Designation: E798 – 16

Standard Practice for Conducting Irradiations at Accelerator-Based Neutron Sources[1]

This standard is issued under the fixed designation E798; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers procedures for irradiations at accelerator-based neutron sources. The discussion focuses on two types of sources, namely nearly monoenergetic 14-MeV neutrons from the deuterium-tritium T(d,n) interaction, and broad spectrum neutrons from stopping deuterium beams in thick beryllium or lithium targets. However, most of the recommendations also apply to other types of accelerator-based sources, including spallation neutron sources (**1**).[2] Interest in spallation sources has increased recently due to their development of high-power, high-flux sources for neutron scattering and their proposed use for transmutation of fission reactor waste (**2**).

1.2 Many of the experiments conducted using such neutron sources are intended to provide a simulation of irradiation in another neutron spectrum, for example, that from a DT fusion reaction. The word simulation is used here in a broad sense to imply an approximation of the relevant neutron irradiation environment. The degree of conformity can range from poor to nearly exact. In general, the intent of these experiments is to establish the fundamental relationships between irradiation or material parameters and the material response. The extrapolation of data from such experiments requires that the differences in neutron spectra be considered.

1.3 The procedures to be considered include methods for characterizing the accelerator beam and target, the irradiated sample, and the neutron flux (fluence rate) and spectrum, as well as procedures for recording and reporting irradiation data.

1.4 Other experimental problems, such as temperature control, are not included.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

C859 Terminology Relating to Nuclear Materials

E170 Terminology Relating to Radiation Measurements and Dosimetry

E181 Test Methods for Detector Calibration and Analysis of Radionuclides

E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques

E263 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Iron

E264 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel

E265 Test Method for Measuring Reaction Rates and Fast-Neutron Fluences by Radioactivation of Sulfur-32

E266 Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Aluminum

E393 Test Method for Measuring Reaction Rates by Analysis of Barium-140 From Fission Dosimeters

E854 Test Method for Application and Analysis of Solid State Track Recorder (SSTR) Monitors for Reactor Surveillance, E706(IIIB)

E910 Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance, E706 (IIIC)

3. Terminology

3.1 Descriptions of relevant terms are found in Terminology C859 and Terminology E170.

4. Summary of Existing and Proposed Facilities

4.1 *T(d,n) Sources:*

[1] This practice is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applicationsand is the direct responsibility of Subcommittee E10.08 on Procedures for Neutron Radiation Damage Simulation.

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[2] The boldface numbers in parentheses refer to a list of references at the end of this practice.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

4.1.1 Neutrons are produced by the highly exoergic reaction $d + t \rightarrow n + \alpha$. The total nuclear energy released is 17.589 MeV, resulting in about a 14.8-MeV neutron and a 2.8-MeV alpha particle at low deuterium beam energies (**3**). The deuteron energy (generally 150 to 400 keV) is chosen to maximize the neutron yield (for a particular target configuration) from the resonance in the d-t cross section near 100 keV. The number of neutrons emitted as a function of angle (θ) between the neutron direction and the incident deuteron beam is very nearly isotropic in the center-of-mass system. At a deuteron energy of 400 keV in the laboratory system, the neutron flux in the forward direction is about 14 % greater than in the backward direction, while the corresponding neutron energy decreases from 15.6 to 13.8 MeV (**4**). In practice, the neutron field also depends on the gradual loss of the target material and the tritium deposition profile. Detailed calculations should then be made for a specific facility.

4.1.2 The flux seen at a point (r, θ, z) in cylindrical coordinates from a uniform T(d,n) source of diameter a is given by the following (**5**):

$$\varphi(r, \theta, z) = \frac{Y}{4\pi a^2} \ln\left\{\frac{(k^4 + 4r^2 z^2)^{1/2} + k^2}{2z^2}\right\} \quad (1)$$

where:

k^2 = $a^2 + z^2 - r^2$, and
Y = the total source strength.

For $z >> a$ and $r = 0$ (on beam axis) this reduces to $Y/4\pi z^2$, as expected for a point source. The available irradiation volume at maximum flux is usually small. For a sample placed close to the target, the flux will decrease very rapidly with increasing radial distance off the beam axis. However, since the neutron energy is nearly constant, this drop in flux is relatively easy to measure by foil activation techniques.

4.1.3 Other existing sources, such as Cockroft-Walton type accelerators, are similar in nature although the available neutron source strengths are much lower.

4.1.4 *Rotating Target Neutron Source (RTNS) I and II* (**5-7**)—RTNS I and II, which formerly were operated at the Lawrence Livermore National Laboratory, provided 14 MeV neutron source strengths of about 6×10^{12} and 4×10^{13} neutrons/s, respectively. Although these facilities have been shut down, they were the most intense sources of 14 MeV neutrons built to date for research purposes. They are discussed here because of their relevance to any future neutron sources. Their characteristics are summarized in Table 1. A discussion of similar sources can be found in Ref (**8**). The deuteron beam energy was 400 keV and the target was a copper-zirconium alloy (or copper with dispersed alumina) vapor-plated with tritium-occluded titanium. The beam spot size was about 10 mm in diameter. In addition to being rotated, the target also was rocked every few hours and the deuteron beam current was increased slowly in an attempt to maintain a constant flux in spite of tritium burn-up in the target. Samples could be placed as close as 2.5 to 4.0 mm from the region of maximum d-t interaction resulting in a typical flux of 10^{13} n/cm^2·s over a small sample. The neutron fields were well characterized by a variety of methods and the absolute fluence could be routinely determined to ±7 %. Calculated neutron flux contours for RTNS-II are shown in Fig. 1.

4.2 *Be or Li(d,n) Sources* (**9**):

4.2.1 When a high-energy (typically 30- to 40-MeV) deuteron beam is stopped in a beryllium (or lithium) target, a continuous spectrum of neutrons is produced extending from thermal energies to about 4 MeV (15 MeV for lithium) above the incident deuteron energy (see Figs. 2-4). In existing facilities, cyclotrons with deuteron beam intensities of 20 to 40 μA provide neutron source strengths in the range of 10^{13} n/s, using solid beryllium targets with water cooling. A more intense source (>10^{16} n/s) is now being designed employing liquid lithium targets. In the remainder of this document the term Be(d,n) source is meant as a generic term including Li(d,n) sources, whether solid or liquid targets.

