considerations for 304 Stainless Steel as LANL ABC/ATW Blanket Material (Park, LANL)
12:30–14:00  Lunch

PANEL III: Modeling of Radiation Damage and Radiation Effects
Session Chairmen: M. Guinan (Lawrence Livermore National Laboratory) and L. Daemen (Los Alamos National Laboratory)

14:00–14:25  Molecular Dynamics Studies of Radiation Effects (Guinan, LLNL)
14:25–14:50  Molecular Dynamics Simulation of Radiation Damage in Metals (Devanathan, LANL)
14:50–15:15  Codes and Data Bases for the Design and Optimization of Spallation Targets (Gabriel, ORNL)
15:30–15:45  Status and Perspectives of Theoretical Predictions for Materials Damage and Gas Production of Spallation Relevant Materials (Filges, Jülich)
15:45–16:00  The Electric Field due to a Charged Particle Beam Passing through a Conductor (Plum, LANL)
16:00–16:30  Coffee break
16:30–17:30  Open Discussion—Summary (M. Wechsler, North Carolina State University)
19:00  Dinner at the Los Alamos Inn (Host: Gary J. Russell, LANL)
Wednesday, February 8, 1995

PANEL IV: Materials-Related Safety Issues and Radiological Considerations
Session Chairmen: A. Goland (Brookhaven National Laboratory) and T. Brun (Los Alamos National Laboratory)

8:00–8:30 Operational Experience at LAMPF (Brown, LANL)
8:30–8:50 Some Operational Consequences of Induced Activity in Materials (Broome, RAL)
8:50–9:10 Isotope Analysis of Spent ISIS Target Material (Wollenberger, Hahn-Meitner)
9:10–9:30 Coatings for APT Tungsten Rods (Park, LANL)
9:30–9:50 Effective Radionuclides Production Cross-Section Measurements in 600-MeV Proton-Irradiated Materials (Gavillet, Ecole Polytechnique, Lausanne and PSI)
10:00–10:30 Coffee break
10:30–11:30 Tour of LANSCE
Afternoon is free—Los Alamos Ski Area open until 4:00 pm

Thursday, February 9, 1995

PANEL V: Review of Irradiation Facilities
Session Chairman: J. Stubbins (University of Illinois, Urbana-Champaign)

8:00–8:20 Materials Irradiation Facilities at Brookhaven National Laboratory (Snead, BNL)
8:20–8:40 The HFIR Irradiation Facility at Oak Ridge National Laboratory (Mansur, ORNL)
8:40–9:00 The PIREX Irradiation Facility: Description and Capabilities (Gavillet, Ecole Polytechnique, Lausanne, and PSI)
9:20–9:40 Spallation Neutron Irradiation Facilities at the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (Bircher, ANL)
9:20–9:40 Irradiation Experiment Capabilities with the Los Alamos 800-MeV Proton Beam (Borden, LANL)
9:40–10:00 The Post-Irradiation Examination (PIE) Facility at Pacific Northwest Laboratory (Garner, PNL)
10:00–10:30 Coffee break
PANEL VI: Critical Materials Issues for Spallation Neutron Sources—Part I
Session Chairmen: H. Ullmaier (Forschungszentrum Jülich) and G. Bauer (Paul Scherrer Institute)
10:30-10:55  Radiation Damage in Spallation Targets (Ullmaier, Jülich)
10:55-11:15  Microstructural Evolution of Target Candidate Materials under Simulation Irradiation (Wollenberger, Hahn-Meitner Institute)
11:15-11:35  Microstructure and Hardening of Copper Single Crystals Irradiated with 590-MeV Protons (Dai, PSI)
11:35-11:55  Helium Embrittlement (Schroeder, Jülich)
11:55-12:15  Elastic Stress Waves in Targets (Conrad, Jülich)
12:15-12:35  Thermal Impulse Stress Analysis (Davidson, LANL)
12:35-14:00  Lunch

PANEL VI: Critical Materials Issues for Spallation Neutron Sources—Part II
Session Chairmen: H. Ullmaier (Forschungszentrum Jülich) and G. Bauer (Paul Scherrer Institute)
14:00-14:20  Effective Radionuclides Production Cross-Section Measurements in 600-MeV Proton-Irradiated Materials (Gavillet, Ecole Polytechnique, Lausanne, and PSI)
14:20-14:40  Target and Moderator Concept for a 5 MW Pulsed Spallation Source (Ludewig, BNL)
14:40-15:00  The Prospects for Liquid Methane Modulators at High-Power Spallation Sources (Broome, RAL)
15:00-15:20  The AUSTRON Target (Schuster, AUSTRON)
15:30-16:00  Coffee break

PANEL VII: Outline of a Materials Selection and Qualification Program
Session Chairmen: F. Garner (Pacific Northwest Laboratory) and W. Sommer (Los Alamos National Laboratory)
16:00-16:30  Considerations for the Selection of Structural Materials for Application in Accelerator-Driven Systems (Stubbins, U. Illinois, U-C)
16:30-16:45  Future Plans for the Investigation of Irradiated Materials at KFA Jülich (Carsughi, Jülich)
16:45-17:00  The Role of Materials Engineering in the Integrated Design of Spallation Neutron Sources (Buksa, LANL)
Friday, February 10, 1995

Open Forum
Session Chairmen: H. Wollenberger (Hahn-Meitner Institute) and D. Parkin (Los Alamos National Laboratory)

8:00-10:00  Open Forum: Participants are invited to contribute additional material, comments, questions, and short presentations.
10:00-10:30  Coffee break
10:30-12:00  Conference summary and closing remarks
12:00  Workshop adjourns
Appendix B
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