Conf-771036--16
HEDL-SA-1309

ROCKWELL INTERNATIONAL
Atomics International Division
8900 De Soto Avenue
Canoga Park, California 91304

HELIUM PRODUCTION MEASUREMENTS FOR NEUTRON DOSIMETRY AND DAMAGE CORRELATIONS*

by

Harry Farrar IV (AI) and E. P. Lippincott (HEDL)

Paper to be submitted for inclusion in the proceedings of the *Second ASTM-EURATOM Symposium on Reactor Dosimetry: Dosimetry Methods For Fuels, Cladding and Structural Materials*, held at Palo Alto, California, 3-7 October 1977

January 1978

*Work performed under the auspices of the U.S. Department of Energy

---

HELIUM PRODUCTION MEASUREMENTS FOR NEUTRON DOSIMETRY AND DAMAGE CORRELATIONS

Harry Farrar IV
Rockwell International Corporation
Atomics International Division
Canoga Park, California 91304 U.S.A.

and

Ezra P. Lippincott
Westinghouse Hanford Company
Hanford Engineering Development Laboratory
Richland, Washington 99352 U.S.A.

Abstract

Accurate neutron fluence and spectral characterization of long experimental irradiations are required for adequate correlation of damage measurements, transmutations, and other phenomena of interest in the development of improved high performance reactor materials. Many radiometric monitors utilized in low power reactor facilities and for short irradiations in high power facilities are limited for these longer irradiations by half-life or burnup considerations. To supplement these monitor sets, especially for the longer irradiations, various helium-producing materials are being developed, tested and used for characterizing fluence. Applications exist in light water, breeder and fusion reactor neutron environments.

Helium accumulation fluence monitors (HAFM's), consisting of miniature vanadium capsules containing small, accurately-known amounts of ^{10}B or ^{6}Li, are now being used routinely for neutron dosimetry measurements in breeder reactor environments. Additionally, solid wires of Al, Fe and Cu have been irradiated by 14.8-MeV neutrons from the d-T reaction, and measurements of the helium production along these wires have given detailed neutron fluence profiles. Additional materials with relatively high (n,α) cross sections are being tested in a wide variety of neutron environments to select HAFM sets that will provide spectral information by unfolding techniques. The mass spectrometric helium measurement technique has been demonstrated to produce results with better than 2% (1σ) absolute accuracy. Intercomparisons with other laboratories have demonstrated good correlations with radiometric and fission chamber dosimetry results.

I. Introduction

A major goal of nuclear power development programs has been the maximization of the lifetime of reactor components. One facet of this effort is the characterization of the environmental conditions affecting components both in test irradiations and in power reactor usage. The test irradiations may include a range of environments nearly bracketing actual reactor conditions, as, for example, for fast reactor in-core components. In other cases, use of the data may involve large extrapolations from the test conditions to actual application. An example is the use of accelerated irradiations nearer the reactor core to predict vessel damage.

Two applications of helium production measurements should be distinguished as part of this effort. First, helium production in certain materials can be used to determine neutron fluences either as a supplement to, or in place of radiometric multiple foil measurements. Second, helium measurements provide damage information where the helium production itself is important. Examples of the latter include burnup determinations of boron-containing control or safety rod components, and damage effects due to helium produced in breeder reactor fuel cladding or fusion reactor first wall materials.

At the present time, considerable research is being undertaken to apply dosimetry techniques developed for breeder reactor (BR) environments[1] to the surveillance of light water reactor (LWR) pressure vessel walls[2-4], and magnetic fusion reactor (MFR) test environments[5,6]. The method most often used for neutron flux or fluence characterization in BR's and which is being increasingly used in LWR surveillance locations and MFR test environments is the multiple foil technique[7-9]. This method consists of irradiating a set of materials, usually encapsulated to prevent interaction with each other and with the reactor environment. These materials are subsequently analyzed to determine the numbers of various nuclear reactions that occurred during the irradiation. Several materials are generally chosen for their differing, but often overlapping, responses to neutrons with different energies. The measured nuclear reaction rates or total reactions are then used with an unfolding code to obtain multiple foil adjusted calculated flux spectra or fluence spectra, respectively.

Most nuclear reactions used for dosimetry purposes produce radioactive products which are subsequently counted radiometrically. The multiple foil method, however, frequently includes reactions that result in stable products, especially for long-term irradiations. Examples of stable products include the formation of helium in a variety of elements resulting from total helium (n,α) cross sections, and the build-up of certain isotopes of neodymium from heavy nuclide fission.