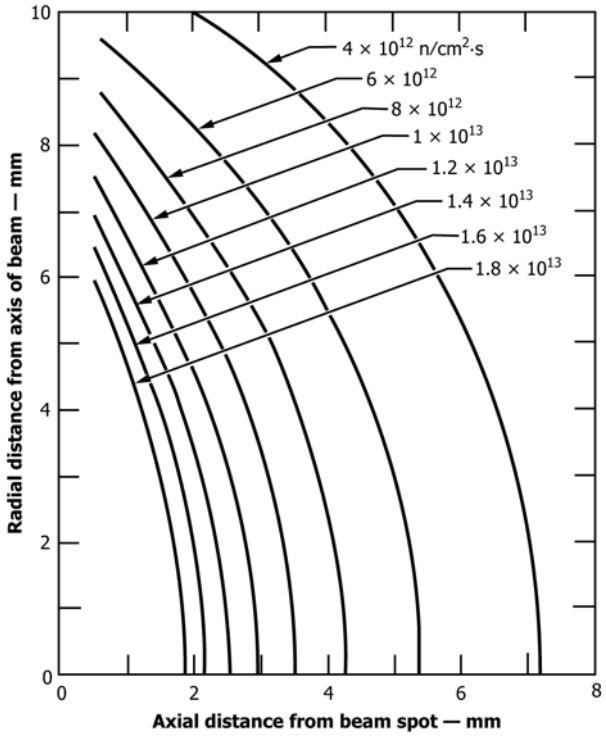
4.2.2 Neutrons are produced by several competing nuclear reaction mechanisms. The most important one for radiation damage studies is the direct, stripping reaction since it produces almost all of the high-energy neutrons. When the incident deuteron passes close to a target nucleus, the proton is captured and the neutron tends to continue on in a forward direction. The high energy neutrons are thus preferentially emitted in the direction of the incident deuteron beam. However, as the deuterons slow down in the target, lower energy neutrons will be produced with angular distributions that are much less forward peaked. Furthermore, when the residual nucleus is left in an excited state, the angular effects are also much less pronounced. These latter two effects tend to decrease the average neutron energy at angles other than 0° in the direction of the beam.

4.2.3 Neutrons can also be produced by compound nuclear reactions in which the entire deuteron is captured by the target nucleus and neutrons are subsequently evaporated. Neutrons are preferentially emitted with energies less than a few MeV

TABLE 1 Characteristics of T(d,n) and Be or Li(d,n) Neutron Sources

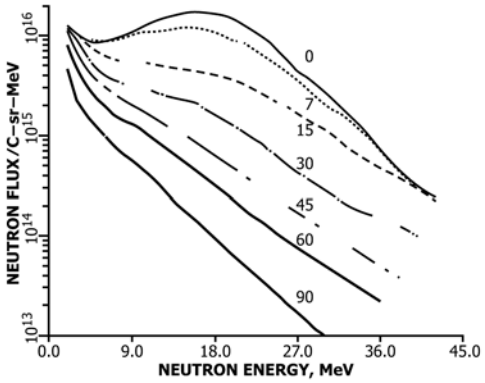
Facility	Availability	Beam	Target	Source Strength, n/s	Maximum Flux at Sample, n/cm^2·s	Experimental Volume for Maximum Flux, cm^3
RTNS I	No longer available	400 keV d	t	6×10^{12}	>10^{12}	0.2
RTNS II	No longer available	400 keV d	t	4×10^{13}	>10^{13}	0.2
					>10^{12}	5.0
Existing Be or Li(d,n)	U.C. Davis Cyclotron[A]	30–40 MeV d	Solid Be or Li	~10^{13}	>10^{12}	~1.0
Proposed Li(d,n)	Conceptual design (**9**)	30–40 MeV d	Liquid Li	3×10^{16}	>10^{15}	10.0
					>10^{14}	600.0

[A] This is the only existing facility that has been well characterized and is readily available, although other facilities can be used.



NOTE 1—Flux contours assume a symmetric, Gaussian beam profile. Figure from Ref. (**5**).

FIG. 1 Flux Contours for RTNS II



NOTE 1—Neutron spectra as a function of energy and angle for ^{9}Be(d,n) source at ORNL, E_d = 40 MeV. (Data from Ref (**8**).)

FIG. 2 Neutron Spectra as a Function of Energy and Angle from the Forward Direction of the Deuteron Beam

and the angular distribution approaches isotropy at neutron energies below 1 MeV. Neutrons also are produced by deuteron break-up, in which the deuteron simply breaks apart in the Coulomb field of the nucleus, although this effect is very small for low-Z materials.

4.2.4 The neutron spectrum thus depends very strongly on the angle from the incident deuteron direction, and the flux is very sharply peaked in the forward direction (see Fig. 2). Materials studies for which the maximum total neutron fluence is desired are usually conducted close to the target and may subtend a large range of forward angles (for example, 0 to 60°). This practice primarily will be concerned with this close-geometry situation since it is the most difficult to handle properly.

4.2.5 Other factors can also influence the neutron field during a particular irradiation, especially beam and target characteristics, as well as the perturbing influence of surrounding materials. At present, these facilities have not been completely characterized for routine use. In particular, some uncertainties exist, especially at low (<2 MeV) and high (<30 MeV) neutron energies, since these regions are either difficult to measure with existing techniques, or the required nuclear data are insufficient. In these cases, neutron dosimetry data should be reported directly to allow reanalysis as procedures and nuclear data improve in the future.

