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R. C. Birtcher, T. H. Blewitt, M. A. Kirk,
T. L. Scott, B. S. Brown (PNS), and
L. R. Greenwood (CEN)

Materials Science Division, Argonne
National Laboratory, Argonne, IL 60439

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ABSTRACT

The decommissioning of reactor-based neutron sources in the U.S.A. has led to the development of a new generation of neutron sources that employ high-energy accelerators. Among the accelerator-based neutron sources presently in operation, the highest-flux source is the Intense Pulsed Neutron Source (IPNS), a user facility at Argonne National Laboratory. Neutrons in this source are produced by the interaction of 500-MeV protons with either of two ^{238}U target systems. In the Radiation Effects Facility (REF), the ^{238}U target is surrounded by Pb for neutron generation and reflection. The REF has three separate irradiation thimbles. Two thimbles provide irradiation temperatures between that of liquid He and several hundred degrees centigrade. The third thimble operates at ambient temperature. In the Neutron Scattering Facility, the second ^{238}U target is surrounded by Be, and there are two irradiation thimbles that operate at ambient temperature.

The energy distribution of the neutron flux has been measured by the use of 36 neutron reactions in 17 materials with spectrum unfolding by the STAYSL computer code. The spatial distribution of the neutrons within the REF irradiation thimbles has been determined from the activation of Ni. The details of the various irradiation thimbles and their neutron fluxes will be described.

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1. Introduction

The use of nuclear energy as a source of power has required the study of the effects of irradiation upon the materials that comprise or may comprise the components of a nuclear power system. Such studies have been motivated by economic and safety considerations but have also increased our understanding of materials at an atomistic level. Basic research in neutron radiation effects has been centered at well-instrumented and -controlled experimental facilities located in medium-flux reactors which have modest gamma heat loads. The desire to obtain higher neutron fluxes has stimulated interest in accelerator-based neutron systems. Development of such systems has been spurred by the decommissioning of several research reactors in the U.S.A. A spallation neutron source offers the possibility of high neutron fluxes with considerably less gamma heating than in a reactor of comparable flux. The Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory, the highest-flux spallation neutron source currently in operation, is described in this paper.

2. Intense Pulsed Neutron Source

The IPNS (Fig. 1) is based upon a rapid cycling synchrotron (RCS) which accelerates protons to 500 MeV [1]. The RCS produces 100-ns pulses of protons at repetition rates up to 30 Hz. The protons from the accelerator are

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transported to one of two target assemblies, the Radiation Effects Facility (REF) and the Neutron Scattering Facility (NSF), which have been optimized for radiation effects and neutron scattering studies, respectively. The proton beam time is divided between the two facilities so that the REF receives the proton beam only ~25% of the operating time. For this reason, two irradiation thimbles were also installed in the NSF. The target in each assembly is made of ^{238}U . Neutrons with all energies up to the incident proton energy are produced by the processes of spallation and fission, at the rate of ~20 neutrons/proton.

2.1 Radiation Effects Facility

The REF, shown in Fig. 2, consists of the ^{238}U target, two vertical irradiation thimbles, and a horizontal irradiation thimble, all surrounded by a Pb neutron reflector. The target material was chosen to maximize the conversion of protons to neutrons [2]. There is some gamma production associated with the fission process in ^{238}U , although much less than in a reactor-based facility where all neutrons are produced by fission. Should the gamma flux pose an experimental problem, it is possible to change to a Ta target, from which there would be a greatly reduced gamma flux. Lead was chosen as the reflector material based on the results of experiments and calculations on a prototype facility [2]. The neutron reflection and high-energy (n,2n) reactions in Pb increase the neutron flux in the irradiation facilities and reduce the flux gradient in a direction perpendicular to the target axis. The Pb reflector alongside the target is in the form of removable sections 10 cm on a side and 45 cm long. For specialized needs, reflector sections can be removed to increase the irradiation volume or to allow replacement with a different reflector material. Such a change in

reflector or target material could change the energy distribution of the neutrons within the irradiation facilities.

The two vertical irradiation thimbles, located on either side of the target at the positions of maximum flux, contain liquid helium cryostats (5 cm inner diameter) that can operate at temperatures between 4 and 1000 K. The liquid helium is supplied by a single 400-W refrigerator (CTI model 2800 R). The two cryostats have separate vacuum systems, which allow the temperature to be controlled independently in each cryostat. The horizontal irradiation thimble (2 cm inner diameter) is located on an axis parallel to and directly below the target. The majority of the ^{238}U target-cooling water is between the target and this thimble. The horizontal thimble operates at ambient temperature and is designed to permit short irradiations with sample removal while neutrons are being produced.

2.2 Neutron Scattering Facility

The ^{238}U target in the NSF is surrounded by C and Be reflectors which are penetrated by 12 neutron beam lines. Moderators for producing the thermal-neutron beams are located directly above and below the target. Two unused horizontal beam lines have been modified to contain irradiation thimbles (~1 cm diameter). These two thimbles radially approach within 4 cm of the target axis at the position of maximum neutron flux along this. The majority of target-cooling water is between the target and these thimbles. Both NSF irradiation thimbles operate at ambient temperature.