The helium generation phenomenon has led to the development of helium accumulation fluence monitors (HAFM's) which usually consist of miniature capsules containing various elements or isotopes with different (n,α) cross section energy responses. The generated helium is subsequently

measured with <2% (1σ) absolute accuracy over a very broad concentration range using specialized high sensitivity mass spectrometric techniques[10]. Over the last few years, HAFM's containing ^{10}B and ^{6}Li have proven very effective for measuring neutron fluence and fluence-spectra in breeder reactor environments[1,10]. Other HAFM materials are now being tested to increase the energy coverage obtained by this method. The fact that the product is stable and does not burn out, makes the HAFM technique very attractive for long-term fluence measurements. The helium analyses can be conducted at a later time at a centralized location, often without the inconvenience of radioactivity.

Computer iterative unfolding techniques[9,11] such as those provided by the SAND-II Code[12-14], SPECTRA[15], and RDMM[16,17] are available to determine a neutron spectrum consistent with the measured dosimetry data. These codes use approximation methods to adjust an initial estimate of the neutron spectrum shape, obtained from reactor physics calculations, or from some functional form, such as a set of polynomials containing adjustable parameters. For example, the SAND-II code combines the input spectrum shape with its library of energy-dependent cross-sections $[\sigma(E)]$, to predict reaction rates for the multiple foils used for the dosimetry. It then compares these predicted rates with the actual measured reaction rates. The neutron spectrum is then adjusted through several iterations to provide the best agreement between predictions and measurements. The more dosimeters (radiometric foils, HAFM's, etc.) that are used, the more redundant the energy coverage, and the less chance of an error due to an incorrect measurement. The redundancy also results in a solution that is less influenced by input spectrum uncertainties. The SAND-II Code currently uses cross-sections from the ENDF/B dosimetry file[18], which are being constantly improved both by point-by-point measurements using neutron spectrometry, and by integral normalizations using well-characterized neutron benchmark fields[19-22].

An often overlooked feature of the multiple foil approach to neutron dosimetry is the fact that the neutron spectrum takes the role of a rather accurate transfer function. Even if a portion of the derived neutron spectrum has an increased uncertainty because one of the neutron cross sections used to obtain the spectrum has not yet been completely characterized, that portion of the neutron spectrum shape will nevertheless be proportional to that dosimeter response. This portion of the neutron spectrum will then, in turn, predict accurately another phenomenon, such as damage, transmutation, etc., that has an energy response similar to that dosimeter foil, even if the absolute cross sections are not well known.

Accurate characterization of both the total neutron fluence and the neutron energy spectrum in each experimental situation are mandatory for the proper correlation of results between experiments. Both the fluence and energy-spectrum ("fluence-spectrum") are required to interpolate or extrapolate results to other reactor environments, to predict component lifetimes, and to develop improved high performance materials. In order

to correlate the changes in materials properties with reactor neutron exposure, however, it is very important to know the fluence spectrum at the specific location of each test specimen. In determining the fluence, however, the flux dependence is often assumed to be proportional to an instrumentally-measured reactor time-history as determined by a radiation detector, or by the reactor heat balance. This approximation often fails when changes are made to the reactor configuration. These changes, including even minor changes such as control rod movement and burnup of neighboring fuel subassemblies, can cause reactor location-to-location flux and energy distribution variations that are not reflected in the reactor power-time history.

II. Helium Measurement System

The mass spectrometer system was specifically designed for low level helium concentration measurements[10]. The system consists of a 2-inch radius permanent magnet mass spectrometer operated in isolation from its vacuum pumps to give high sensitivity[23]. Attached to the mass spectrometer through a getter system are several furnaces which are used to vaporize and thereby release helium from the samples, and several "spike" systems which dispense precisely-known small quantities of ^{3}He or ^{4}He.

Determination of the helium content is accomplished by melting and vaporizing a known amount of the sample material under vacuum, using resistance heating of either a miniature coil made from 0.25 mm tungsten wire, or a 4.8 mm diameter graphite rod. Each graphite rod is hollowed out to allow insertion of a 1.3 mm diameter HAFM capsule, so that when ~250 amperes of current are passed through the graphite, the entire capsule and contents are vaporized along with the central portion of the graphite[10].