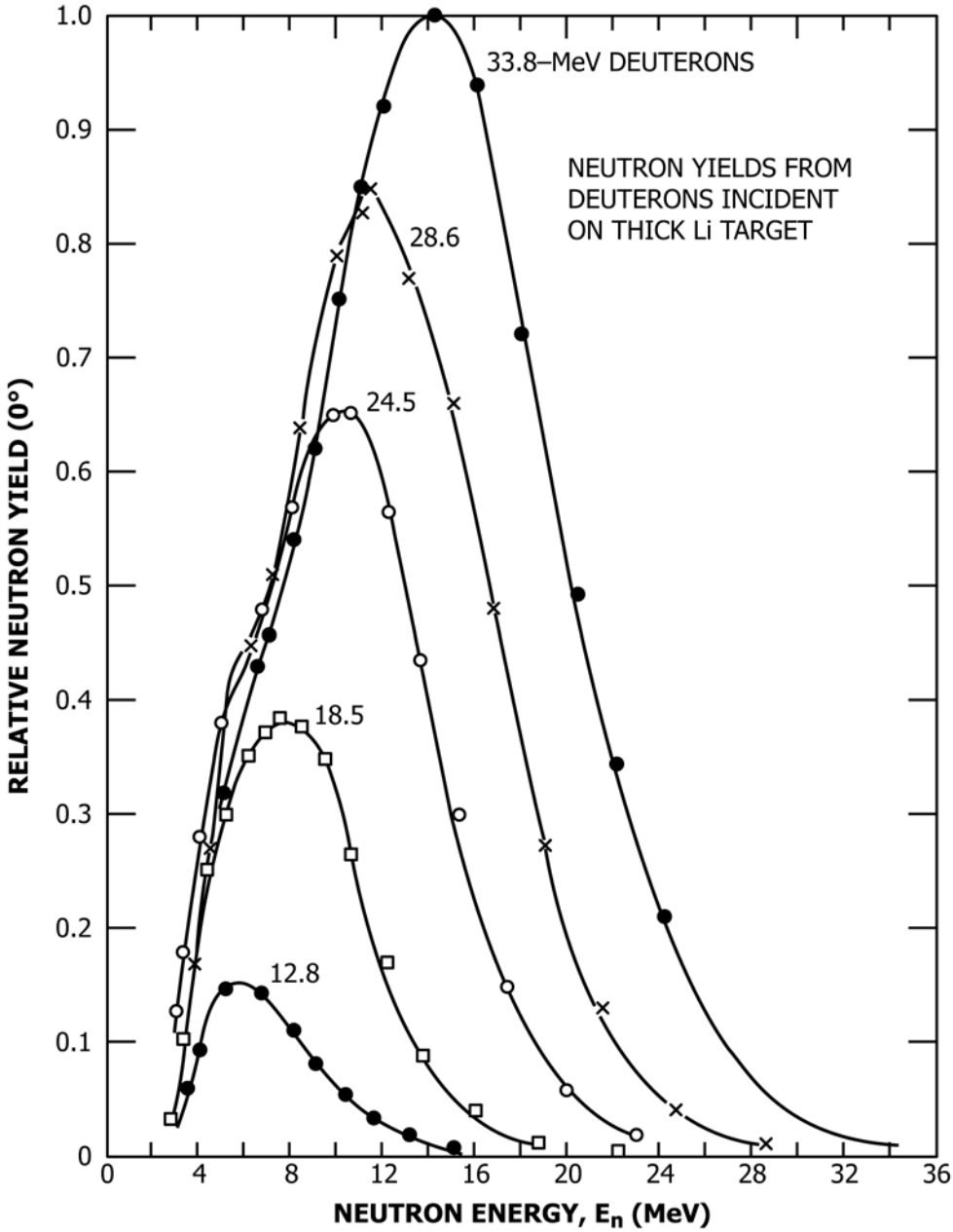
4.2.6 *Existing Sources:*

4.2.6.1 Whereas virtually any deuteron accelerator with reasonable energy and intensity can be used as a neutron source, only two facilities have been used routinely for materials effects irradiations, namely the cyclotrons at the University of California at Davis (**10**) and at Oak Ridge National Laboratory (**11, 12**). Typical flux-spectra obtained are shown in Figs. 2-4 (**9, 11, 13**), and typical characteristics are listed in Table 1.

4.2.6.2 Since the neutron flux and spectral gradients are so steep, experimenters are faced with the problem of nonuniform irradiations over their samples unless specimen sizes are severely limited. Alternatively, the field gradients may be moderated by deliberately moving or enlarging the beam spot on the target. This technique will result in a lower total fluence as well as a lower average neutron energy for a small-size sample on the beam axis, although larger samples will not be so severely affected and may in fact show an overall improvement in average fluence and neutron energy.

4.2.6.3 At present, the neutron field can be determined reasonably well at existing facilities. The flux-spectrum can be measured to within ±10 to 30 % in the 2- to 30-MeV energy region where about 90 % of neutron damage is initiated (assuming E_d = 30 to 40 MeV). Highly accurate (±10 %) time-of-flight spectrometry has been used to study the field far from the source, except for the energy region below a few MeV (**11**). However, close geometry irradiations must rely on passive dosimetry with larger errors due to uncertainties in the nuclear cross sections, especially above 30 MeV (**12**).

4.2.7 *Conceptual Design for Li(d,n) Source* (**9, 14**)—A conceptual design for a fusion materials irradiation facility was done at the Hanford Engineering Development Laboratory (HEDL). The design consisted of a high-current (100-mA) deuteron accelerator and a liquid lithium target. This was expected to produce a neutron source strength of about 3×10^{16} n/s (**14**). The designs called for a wide-area beam spot on the target (for example, 3 by 1 cm), thereby moderating the steep neutron field gradients in close geometry. Neutron fluxes up to 10^{15}n/cm^2·s could be produced over a volume of several cubic centimetres, allowing much larger samples than with present sources. This facility would thus have a higher flux of high-energy neutrons over a larger volume than any available accelerator source. A subsequent design that took advantage of improvements in accelerator technology is discussed in Ref



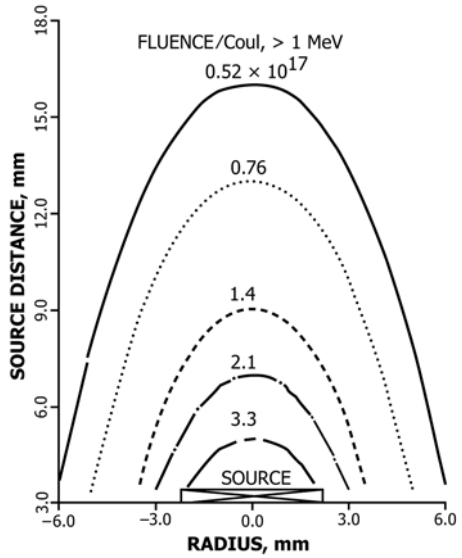
NOTE 1—The maximum occurs at about 40% of the deuteron energy. (Data from Ref (**6**).)

FIG. 3 Li(d,n) Spectra at 0° as a Function of Deuteron Energy

(**15**). More recently, similar technology has been assessed in the design and fabrication of prototypic components for an International Fusion Materials Irradiation Facility (**16**).

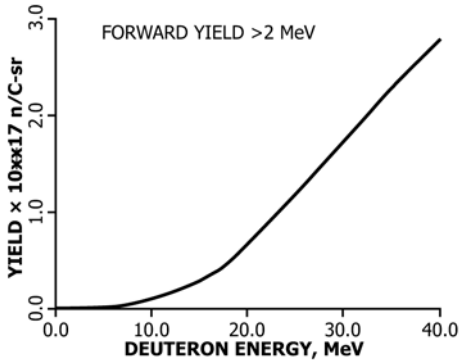
4.3 *Other Sources:*

4.3.1 There have been other accelerator-based neutron sources available, generally having lower neutron energy and flux. Most are used for medical or nuclear research applications. Van de Graaffs and cyclotrons have also been used with other nuclear reactions such as $d(d,n)^3He$ and $^7Li(n,p)^7Be$. Facilities with much higher charged particles such as the Intense Pulsed Neutron Source (IPNS) (**17**) and the Los Alamos Meson Physics Facility (LAMPF) (**18, 19**) have also been used. For example, the IPNS neutron flux spectrum is shown in Fig. 5 (**17**). A new irradiation facility was brought on-line at the LAMPF in the 1980s (**19**). The primary objective of this facility is to study the basic aspects of radiation effects as produced by medium energy protons and neutrons that are born through spallation reactions as the protons interact with the target nuclei. Another objective is to study radiation damage to structural and detector materials used with accelerators. A description of the facility is given in Ref (**20**). The available neutron flux and spectrum are described by the results of calculations (**21**) and foil activation measurements (**22**). Radiation damage parameters for the facility have also been calculated (**23**). In the case of facilities such as LAMPF and IPNS, the dosimetry and damage analysis must take into



Note—Neutron fluence contours measured at the University of California with Davis Cyclotron Be(d,n), E_d = 30 MeV. (Data from Ref (10).)

