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NEUTRON-SOURCE CHARACTERIZATION FOR FUSION-MATERIALS STUDIES*

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NEUTRON-SOURCE CHARACTERIZATION FOR FUSION-MATERIALS STUDIES*

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Neutron flux and energy-spectrum measurements are conducted for all major fusion-materials irradiation facilities, including fission reactors and accelerators. Dosimetry-characterization experiments and integral cross section measurements have been performed. Multiple activation and helium-production measurements are performed routinely to provide materials experimenters with neutron-exposure parameters including fluence, spectrum, displacements, gas production, and transmutation with typical accuracies of 10-15%. Such data are crucial to the fusion-materials program in order to correlate materials-property changes between irradiations and facilities and to confidently predict the performance of materials in fusion reactors.

1. INTRODUCTION

The characterization of neutron radiation sources for materials studies (1) includes both the measurement of neutron flux and energy spectrum and the calculation of damage parameters such as displacements-per-atom (DPA), helium and transmutant production. Experiments have been conducted at most materials irradiation facilities. Accurate fluence and damage values are needed to correlate material property changes between facilities and to confidently predict the performance of materials in fusion reactors. These crucial exposure parameters can generally be routinely provided with about 10% accuracy. Examples are included for several recent fusion experiments in various facilities, including the Oak Ridge Research Reactor (ORR), High Flux Isotopes Reactor (HFIR) at ORNL, the Omega West Reactor (OWR) at LASL, the Experimental Breeder Reactor (EBR II) at ANL-W, the Rotating Target Neutron Source (RTNS II) at LLL, the University of California at Davis (UCD) d-Be source, and the proposed Fusion Materials Irradiation Test Facility (FMIT) at HEDL.

2. NEUTRON FLUX AND ENERGY SPECTRUM MEASUREMENTS

Neutron measurements are made by the multiple activation of various materials followed by gamma counting and spectral unfolding. The selection and preparation of dosimeters is usually considered during the design of experimental assemblies. Only small quantities of foils or wires are usually needed to characterize an irradiation with 5-10 activation reactions and very little space is generally required. These routine fluence measurements are then related to more comprehensive spectral measurements at each facility.

Comprehensive spectral measurements usually require a separate, short irradiation to allow for short half-lives, cadmium or gadolinium covers, and heating problems with fissionable materials. In this way, up to 30 different reactions can be used to adjust the energy spectrum. The STAYSL (2) computer code adjusts the measured activities, activation cross sections, and presumed neutron spectrum using a least squares procedure. Complete covariance error matrices are provided for all input data. At present, gaussian covariances are assumed for the cross sections and flux spectrum. The output covariance matrix is then used to compute uncertainties in fluence and damage parameters.

Neutron activation cross sections have been taken from ENDF/B-V (3) and extrapolated to 44 MeV for accelerator experiments.(4) Integral testing has been performed to evaluate the cross sections, especially above 14 MeV where data is generally not well known.(5,6) The data base has been shown to be adequate for unfolding up to about 30 MeV, where most of the materials damage is generated in FMIT-like spectra. However, additional neutron cross section data is needed to handle long irradiations, reactor measurements in the 1-500 keV energy region, and accelerator measurements above 30 MeV neutron energy.

3. DISPLACEMENT AND GAS PRODUCTION CROSS SECTIONS

Displacement cross sections have been calculated for 36 isotopes using the DISCS (7) computer code and ENDF/B-V cross sections including the (n, γ) reaction. Six elements (Cr, Fe, Ni, Cu, Nb, Au) have displacement rates calculated to 50 MeV for accelerator experiments. DPA cross sections and recoil atom energy distributions have been placed at the Magnetic Fusion Energy Computer Center and can be accessed with the SPECTER computer code. Table I lists some average DPA values for reference fusion and

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Table I. Spectral-Averaged Displacement Cross Sections:
A Comparison of ENDF/B Versions IV and V