For the analysis of most samples, a precisely-known number of atoms of ^{3}He "spike" is added immediately before the ^{4}He is released by the heating operation. After mixing of the isotopes, a portion of the gas passes through getters directly into the mass spectrometer volume, which is isolated from its vacuum pump for "static mode" operation. A measurement of the $^{4}He/^{3}He$ ratio and a knowledge of the weight of the HAFM material then gives the helium concentration. The low-level ^{3}He spikes are obtained by partitioning helium through calibrated volumes. The nearly constant mass discrimination of the mass spectrometer is repeatedly measured during each series of runs by analyzing precisely-known mixtures of ^{3}He and ^{4}He.

One analysis of each material is made without the addition of the ^{3}He spike to verify that this isotope is not already present. In the case of neutron reactions with ^{10}B and ^{6}Li, however, tritium is always formed, and this decays slowly to ^{3}He. Fortunately, when these two isotopes are irradiated in power reactors, enough helium is generated to make it possible to measure both ^{3}He and ^{4}He from the same sample. To do this,

the procedure has been modified to allow removal of a known small fraction (0.1%) of the sample gas before the spike is added. Analysis of the unspiked and spiked gas isotopic ratios then permits calculation of the amounts of ^4He and ^3He originally in the solid sample.

The reproducibility of the helium measurements for milligram-size specimens at concentrations above 10 appb (10^{-8} atom fraction) generally has a 1σ standard deviation of <1%. The absolute accuracy, determined from uncertainties in sample mass, sample purity, spike size, and isotopic ratio measurement is generally <2%. The lower limit of detection is set by the $\sim 10^9$ atoms of ^4He released by the graphite crucible and its surroundings upon heating. Since up to 10^{18} atoms of ^4He or ^3He can be measured using the system, and since the amounts of sample material can be increased for low fluence irradiations, the effective dynamic range of the technique spans well over 9 orders of magnitude in helium concentration. This makes it possible to test and characterize the HAFM materials in very low-flux benchmark neutron fields. Once characterized, these materials can then be used routinely as a part of flux-spectral sets in long-term power reactor irradiations.

III. HAFM Description

Helium accumulation fluence monitors consist of various materials which are irradiated and subsequently analyzed for helium by gas mass spectrometry. The materials are chosen for the differing energy responses of their helium production cross sections. For breeder reactor and other relatively high temperature environments, the HAFM materials are encapsulated, usually in vanadium, both to prevent chemical or physical interaction between HAFM and other multiple foil materials or their surroundings, and to minimize loss of helium generated by the irradiation. Vanadium has been chosen for an encapsulating material because of its low permeation rate for helium[24], its low induced radioactivity, and its relatively low (n,α) cross section. Typical capsules are 6.4 mm long and have diameters of 0.9 or 1.3 mm. Entire capsules and their contents are later vaporized in a high temperature furnace to release the helium. The amount of helium generated by the vanadium capsules themselves, determined by calculation or by analyzing irradiated empty capsules, generally represents <0.1% of the total helium released by HAFM's containing boron and ^6LiF.

Vanadium is satisfactory for encapsulating isotopes with high (n,α) cross sections, such as ^6Li, ^{10}B, ^{14}N and ^{32}S. For potential HAFM target materials with (n,α) cross sections that are within an order of magnitude of that of vanadium, however, the helium generated by the relatively massive capsule would dominate that produced by its contents. For that reason, both gold and platinum, which have even lower (n,α) cross sections than vanadium in fast reactor neutron spectra, are being tested for encapsulating experimental HAFM target materials in EBR-II.

The first HAFM's to be used contained natural boron and enriched ^{6}LiF, and now these two are included routinely as an integral part of the U.S. breeder reactor program's multiple foil flux-fluence spectral sets. For typical power reactor fluences, however, the amounts of boron and ^{6}LiF have been minimized to keep the helium generation down to levels of $<10^{17}$ atoms for convenience in mass spectrometric measurement. It has been found that single 0.07 to 0.15 mg crystals of natural boron (19.80% ^{10}B) and enriched ^{6}LiF (99.1% ^{6}Li) generate amounts of helium in a convenient measurement range. The small size of the crystals makes possible the use of vanadium capsules with small cavities and thick walls (0.33 mm), which is desirable since several atmospheres of helium may be generated by these two HAFM materials.

For HAFM materials such as TiN (for ^{14}N) and PbS (for ^{32}S), which have different neutron energy responses and much lower (n,α) cross sections, it becomes desirable to include as much material as possible within the HAFM capsule. In this case, capsules with the same outside dimensions but with thinner capsule walls (e.g., 0.24 mm), provide a larger cavity while at the same time reducing the helium contribution from the vanadium. For irradiations in benchmark facilities, low flux levels make it necessary to maximize even the amounts of ^{10}B and ^{6}Li present. Whenever the HAFM capsules contain several crystals or a powder, the mass of the contents is determined by weighing the capsule both before and after the filling operation.