FIG. 4a Neutron Fluence Contours



NOTE 1—Forward (0°), thick target neutron yield above 2 MeV from the ^{9}Be(d,n) reaction as a function of deuteron energy.

FIG. 4 b Forward (0°), Thick Target Neutron Yield

account the presence of very high-energy neutrons (>40 MeV), as well as a small flux of charged particles. The LAMPF is now known as the Los Alamos Neutron Science Center (LANSCE).[4]

4.3.2 Modern spallation neutron sources have also been used for irradiation experiments. For example, the Swiss Spallation Neutron Source, SINQ[5], has a unique SINQ Target Irradiation Program (STIP). The STIP has been used in a series of materials irradiation experiments to investigate the effect high damage rates with high helium and hydrogen generation rates (**24**).

4.3.3 The procedures recommended in this work also apply to these other sources and should be used where applicable. However, the experimenter should always be aware of the possibility of additional problems due to peculiarities of individual sources.

5. Characterization of Irradiation Environments

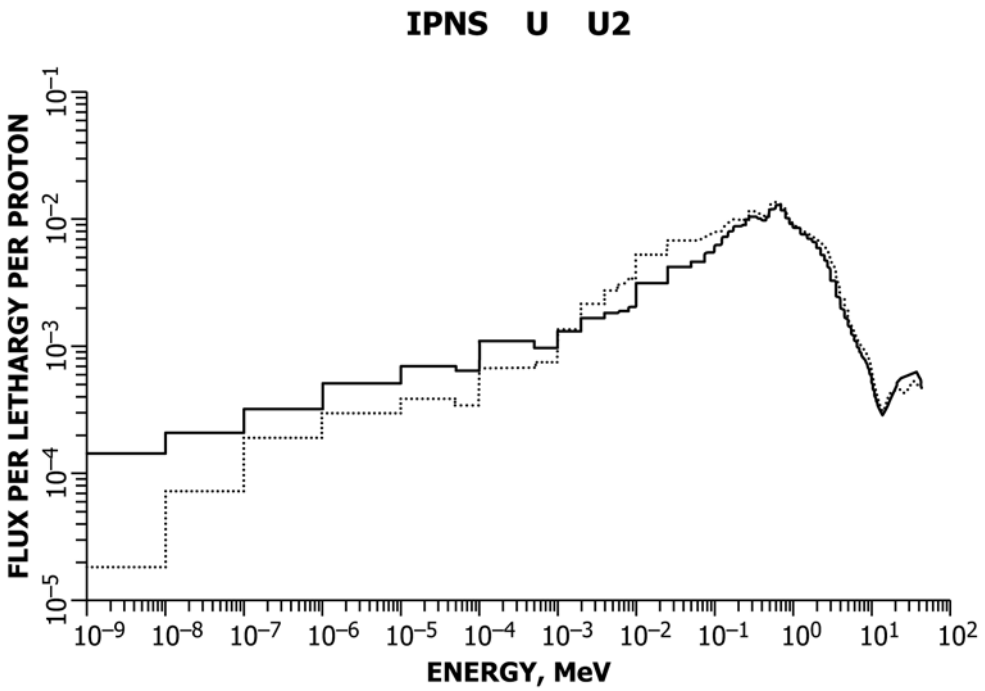
5.1 *Scope*—The methods used to define the flux, fluence, and spectra precisely in accelerator environments are significantly different from those used in reactor environments. The reason for this difference is that, whereas reactors generally produce stable fields with gentle gradients, accelerators tend to produce fields with very sharp spatial flux and spectral gradients, which may vary over short time intervals and may not scale linearly with beam current. For example, small changes in accelerator tuning can move the spatial location of the neutron source relative to the irradiated sample, thereby changing the flux and spectrum. Consequently, it is critically important to follow well established and well calibrated procedures in order to measure adequately the irradiation exposure parameters. Otherwise, it will be impossible to correctly calculate damage parameters such as DPA or to correlate materials effects measured at different facilities.

5.2 *System Parameters*—In the following section, it is important to distinguish between T(d,n) (14-MeV) sources and broad spectrum ^{9}Be(d,n) sources. Whereas both types of sources exhibit strong flux gradients, only the broad-spectrum sources exhibit significant spectral gradients. Consequently, in the following subsections it should be understood that references to flux measurement refer to both facilities, whereas references to spectral measurement refer only to the ^{9}Be(d,n) sources.

5.2.1 *Beam Characterization*—It is important to realize that virtually any change in the accelerator beam will produce some alteration of the neutron field. Two classes of instabilities can be defined according to whether they affect only the neutron flux or the neutron spectrum as well. Whereas the flux may vary independently of the spectrum, spectral changes always imply a change in flux. Flux changes are usually easy to measure and to account for in calculating total exposure or damage rates (see 5.3). However, spectral changes are much harder to measure or to account for in subsequent calculations. For example, if the spectrum changes significantly even once during a long run, then activated foils with short half-lives may indicate an average spectrum that is quite different from that indicated by foils with long half-lives. Furthermore, it may be impossible to account for this difference unless great care is exercised to record the pertinent beam information, namely beam current, beam energy, and spatial alignment.

5.2.1.1 *Flux Instabilities*—The most important sources of flux instability are the beam current and target condition. If the beam is well collimated, stable in energy, and stable in spatial position, then the flux should be directly proportional to the beam current, neglecting target effects. At solid Be(d,n) sources, target effects are usually unimportant. However, at T(d,n) sources, time-dependent changes in the target are the dominant cause of flux instabilities (**6**). The beam current should be read using a Faraday cup or well-insulated target assembly where possible. The current-sensing equipment

[4] See http://lansce.lanl.gov/.
[5] See http://www.psi.ch/sinq/.



NOTE 1—Neutron flux spectrum at the Intense Pulsed Neutron Source of ANL with 500 MeV protons and a depleted uranium target. The solid line is calculated and the dashed is an adjusted spectrum based on radiometric dosimetry. (Data from Ref (**12**).)