3. Neutron spectrum determination

The study of radiation effects has reached the stage where the neutron flux cannot be adequately described by a single number; rather, the energy

distribution of the neutrons is required to fully understand and compare experiments. A multiple-foil activation technique [3] was used to determine the neutron energy spectrum in the horizontal thimble and one vertical thimble of the REF, and one thimble of the NSF. More than 36 different neutron-activation reactions were measured at approximately the maximum flux location in each thimble. The foil activities were measured with Ge(Li) detectors over several decay- γ half-lives for each reaction. Peak integrations and Compton-background subtractions were done by means of standard computer codes [3]. Prior to spectrum unfolding, activation corrections for neutron and gamma self-shielding, cover foils, and decay during and after irradiation were made for foil geometries in an isotropic flux. The STAYSL computer code was used to iteratively unfold the neutron energy spectrum (100 energy groups) by fitting the foil activities. This method calculates the activity for each activation reaction using the ENDF/B-V nuclear cross sections and an initial input neutron spectrum. The computer code compares the calculated activities with the measured activities; it then adjusts the neutron energy spectrum and repeats the activity comparison. This process was repeated until the standard deviation of the measured-to-calculated activity ratio became stable to within less than one percent per iteration. The input spectrum was taken from computer-model calculations of the neutron generation, production, and transport in a ^{238}U target and Pb reflector system [2]. The measured neutron intensity within an energy group is uncertain by 30 percent, but the correlations between energy groups of similar energy decreases the uncertainty in the integrated neutron fluxes to 17 percent.

In addition to neutrons, the incident proton beam creates many other types of secondary particles. The secondary particles are predominantly protons with energies between 20 and 40 MeV. The secondary proton flux was estimated

from the $^{51}\text{V}(\text{p},\text{n})^{51}\text{Cr}$ and $^{65}\text{Cu}(\text{p},\text{n})^{65}\text{Zn}$ reactions. The cross sections for these reactions are uncertain. The proton energy spectrum is highly uncertain, but we believe that most proton energies are between 20 and 40 MeV, since higher-energy protons would have produced more spallation in Al than was observed.

The proton flux incident upon the ^{238}U targets was determined from the current induced in a toroid located 3.5 m upstream from the target. This measurement is uncertain by 5 percent. The protons had an energy of 500 MeV.

4. Neutron spectrum

4.1 Radiation Effects Facility

The energy distribution of the neutrons at the position of maximum flux along the center of the REF vertical thimble is shown in Fig. 3 along with the energy distribution for fission neutrons. The neutron flux measurements were made with 1 atm of He gas in the irradiation thimble, and only minor changes are expected if the cryostats contain liquid helium. The neutron flux is plotted as the flux per unit lethargy ($d\phi/d\ln E$, or equivalently, $E d\phi/dE$). The REF neutron spectrum can be characterized as a degraded fission spectrum with a high-energy component. The local minima above 10 MeV are due to neutron multiplication reactions ($\text{n},2\text{n}$) in the Pb reflector and ^{238}U target. The flux of neutrons with $E > 0.1$ MeV is $(\text{n}/\text{m}^2)/\text{p}$, and the ratio of thermal to "fast" ($E > 0.1$ MeV) neutrons is 0.014 for 500-MeV protons incident upon the ^{238}U target. The secondary proton flux is estimated to be $0.7 \pm 0.5 (\text{p}/\text{m}^2)/\text{p}$ or 0.4% of the flux of neutrons with $E > 0.1$ MeV.

The neutron energy distribution for the REF horizontal thimble is also shown in Fig. 3. This spectrum is very similar to the spectrum for the vertical thimble, and the minor differences are likely due to the increased

target-cooling water near the horizontal thimble. In the horizontal thimble the flux of neutrons with $E > 0.1$ MeV is $(n/m^2)p$, and the ratio of thermal to "fast" ($E > 0.1$ MeV) neutrons is 0.014 for 500-MeV protons incident upon the ^{238}U target. The lower number of neutrons per proton for the horizontal thimble is due to the differences in the distance between the target axis and the two irradiation thimbles. The proton flux in the horizontal thimble is estimated to be $0.20 \pm 0.15 (p/m^2)/p$ or 0.2% of the flux of neutrons with $E > 0.1$ MeV.

4.2 Neutron Scattering Facility

Figure 4 shows the neutron energy spectrum for one of the horizontal thimbles in the NSF, the REF vertical thimble and a pure fission spectrum. The neutron energy distributions for the NSF and REF are quite different, particularly at low neutron energies. The additional low-energy neutrons are produced by $(n,2n)$ reactions and down-scattering in the C and Be. The flux of neutrons with $E > 0.1$ MeV is $59 (n/m^2)/p$, and the ratio of thermal to "fast" ($E > 0.1$ MeV) neutrons is 0.77 for 500-MeV protons incident upon the ^{238}U target.