In certain reactor applications where there is a high proportion of low energy neutrons, such as at the vessel walls of breeder and light water reactors, the amounts of ^{10}B and ^{6}Li in the HAFM must be reduced even further. This is because the low energy (n,α) cross sections for these isotopes are very large. In these cases the usual 0.1 mg crystals would not only generate too much helium for convenient measurement, but would also exhibit significant neutron self-shielding effects. Two methods are now being used to reduce the content of these isotopes. The first uses very small crystals (~0.05 mg) of depleted boron (~5% ^{10}B) or natural lithium fluoride (7.5% ^{6}Li). This requires a very precise knowledge of the isotopic content and chemical purity of the materials. The second uses alloys containing enriched ^{10}B or ^{6}Li. Highly enriched isotopes both minimize the amount of material that must be dissolved, and make the isotopic determination less critical. At the present time, alloys of ^{10}B in aluminum, ^{10}B in nickel, and ^{6}Li in aluminum, each in the 0.1 to 0.7% (by weight) concentration range, are being tested. The homogeneity of the ^{10}B and ^{6}Li concentrations in these alloys (for ~2 mg HAFM targets) must be determined, however, before they can be used for accurate dosimetry.

For low fluence irradiations at near-ambient temperatures, it appears feasible to irradiate certain HAFM target materials without encapsulation. Experiments have revealed that no significant helium will leave boron or LiF crystals when irradiated at ~30°C to helium levels of up to ~15 appb (15×10^{-9} atom fraction). In separate experiments, described in Section IV, aluminum, iron, and copper wires (0.5 mm diameter) have been

irradiated to generate these same levels of helium with 14.8-MeV neutrons. These wires were subsequently etched to remove surface material depleted in helium from α-recoil effects, and then partitioned into segments for mass spectrometric helium analysis.

IV. Dosimetry in Low Fluence Environments

Helium accumulation fluence monitors have and are continuing to be used effectively to measure neutron fluences in low power breeder reactor mockup facilities such as the Zero Power Plutonium Reactor (ZPPR), at Idaho Falls, and reference benchmark neutron fields such as the Coupled Fast Reactor Measurements Facility (CFRMF) at Idaho Falls[20], the 10% enriched ^{235}U critical assembly "BIG-10" at Los Alamos[21], and the Sigma Sigma Cavity at Mol, Belgium[22]. For the lowest power situations, it has been necessary to use HAFM's containing as much as ~50 mg of ^{10}B or ^{6}LiF in order to generate enough helium ($\geq 10^{11}$ atoms) for precise measurement by present techniques. This corresponds to a breeder reactor spectrum total neutron fluence of only $\sim 2 \times 10^{13}$ neutrons/cm^2.

The results of the HAFM fluence measurements in these low power facilities provided the first cross section intercalibrations in accurately known spectra, and provided a demonstration of the HAFM technique in low power environments as a supplement to radiometric measurements. Further discussion of the benchmark results is presented in Section VI.

Precise measurements have also been made of the neutron fluence variation over the volume of an experiment in the 14.8-MeV d-T neutron environment of the Rotating Target Neutron Source (RTNS-I) at Lawrence Livermore Laboratory[5]. The experiment was conducted as part of a program to determine helium generation rates and spectrum-integrated helium production cross sections of a number of materials of interest to magnetic fusion reactor development. The results demonstrated the application of helium accumulation fluence dosimetry to high energy neutron fields as a valuable tool complementary to radiometric foils.

V. Dosimetry in High Fluence Environments

Applications of B and ^{6}LiF HAFM's for high fluence measurements are currently being made routinely in EBR-II and other fast reactors. An example of data obtained is presented in Figure 1, which plots some results from the EBR-II Run 75D dosimetry test. Shown is the variation of the measured ratio of the ^{10}B and ^{6}Li cross sections (R) versus the mean neutron energy ($\bar{E}$) as determined by the SAND-II unfolding code using radiometric foils placed at the same reactor locations. These data were taken from 22 locations starting in the EBR-II core and extending through Row 8 positions 60 cm above and below core midplane. The data appear to follow a straight line over the entire energy range 0.13 to 0.81 MeV.