FIG. 5 Neutron Flux Spectrum at the Intense Pulsed Neutron Source

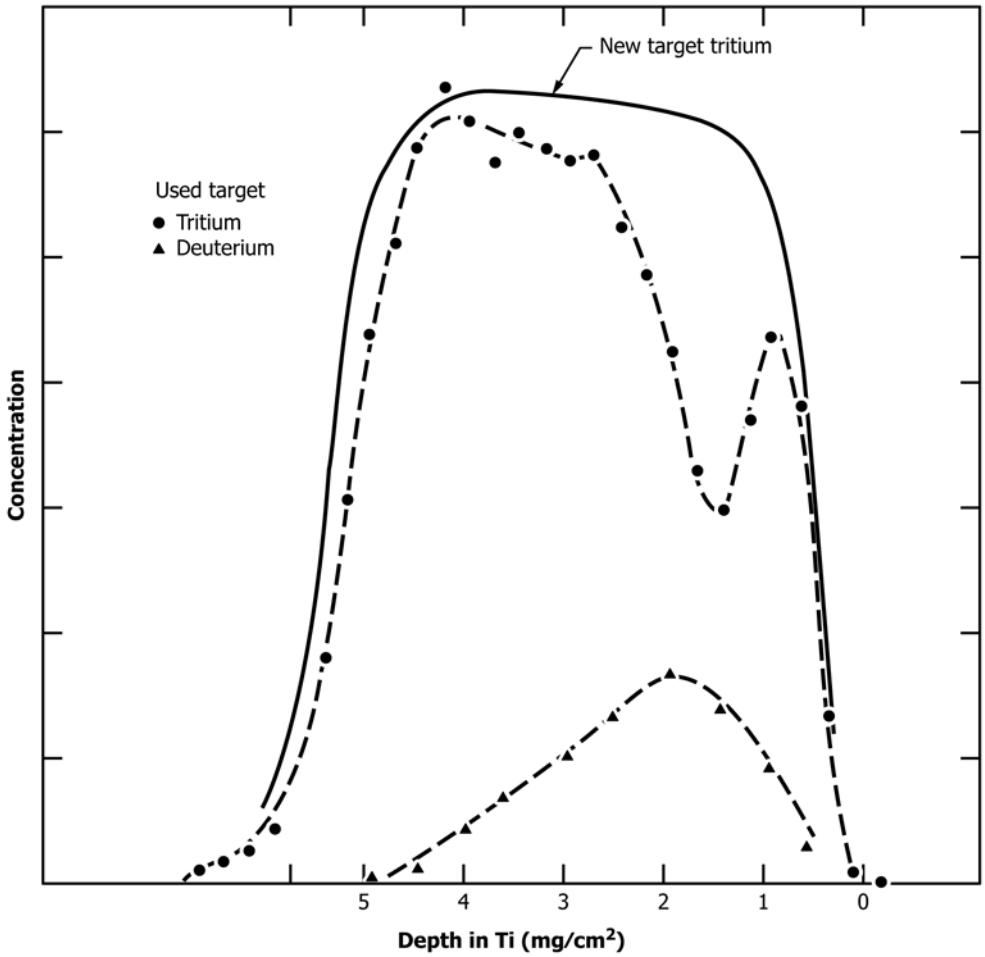
should be checked for beam leakage, linearity, and long-term stability. The output should then be recorded at regular time intervals.

5.2.1.2 *Flux and Spectral Instabilities*—A change in the beam energy will alter both the flux and spectrum, although most accelerators have active means of keeping the beam energy constant within relatively small preset limits. It is worth mentioning that beam stability is often linked to beam current since beam control systems may use slits or apertures which in turn limit the transmission through the machine. Hence, attempts to maximize the beam current may allow a wider range of particle trajectories, resulting in a larger energy spread as well as poorer spatial definition. The experimenter should be aware of these problems and check that the energy stability, beam current monitoring, and target integrity are adequate. The most important source of spectral instability at broad-spectrum sources is the movement of the beam on the target (at T(d,n) sources this will only significantly affect the flux). Collimation aperatures are generally used to define the beam size and location. It is again important to note that attempts to maximize the beam current and hence the flux may result in unacceptably large variations in beam spot size and location on the target. The collimation system should thus be analyzed to predict the maximum possible variations. This can be translated into flux/spectral information by examining measured angular distribution data. For example, at a deuteron beam energy of 30 MeV on a Be target, the total flux falls a factor of two as the angle from the beam axis changes from 0° to only 10° (**25**). At a close irradiation distance of about 0.5 cm, this would correspond to a change in the beam spot location of only 1 mm. Beam spatial alignment and stability are thus crucial to the characterization of an irradiation. Active and passive methods of measuring flux and spectral instabilities are covered in 5.3.2 and 5.3.3.

5.2.2 *Target Characterization:*

5.2.2.1 Physical characteristics of the target assembly are also vitally important in determining the neutron field. The design of the target will strongly influence the field produced and instabilities in the target can lead to large variations in the flux and spectra. In order to understand these effects, it is important to understand neutron production in the target. Well designed targets are thick enough to stop the deuteron beam. This can be checked with any standard range-energy table such as Refs (**26, 27**). However, improper target design may cause the target to burn up during exposure, leading to drastic alterations of the neutron field. Such catastrophic failures are easily seen by remote sensing systems (see 5.2.6.2).

5.2.2.2 As the deuteron beam is stopped in the target, it interacts with the tritium or beryllium, as discussed previously. For T(d,n) sources the primary cause of concern is the burn-out and boil-off of tritium and slow build-up of deuterium (see Fig. 6). The former causes a reduction in flux but no significant difference in the geometric source specification. The latter can lead to neutron production from the $d(d,n)^3He$ reaction, although this contribution is generally negligible since massive exposures are required to build up significant deuterium in the target and the neutron production cross section is much smaller than from tritium. At the RTNS, these effects were well understood. Remote neutron detectors were used to continuously monitor the target condition and the target was then slowly rocked in position in an attempt to maintain a nearly



NOTE 1—Depth profiles of tritium in new (solid line) and used (dashed line) targets. Deuterium accumulated in the target is also shown. (Data from Ref (4).)

FIG. 6 Depth Profiles of Tritium in New and Used Targets at the RTNS I

constant neutron flux. The experimenter could thus obtain an accurate time history of the neutron exposure.

5.2.2.3 More complex target problems are encountered at Be(d,n) facilities. The amount of material that backs the active Be region as well as the surrounding support material will attenuate or scatter the neutrons, probably accounting for some differences in the low-energy neutron flux reported at different facilities. On the other hand, backing material cannot be too thin or high energy protons from (d,p) reactions may escape from the target and irradiate the specimen. The lifetime of a beryllium target is not well established, although experience at U. C. Davis indicates that they should be able to withstand deuteron exposures of at least 200 C/cm^2. However, if target cooling is inadequate, the beryllium may evaporate or melt within a matter of minutes. Such failures are readily apparent by sudden changes in the neutron flux. A more serious concern is the slow erosion of the beryllium since this leads to a gradual change in the location of the source in the beryllium and may produce perturbations in the flux and spectrum at close geometries. Passive in situ dosimetry should be able to integrate over such changes, although shorter-lived dosimetry materials may have to be replaced during very long irradiations.

5.2.3 *Sample Positioning:*

5.2.3.1 A major problem in determining the flux and spectrum seen by an irradiated sample is that it is often difficult to determine in advance the precise location of the sample relative to the source. For this reason, passive in situ dosimeters should be included with all close-geometry irradiations. For example, changes in position of less than 1 mm can easily change the flux at existing Be(d,n) sources by as much as a factor of two when samples are placed within 0.5 cm of the target. Careful measurements of sample and dosimeter locations should thus be made to ensure adequate information for complete dosimetric analysis.

5.2.3.2 Techniques such as autoradiographs are very useful in determining the position of the sample relative to the beam and, if done prior to irradiation, can ensure maximum fluence in the samples (see 5.2.6.1).