5. Damage energy

The integrated damage energy as a function of primary atom recoil energy is shown in Fig. 5 for Ni irradiated with REF, NSF, fission, degraded fission (from the CP-5 reactor [5]), and 14-MeV neutrons. Such detailed calculations are needed to understand the different damages produced by different neutron spectra. The details of the damage energy spectrum will vary for different materials, but the general features will remain the same. In the REF, neutrons with energy above 10 MeV produce approximately 15% of the total

displacements in Ni even though they comprise only 3% of the flux of neutrons with $E > 0.1$ MeV. One method of comparing the different neutron spectra is the damage energy, $T_{1/2}$, for which half the damage is produced by higher- or lower-energy events. The $T_{1/2}$ is 35 keV for the REF and 20 keV for the NSF thimbles. These compare to values of 500 keV for 14-MeV neutrons, 70 keV for pure fission neutrons, and 35 keV for degraded fission neutrons. The damage energy cross section, the energy available to create defects per neutron, is given in Table 1 for Ni irradiated in the REF and NSF. Results of such calculations are available for most elements.

6. Flux spatial distribution

For the majority of radiation effects studies, damage is primarily produced by those neutrons with energies above 0.1 MeV. The spatial variation of these neutrons within the REF thimbles has been determined from the activation of Ni dosimeter wires [$^{58}\text{Ni}(n,p)^{58}\text{Co}$]. The fluxes were determined by comparing the measured activities with those measured at the positions of the full spectral dosimetry packages. Any changes in the neutron energy spectrum have been ignored.

Figure 6 shows the variation of the neutron flux ($E > 0.1$ MeV) within the REF vertical thimble. The surfaces of constant neutron flux within the thimble can be approximated by cylinders centered on the ^{238}U target axis. The maximum flux is $320 \text{ (n/cm}^2\text{)}/p$ at the position nearest the target. The flux decrease in a direction perpendicular to the target axis is nearly linear. The 50% decrease across the vertical thimble is larger than the ~30% decrease expected in a solid Pb reflector but the same as the decrease expected in a solid Ta reflector [2]. The difference between these two reflector materials is due to the additional neutron generation in Pb by

multiple neutron reactions.

Figure 7 shows the variation of the neutron flux ($E > 0.1$ MeV) along the length of the REF horizontal thimble located below the ^{238}U target. The neutron flux is a maximum at a position 4-5 cm behind the front face of the ^{238}U target, in agreement with previous calculations. This measurement was made along the bottom of the horizontal thimble. At the top of the horizontal thimble (1.5 cm closer to the target), the flux is 30% higher.

In the case of the NSF horizontal thimbles, which are nearly radial to the target axis, the neutron flux decreases rapidly with increasing distance from the target. The rate of flux decrease is the same as in the midplane of the REF vertical thimble (Fig. 6).

7. Summary

A new neutron source, the IPNS, has recently been constructed at Argonne National Laboratory. This source is a national facility for radiation effects and condensed matter research. The Radiation Effects Facility (REF) has two cryogenic thimbles and one ambient-temperature thimble, and the Neutron Scattering Facility has two ambient-temperature thimbles. The large, well-controlled and -instrumented irradiation volume, the well-characterized neutron spectrum and flux, and the dedication to radiation effects studies make the REF ideally suited for both basic and applied research.

Table 1 Neutron fluxes, and resultant damage parameters for Ni, at the IPNS with 8 μ A of 500-MeV protons incident upon a ^{238}U target

	Neutron Flux				
Radiation Facility	E > 0.1 MEV, 10 ¹¹ n/cm ² ·s	E > 10 MEV, % ^a	Thermal, % ^a	<σ·T> ^{Ni} , (keV-b)/n	T ^{Ni} _{1/2} , keV
REF Vertical Thimble (Central Plane)					
Near Center	9.2				
Max	16.0	2.9	1.4	63.4	35
REF Horizontal Thimble (Max. Axial)					
Bottom	6.1	2.4	1.4	61.1	35
Top	9.8				
NSF (Max.)	2.9	1.9	77	55.7	20

^aExpressed as % of flux of neutrons with E > 0.1 MeV.

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Figure Captions

1. Layout of IPNS-I linear accelerator (LINAC), rapid cycling synchrotron (RSC), proton transport lines and neutron generating systems.
2. IPNS-I radiation effects assembly.
3. Neutron spectra produced in the vertical and horizontal thimbles of the REF by 500-MeV protons incident upon the ^{238}U target; a pure fission neutron spectrum is shown for comparison.
4. Neutron spectra produced in the REF vertical thimble and NSF horizontal thimble by 500-MeV protons incident upon ^{238}U targets; a pure fission spectrum is shown for comparison.
5. Comparison of integral damage-energy distributions in Ni irradiated with NSF, REF, degraded fission (CP-5), fission, and 14-MeV neutrons.
6. Spatial variation of the neutron flux ($E > 0.1$ MeV) within the REF vertical thimble.
7. Spatial variation of the neutron flux ($E > 0.1$ MeV) within the REF horizontal thimble.

IPNS-I

IPNS-I RADIATION EFFECTS EXPERIMENTAL ASSEMBLY

ISOFLUX LINES IN THE REF CRYOSTAT