Element	DAMAGE CROSS SECTION (keV-b)			
	²³⁵ U-Fission		14-15 MeV	
	IV	V	IV	V
C	51.3	52.0	41.7	39.0
Al	98.3	96.3	176.0	176.9
Ti	95.7	92.8	268.7	243.7
V	97.1	100.9	261.5	269.9
Cr	91.6	94.8	278.8	278.4
Mn	98.2	94.6	258.6	259.6
Fe	80.3	84.4	282.4	290.1
Ni	82.2	85.0	308.3	300.1
Cu	81.3	79.2	286.3	296.0
Nb	79.5	79.5	260.4	270.9
Mo	83.4	83.5	259.6	259.2
Ta	-	53.5	-	215.5
Au	50.5	50.2	218.6	217.7
316SS	82.7	86.3	283.5	288.0

fission spectra. As can be seen, most values have changed less than 10% between ENDF/B-IV and V.

Gas production (H,He) cross sections are also included with our DPA cross sections. We are collaborating with Rockwell International (8) to simultaneously measure radiometric and helium production cross sections in all types of radiation facilities. During the ORR-MFEL experiment the ratio of measured-to-calculated (ENDF/B-IV) helium production was 0.95 (Al), 1.27 (Fe), 1.24 (Cu), 1.00 (Ni), and 1.85 (Ti). This indicates that some cross sections may have large errors (present accuracy $\pm 10-15\%$). Additional experiments are now being analyzed in OWR, ORR, HFIR, RTNS II, and d-Be spectra. Beyond simply measuring helium production cross sections, the helium monitors can also be used for fluence determinations and the reaction rates can be included with radiometric data for spectral adjustments. This will be especially useful for long irradiations due to the shortage of long-lived radiometric monitors.

Helium production in nickel in the mixed-spectrum reactors (e.g., OWR, ORR, HFIR) can be calculated directly from the $^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}$ and $^{59}\text{Ni}(n,\alpha)^{56}\text{Fe}$ cross sections.(9) However, neither cross section is well known except at thermal energies. Since all of the present reactors have significant epithermal fluxes, true spectral-averaged cross sections cannot be computed at present. Nevertheless, joint tests

in ORR with Rockwell International (8) show that the correct level of helium is computed using the measured thermal flux (total below 0.5 eV) and the thermal cross sections. This procedure also works for the $^{59}\text{Co}(n,\gamma)$ and $^{58}\text{Fe}(n,\gamma)$ reactions and suggests that resonance integrals are also small for the two nickel reactions. Obviously, more extensive testing is needed before helium production in nickel can be confidently predicted in all reactors of interest. Such experiments have been conducted at OWR, ORR, and HFIR and analysis is now in progress.

4. COMPARISON OF IRRADIATION FACILITIES

Figure 1 compares the DPA and He production rates for various facilities on a weekly basis. The lines for each source represent typical variations in fluence for regions of maximum flux (in core or near the source). The helium (appm)-to-DPA ratio is nearly constant for each facility and is typically 0.15 for fast reactors, 0.3 for mixed-spectrum reactors, and 10-15 for accelerators or fusion reactors. For mixed spectrum reactors, the helium generation is much higher for nickel; a level of 100 appm He can be reached with a thermal fluence of 2×10^{21} n/cm² (about four months in ORR or one week in HFIR). The fusion line on Fig. 1 starts at 1 kW/m². Only FMIT exceeds this level for most materials for both helium and DPA production, although EBR II, FFTF, and HFIR can produce fusion DPA rates and HFIR can also produce fusion helium rates in nickel-bearing

Figure 1: Comparison of weekly DPA and He production rates in Fe for most major fusion irradiation facilities. Only the highest flux regions are shown. Plant factors are not included.

materials. The fusion materials program assumes that property changes produced in all of these facilities can be correlated on the basis of DPA, gas, and transmutant production rates. It is thus vitally important that accurate damage exposure rates are measured during each materials experiment.