5.2.4 *Other Perturbation Effects:*

5.2.4.1 Experimental equipment and sample materials may themselves perturb the neutron field through attenuation and scattering effects. A particularly important example has been found with organic materials, which can greatly increase the thermal or epithermal flux. In close geometries, attenuation effects have been found to be the most important since

scattered fluxes (for example, room return) are generally very small compared to the primary flux. As an example, metallic dosimetry packages measuring 7 mm in total thickness were found to produce total attenuations of about 15 % in Be(d,n) fields (**28**). Multiple-specimen irradiations thus require passive dosimeters at many locations, preferably with each group of specimens, in order to map these small perturbation effects.

5.2.4.2 It has also been suggested that materials may be deliberately placed near the target to tailor the spectrum. For example, a uranium shell may be used near a T(d,n) source to simulate more closely a first wall fusion reactor spectrum. Such facilities should be well documented and may require special procedures.

5.2.4.3 At existing Be(d,n) facilities there are occasional changes in the source configuration since the facilities are not dedicated solely to materials irradiations. For example, different beam lines may be used and massive, extraneous equipment and shielding may be repositioned. Such changes may produce changes in the neutron field, especially at low energies. Therefore experimenters cannot assume that the neutron flux-spectrum will necessarily be identical to previous measurements at that facility.

5.2.5 *Beam Rastering Techniques*—The sharp flux and spectral gradients produced at Be(d,n) sources can be moderated somewhat by deliberately moving the beam on the target in a prescribed raster pattern, although this may lower the total fluence in small irradiated samples. The problems of beam and target instabilities are still present and may be further complicated by this approach if the raster pattern varies in spatial position. The periodic time dependence (for example, 10 Hz) of the neutron flux also may produce changes in the damage production, especially at elevated temperatures. Passive in situ dosimetry is thus required in order to determine the average flux and spectrum seen by a sample, and the precise rastering technique should be reported along with the dosimetry results.

5.2.6 *Measurement of System Instabilities*—Many of the possible instabilities noted above are routinely measured at most accelerator facilities, especially beam current and energy. However, the experimenter usually is responsible for positional effects and the following methods are recommended:

5.2.6.1 *Autoradiographs*—A very simple means of determining the beam spot size and location on the target (to within <1 mm) is to take an autoradiograph. This is done by attaching a sheet of Polaroid film to the target assembly following a brief irradiation. Alternatively, a thin sheet of metal may be attached to the target, irradiated, and then autoradiographed. The induced activity in the target usually will be quite high (>1 R) so that exposures of a minute or less will give a clear image of the center of the activated target assembly material. This should be done after the machine has been tuned and before the specimens are mounted in order to ensure the best alignment of the specimens. This will not only simplify the irradiation characterization but will also maximize the fluence seen by the sample. Autoradiographs also should be taken after the irradiation of both the target assembly and the specimen and dosimetry packages. Due to the very high residual activity, some delay may be required before such exposures are possible. This delay is desirable in any case, since this allows short-lived activities to die out, leaving the longer-lived activities, which are representative of the entire irradiation rather than just the last few minutes or hours.

5.2.6.2 *Active Methods of System Measurement*—In addition to monitoring beam current and energy, it is also recommended that some active method be used to measure the neutron flux. A remote detector will not be sensitive to small position changes but will detect any significant changes in beam intensity or energy as well as target degradation effects (see 5.3.2). Many accelerators also have other active beam sensing devices, such as *x-y* scanners, which can be used to monitor the spatial position of the beam. It is also often possible to position small detectors or fission chambers at back angles in close proximity to the target in order to monitor small changes in beam location. All such devices should be used where practical to provide the best record possible concerning the time history of the actual neutron field.

5.2.6.3 *Passive Methods of System Measurement*—The most accurate method of determining the irradiation received by a sample is through the use of passive in situ monitors such as multiple-foil activations, helium accumulation fluence monitors (HAFM) (**29**), or solid-state track recorders (SSTR) (**30**). The latter two stable product monitors will not be discussed in detail in this practice since they involve specialized techniques and they are described in Test Method E854 and Specification E910. However, the basic procedures involved in using these devices during an irradiation are the same as for the foil activation technique, as discussed in 5.3.3.

5.3 *Neutron Field Characterization:*

5.3.1 *Calculational Methods*—It is generally not feasible to calculate from first principles the neutron flux and spectrum as a function of position at accelerator-based sources since the required input data are usually not available. However, models can be quite useful in planning irradiations, in design studies, and for assessing variations in the field due to beam, target, or sample effects. Furthermore, models may be constructed so that parameters can be fit by experimental data, thus allowing positional interpolation or extrapolation into regions not covered by active or passive dosimetry. An example of this for the RTNS I is given in Ref (**29**). In order to describe the neutron field adequately, several important characteristics of accelerator-based sources must be considered, as follows:

5.3.1.1 *Source Term*—As discussed previously, the neutron source is very complicated since neutrons are produced continuously as deuterons are stopped in the target material. This is not serious at T(d,n) sources since the deuteron energy is low (for example, 400 keV) and the neutron energy changes only slightly over the deuteron range (**5**, **6**). However, the d-t neutron flux cannot be directly calculated from the beam current due to time-dependent changes in the target composition and homogeneity. The Be(d,n) source term is at present not known in detail. The beam-target interaction volume is a cylinder whose cross section depends on the beam profile, which may not be regular, may change with time, and may not be known. Each slice through this cylinder perpendicular to the beam axis will produce neutrons according to the deuteron energy distribution at that slice. The neutron spectrum from each slice will consist of several components, including: (*a*)

distinct peaks at high neutron energy due to ^{9}Be(d,n) reactions to specific energy levels in ^{10}B; (*b*) unresolved peaks at moderate neutron energy; and (*c*) a continuum due to high-energy direct excitations in ^{10}B as well as compound nuclear reactions. The strength of all three components varies with deuteron energy and angle from the beam axis, and these variations (excitation functions and angular distributions) have not been adequately measured. In order to calculate the flux and spectrum at a given sample location, one must integrate the contributions due to each slice in the beam-target interaction volume. Close to the target distance effects will dominate, since they depend on the distance squared and angle between two points in the sample and source. For example, low-energy neutrons will be favored since they originate mainly in the rear of the target which is closer to the sample. Careful experimental measurements of thin target (for example, a few MeV) yields must be made before accurate source calculations can be performed. If all of the above effects are known and contributions to the neutron field from each slice through the target can be calculated, attenuation and scattering effects due to the remaining target or nearby materials must also be included. For example, the highest neutrons produced at the front of the target suffer the most degradation since they must traverse the entire target and backing. Hence, transport calculations must be done for each slice in order to determine the total neutrons actually emitted from the target assembly. Scattering and absorption by the air or other objects also must be considered, as discussed later. Obviously, calculations of the source term from first principles may not be feasible since the required data concerning the beam profile in space and time, target inhomogeneities, beam-target atomic interactions, and nuclear cross sections and angular distributions are not known in sufficient detail. Nevertheless, calculations have been made with simplifying assumptions resulting in very useful models of the neutron field (**31**). Furthermore, calculations may be normalized to thick target yield data and details of the model may be fit to specific passive dosimetry data. In this way, more accurate calculations can be generated for a specific source, greatly improving routine dosimetry capabilities.