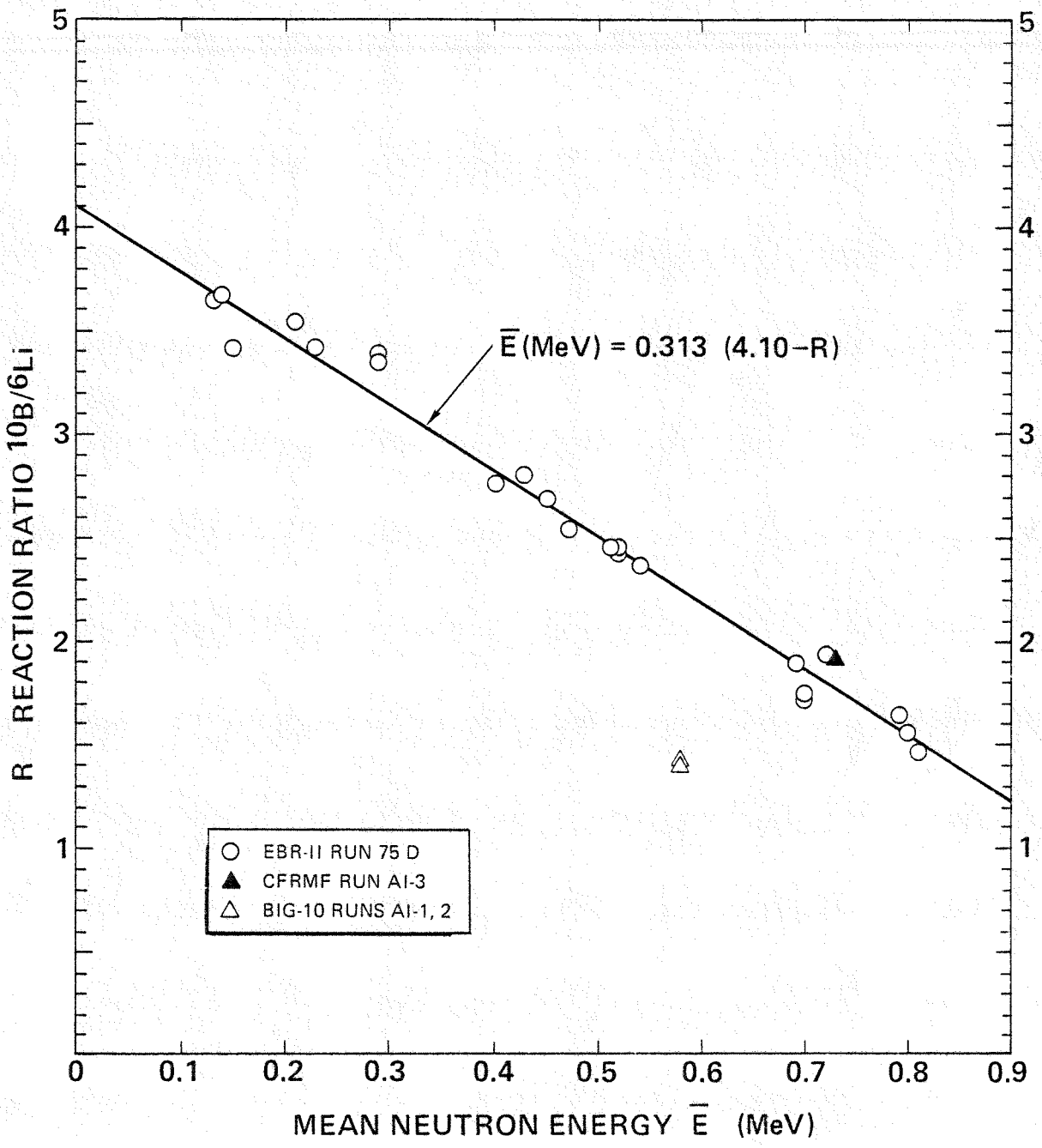

Figure 1: Energy Dependence of the Ratio of the ^{10}B and ^{6}Li Reactions From HAFM's Irradiated Throughout EBR-II and in CFRMF and BIG-10

Several observations can be made from the results shown in Figure 1. First, the ratio R varies from 1.47 to 3.67, and is strongly dependent on the location within the core and blanket regions, being lowest at midplane and highest at the farthest-out locations. The straight-line relationship with $\bar{E}$, shown in Figure 1, is described by the equation:

$$\bar{E} = 0.313\ (4.10 - R) \qquad \ldots.(1)$$

The strong dependence of the $^{10}B/^{6}Li$ cross section ratio R on $\bar{E}$, and the closeness of the ^{10}B and ^{6}Li HAFM data to the curve demonstrate the value of even a pair of HAFM target materials as sensitive fluence spectrum monitors. It should be noted that simple correlations of the ^{10}B and ^{6}Li ratio with $\bar{E}$ should be expected only over similar neutron spectrum compositions. As will be seen in Section VI, sophisticated unfolding techniques (e.g., the SAND-II Code) must be used to correlate detector responses with different complex neutron spectrum shapes.