5. FISSION REACTOR DOSIMETRY

Dosimetry measurements have been completed for OWR, ORR, and EBR II and irradiations are in progress at HFIR. Figure 2 compares neutron energy spectra determined during recent experiments at the three above mentioned facilities. It is important to note that group-to-group covariances are typically very large. Hence, errors in integral quantities such as DPA rates are only 10-15%, even though individual flux groups may be uncertain to 15-30%. The measurements shown in Fig. 2 for OWR and ORR used 28 different activation reactions with cadmium covers and fissionable materials. Neutronics calculations were obtained for ORR (10) and EBR II (11) and the OWR spectrum was assumed to be similar to that in ORR.

Fluence gradients must also be measured along the length of the experimental assemblies in

most reactor experiments. Figure 3 shows fluence and damage maps for the ORR-MFE2 irradiation. Fe, Ni, Ti, and Co-Al wires were placed in a thin stainless steel tube and welded to the side of the experimental assembly. The $^{54}\text{Fe}(n,p)$, $^{46}\text{Ti}(n,p)$, $^{58}\text{Co}(n,\gamma)$, and $^{58}\text{Fe}(n,\gamma)$ reactions were found to agree quite closely with our previous spectral measurements, thus ensuring accurate fluence determinations. The ^{56}Ni and $^{60}\text{Ni}(n,p)$ reactions cannot be used since ^{58}Co is rapidly consumed in the high thermal flux and eventually converted to ^{60}Co .

6. ACCELERATOR NEUTRON MEASUREMENTS

Joint experiments have been conducted at RTNS II and UCD (d-Be) with M. Guinan (Lawrence Livermore Lab) and D. Kneff (Rockwell International) to characterize the neutron field and to measure a variety of radiometric and helium generation cross sections. Several hundred samples were used to map the flux distribution immediately behind the source as well as a variety of other locations throughout the target room.

At RTNS II, room-return neutrons were detected beyond 30 cm from the source and they appear to be isotropic throughout the target room. The thermal flux was determined to be 10^7 n/cm²-s, which is about equal to the 14-MeV flux at the back wall (3.8 m from the source), but a factor of 10^5 less than the 14-MeV flux near the target. Neutronics calculations are now in progress and we plan to unfold the room-return spectrum.

Integral cross section experiments (5,6) and fluence and DPA maps have been completed for the d-Be source at the University of Davis for a deuteron energy of 30 MeV. (12) Figure 4 shows fluence and DPA gradients measured close to the source. Although the neutron flux spectra, shown in Figure 5, are similar to those expected for FMIT, the FMIT source is much larger thereby moderating the extremely steep contours measured at UCD.

Spallation neutron sources such as the Intense Pulsed Neutron Source (IPNS) at ANL or the Los Alamos Meson Physics Facility (LAMPF) have also been studied for fusion experiments. (13,14) Although the damage rates obtainable at IPNS I are rather low, this facility may shortly be the only instrumented cryogenic facility operating in the U.S. The neutron energy spectrum (see Fig. 2) vaguely resembles that of a fast fission reactor, since the very-high energy neutrons are quite weak and don't contribute much to the damage produced. Spallation reactions are now being used to extend the multiple-activation technique to higher neutron energies as well as to monitor and profile the incident proton beam.

Figure 2: Neutron energy spectra measured at various irradiation facilities. Flux per unit lethargy is simply flux times energy. The IPNS spectrum extends upwards to 500 MeV.

Figure 3: Fluence and displacement rates measured during the ORR-MFE2 irradiation. Experimental assemblies were located near each cluster of data points; level 4 was on the left and level 1 on the right side.

Figure 4: Fluence contours measured at the University of California at Davis $\text{Be}(d,n)$ ($E_d = 30$ MeV) neutron source, shown per coulomb of deuteron current. Note the very fine scale and steep gradients, especially off-axis.

Figure 5: Neutron energy spectra unfolded at University of California at Davis, Be(d,n), $E_d = 30$ MeV, at various angles at 30 cm from the source.

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