5.3.1.2 *Perturbation Effects*—Given the source term we still may not know the actual flux and spectrum at a sample due to the effects of materials placed close to the source, including the sample itself. Consequently, transport calculations also may be required to assess these added scattering and absorption effects. With thin samples, absorption effects usually dominate for fast neutrons, although organic materials can greatly increase the thermal portion of the spectrum.

5.3.1.3 *Time-Dependent Effects*—Changes in the beam and target characteristics will alter the source term and must be considered. Target effects are especially hard to measure and are especially serious at T(d,n) sources where the tritium depth profile changes rapidly (**6**). Beryllium targets are far more stable, although changes are hard to assess due to the complexity of the source term (see 5.2.2).

5.3.2 *Active Methods:*

5.3.2.1 The neutron field can be studied with a variety of active detectors including time-of-flight spectrometers, recoil detectors, and fission chambers. Whereas detailed consideration of these techniques is outside the scope of this practice, several important points should be mentioned for the present application.

5.3.2.2 Due to high neutron fluxes, timing, and background problems, most active detectors cannot be operated close to the source. Unfortunately, this is the region of most interest. Measurements made several metres away from the source can be extremely valuable in monitoring source stability, defining the source term, estimating the close geometry flux and spectrum, and as input to foil activation unfolding procedures. However, such long-distance measurements cannot be used to determine the neutron field in close proximity to the source since all of the finite size effects discussed in the previous section will not be seen beyond a few tens of centimetres from the source. Furthermore, scattering effects such as room return are large at long distances but are usually negligible close to the target.

5.3.2.3 Active measurements should be made prior to irradiations, especially at new facilities, to help characterize the source, and during irradiations to monitor source stability and provide a time history for foil activation data. Spectral measurements should be made over as large a range of angles as possible since close-in samples will usually subtend a very large angular range. Estimates of the close-in spectrum can then be made by integrating over the actual range of angles subtended.

5.3.2.4 Active detectors should be placed as close to the source as practicable and should monitor the source from various directions in order to monitor the source stability. Simple geometric calculations or experimental measurements can be made to determine the sensitivity to small movements of the beam.

5.3.2.5 Irradiations require an accurate time history of the neutron flux seen by the samples. Such information is crucial to foil activation dosimetry, as discussed in 5.3.3.2. Depending on the facility, the time history may be determined from either active neutron detectors or beam monitoring devices. At T(d,n) sources, the beam current will not be correlated with the neutron flux since tritium is slowly depleted in the target. However, active neutron detectors are not sensitive to small changes in the beam position and may not have an unperturbed view of the source. Consequently, both active neutron detectors and beam monitors may be required to obtain a reliable irradiation history.

5.3.3 *Passive Methods:*

5.3.3.1 The most practical and reliable means of measuring the neutron field close to the source is with passive dosimeters. This includes multiple-foil dosimetry as discussed in Practice E261, solid state track recorders (SSTR) (**30**), helium accumulation fluence monitors (HAFM) (**29**), and emulsions. Details of these methods are outside the scope of this practice. However, there are many important considerations peculiar to accelerator-based sources which are discussed below. Multiple-foil dosimetry is stressed since it provides the most information about the neutron flux and spectrum. Furthermore, data from other devices such as HAFMs can be used interchangeably with foil activation if helium generation cross sections are

known. The term multiple-foil dosimetry is consequently used generically to include stable product monitors.

5.3.3.2 Multiple-foil dosimetry is accomplished by irradiating materials and then measuring the radioactive or stable products. The activation integrals A_i are then related to the neutron field as follows:

$$A_i = Mu \int_0^\infty \int_0^t \sigma_i(E)\varphi(E, t)\, dE dt \quad (2)$$

where:

$\sigma_i(E)$ = the cross section for making product i at energy E, and
φ = the neutron flux at energy E and time t.

If the cross sections are well known, then the flux-spectrum may be unfolded by simultaneously satisfying a series of integrals using computer codes such as SAND II (**32**), STAYSL (**33**), or FERRET (**34**). The latter two codes are preferred since they include covariance information.

5.3.3.3 At T(d,n) sources one foil material may be sufficient since the flux is known to be concentrated in a narrow range of energies near 14.8 MeV. For example, the ^{93}Nb(n,2n)^{92m} Nb reaction has been routinely used at RTNS I (**35**).

5.3.3.4 At Be(d,n) sources, many foils must be used due to the complexity of the neutron field. Unfortunately, many of the required activation cross sections are not well known above 14 MeV. Several important cross sections have been measured up to 28 MeV (**36**). A list of reactions commonly used is given in Ref (**37**). Although many of these reactions are not well known at higher energies, integral tests (**38**) are now being made in Be(d,n) fields, which should lead to a set of recommended reaction cross sections.

5.3.3.5 The recommended procedures given in 5.3.3.6 and 5.3.3.7 are intended to cover special problems encountered at accelerator-based neutron sources. Practice E261 and Test Methods E263, E264, E265, E266, and E393 should be referred to concerning counting techniques for specific activation products and selection of foil materials.

5.3.3.6 *Geometric Considerations*—The placement of multiple-foil materials in Be(d,n) accelerator fields is crucially important due to the steep flux and spectral gradients. Ideally a large number of passive dosimeters should be irradiated to obtain maximum information. However, it is not possible to put more than a few thin foils in the same geometry without requiring significant geometric corrections. Furthermore, such corrections are difficult to calculate unless the materials are sufficiently far from the source that (*a*) all materials subtend the same angular range and (*b*) the flux and spectral gradients are well known (for example, $1/R^2$). There are several ways to experimentally reduce the errors in geometric placement of dosimetry materials. The amount of material used should be minimized so that absorption and scattering corrections will be reduced. Scoping calculations can be performed easily with computer codes, such as SAND II (**32**), that calculate spectral-averaged cross sections. These values can then be used to estimate the activity in a foil at counting time. Multiple material sets should have similar if not identical shapes. Radiometric foils are thus preferred to wires since they can be cut identically and stacked into a thin package. Wires placed side by side, on the other hand, may see very different fluxes and spectra. In any case, gradients must be taken into consideration or correct analysis of the results may be difficult. Geometric corrections will always be required for a multiple-foil set since no two foils have exactly the same location. In planning an experiment, the size of these effects may be estimated by assuming a $1/R^2$ dependence. However, this dependence is not correct in close geometry and neglects spectral scattering and absorption effects. Consequently, at least one foil should be duplicated at the front and rear of a foil stack to actually measure the total correction required. For thick foil stacks, one material should be repeated at several locations. A foil such as gold is a good choice since several activation products may be analyzed. Since these reactions have different neutron spectral sensitivities, this procedure also indicates whether or not the total corrections are dependent on the neutron energy.

5.3.3.7 *Time History Corrections*—Since the flux and spectrum may change with time, corrections are required to determine the saturated activity level in a foil. The activity $A_i(t)$ at time t for reaction i is given as follows (**32**):

$$A_i(t) = m_i e^{-\lambda_i t} \int_0^\infty \int_0^t \sigma_i(E)\varphi(E, u) e^{\lambda_i u} dE du \quad (3)$$

where:

m_i = number of atoms for reaction i,
σ_i = cross section, and
φ = neutron flux.

If the flux and spectrum are constant in time, then this reduces to the following:

$$A_i(t) = m_i \bar{\sigma}_i \varphi (1 - e^{-\lambda_i t}) \quad (4)$$

where $\bar{\sigma}$ is the spectral averaged cross section and the term in parentheses corrects for decay during irradiation. In case the flux changes with time, as indicated by a beam current monitor or active neutron detector, then the term in parentheses must be replaced by the following equation:

$$\bar{\varphi} = \sum_{j=1}^{N} \varphi_j (1 - e^{-\lambda_i t_j}) e^{-\lambda_i t_j} \quad (5)$$

where the flux has been subdivided into N time intervals t_j of nearly constant flux φ_j and t_j is the time remaining to end of irradiation $(t - t_j)$. In this case the $\bar{\sigma}$ in Eq 5 is the average flux for the run given by:

$$\bar{\varphi} = \sum_{j=1}^{N} \varphi_j t_j / t \quad (6)$$

If the spectrum also changes with time, then corrections can be made in principle by substituting the spectrum averaged cross-section $\bar{\sigma}_j$ for each time interval t_j into Eq 4 and dividing by the averaged cross section $\bar{\sigma}_j$. However, the $\bar{\sigma}_j$'s may be unknown since they may be due to unmeasured shifts of the beam on the target, for example. This can be a serious problem unless adequate beam monitoring is provided. At existing sources a precise beam alignment is maintained to minimize such problems. As an example, consider two reactions, one having a very long decay constant compared to the total irradiation time t, the other having a very short decay constant. If the beam spot changes slightly during the run, then the spectrum is changed since the foils now subtend a different

angular range. The long-lived activity will show a proper average of the two activities. However, the short-lived activity will only indicate the later flux and spectrum and will thus be inconsistent with other foils. Hence the need for proper monitoring of the irradiation is extremely important. Of course, the use of longer-lived or stable product monitors reduces or eliminates the need and importance of time-dependent corrections for fluence measurements.

5.3.3.8 *Positional Dosimetry and Utilization of Results*—Assume that a flux and spectrum have been properly deduced for a well-defined location relative to the neutron source. It still remains to relate these data to irradiated samples that may be at another location. Of course, the preferred procedure is to place the dosimetry foils in almost the same location with the same shape as the samples so that only minor corrections may be needed. If this is not possible, then at least one dosimeter, preferably with multiple reactions, should be placed as close as possible to the sample location in order to check on the extrapolation or interpolations required. The available data may also be fit to an analytical model to improve the reliability of the results. Nevertheless, care should be taken to consider possible perturbing effects in order to obtain correct results.

5.3.4 *Error Analysis:*

5.3.4.1 The complete error analysis for foil activation dosimetry during an irradiation is complicated since so many factors are involved, as discussed in 5.3.3. The computer code STAYSL, using the least-squares method with covariance effects, was developed by Perey (**33**). Errors in the cross sections have been estimated by McElroy et al. (**39**) although these errors were intended for reactor dosimetry and must be extrapolated to higher neutron energies. Better cross-section errors with covariances will be published in ENDF/B-V. Errors due to the input trial solution can be minimized by obtaining the best possible estimates from time-of-flight or recoil spectrometry as well as previous characterizations. All other sources of error will be contained in the activation integrals since these must be corrected for system and geometric effects as well as the better known counting uncertainties.

5.3.4.2 It should be pointed out that experimenters are usually interested in integral damage or dose rates rather than the actual differential neutron spectrum. Fortunately, errors in the integral quantities will be significantly less than those in the differential quantities since differential group fluxes will always be found to have very large cross-correlations.

5.3.4.3 If integral gas rates are desired, then stable product monitors, such as Helium Accumulation Fluence Monitors (HAFM) (**29**), have very low errors (<2 %) since they provide the desired information almost independently of system effects and do not require any knowledge of the differential flux and spectrum. Such monitors also provide an excellent check on unfolded differential results since the latter can be used to calculate integral gas rates for comparison. Alternatively, the stable product results can be included with radiometric foils in the unfolding. If the stable product monitors are used to measure the neutron fluence, then knowledge of the spectrum is, of course, required, although time-dependent effects are not important.

5.3.4.4 Although presently it may not be possible to completely assess all errors correctly in Be(d,n) environments, careful documentation of procedures will ensure that data may be reanalyzed in the future so that data may be correctly correlated with data obtained at the same or other facilities.

5.4 *Summary of Recommended Procedures*—The following outline is intended to summarize procedures that should be followed during accelerator irradiations. Whereas some of these points may be routinely attended to, especially at well established facilities, experimenters should be aware of these procedures and check to see if they are in fact being done. Documentation should always be obtained. Some of the following procedures may be required only during the initial characterization of a facility, but should be checked periodically, especially when any major changes are made. Such changes may be common at existing, nondedicated facilities.

5.4.1 *Procedures Prior to Irradiation:*

5.4.1.1 Study possible instabilities in beam and target systems and assess importance; provide monitors to measure important instabilities,

5.4.1.2 Map typical neutron field by active and passive methods,

5.4.1.3 Provide for accurate sample alignment relative to source and dosimetry materials,

5.4.1.4 Scope required dosimetry to obtain desired data with minimum uncertainties, and

5.4.1.5 Design dosimetry to map accurately the flux and spectra at all sample locations.

5.4.2 *Procedures During Irradiation:*

5.4.2.1 Check alignment of samples relative to source and dosimetry materials using active means or autoradiographs,

5.4.2.2 Record time-history of irradiation using beam current or other system monitors and active neutron detection systems,

5.4.2.3 Record details of any beam rastering technique used to moderate flux/spectral gradients,

5.4.2.4 Record layout of all experimental equipment to assess perturbation effects, and

5.4.2.5 Check condition of target before and after run to look for undetected deterioration.

5.4.3 *Procedure After Irradiation:*

5.4.3.1 Measure alignment of samples and dosimetry materials with autoradiographs to check on movement of neutron source,

5.4.3.2 Obtain all system records for time history of the irradiation,

5.4.3.3 Analyze all dosimetry data,

5.4.3.4 Correct dosimetry data for system and geometric effects,

5.4.3.5 Record dosimetry data such that data may be reanalyzed if required in the future as new information becomes available, and

5.4.3.6 Assess errors in all derived quantities and record procedures used.

6. Keywords

6.1 accelerators; cyclotrons; fusion; ion irradiation; radiation damage simulation; spallation

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