The extrapolation of the straight line in Figure 1 predicts a value of 4.10 for the reaction ratio R at zero mean neutron energy ($\bar{E} = 0$). This differs by only 0.7% from the ratio of the thermal cross sections of ^{10}B and ^{6}Li. This adds credence to the linear extrapolation and, indeed, to the whole set of data.

Preliminary predicted values of the boron and lithium helium generation rates have been calculated for comparison with the measured results shown in Figure 1. The predicted values are based on the ENDF/B-IV total helium production cross sections for ^{6}Li and ^{10}B. The neutron spectrum at each position was calculated using radiometric multiple foil results, and the SAND-II code. The boron and lithium results were not utilized in the spectrum unfolding process for this particular comparison.

The calculated curve of the $^{10}B/^{6}Li$ cross sections, R, versus $\bar{E}$ is similar to the empirical curve in Figure 1. Although the scatter in the preliminary calculations is greater than that obtained from the HAFM data, it appears that some deviation from the straight line exists. For neutron energies below 0.3 MeV, the calculated ratio has a similar slope but is 4 ± 3% higher than the measured line in Figure 1. At mean neutron energies above 0.3 MeV the calculations are 9 ± 7% below the measurements. It should be noted that these calculational results are preliminary and they also may be influenced by B_4C control rods located at nearby positions above the EBR-II core. There are, however, not sufficient data available at present to investigate this effect further.

Helium production in reactor materials such as stainless steel, which is important for damage studies, as discussed in Section VI, may also provide useful fluence definition. Measurement of helium in cases where it can be established that the helium is completely contained, provides flux integration over an entire irradiation period. One requirement,

however, is accurate characterization of the material. For example, ppm levels of boron in the material can make a significant but predictable contribution to the total helium production for out-of-core irradiations in breeder and light water reactors.

VI. Cross Section Evaluations

An important part of the development of helium production monitors for dosimetry is the validation and calibration of the technique by irradiation in benchmark facilities. As mentioned in Section IV, numerous ^{10}B and ^{6}LiF specimens have been irradiated together in the benchmark neutron spectra of the CFRMF and the BIG-10 facilities as part of the Interlaboratory Reaction Rate (ILRR) program. The results have provided important integral normalizations of the ^{10}B and ^{6}Li helium production cross sections, which are now being compared with the data from the EBR-II Run 75D dosimetry test (Figure 1).

Further normalizations are in progress. Additional ^{10}B and ^{6}LiF HAFM's have been irradiated for 108 h in the Fission Cavity and Sigma Sigma ($\Sigma\Sigma$) benchmark neutron facilities of the BR1 Reactor at Mol, Belgium.

The results from the CFRMF and BIG-10 irradiations show that the ratios of the reactions (or spectrum integrated helium production cross sections) for ^{10}B and ^{6}Li are 1.424 ± 0.004 (1σ) for BIG-10, and 1.912 ± 0.012 (1σ) for CFRMF. These ratios are plotted in Figure 1 versus the mean neutron energy, for comparison with the results from the HAFM irradiations in EBR-II. Whereas each EBR-II point represents the results from a pair of B and ^{6}LiF HAFM's, the BIG-10 and CFRMF points represent combined results of numerous samples. The CFRMF data agree very well with the EBR-II data. As expected, the data from the two BIG-10 irradiations fall far below the line. This is because below 40 keV--a region of importance due to the high ^{10}B and ^{6}Li (n,α) cross sections--the neutron spectrum shape of the facility is significantly different from EBR-II and CFRMF.

In the low fluence environments of CFRMF and BIG-10, only the ^{6}Li and ^{10}B reactions at present generate enough helium for accurate measurements. However, when the results are compared with certain radiometric reaction measurements made during the same irradiations, a discrepancy appears between the measured and calculated helium production ratios for these isotopes. Even though the ^{10}B and ^{6}Li (n,α) cross sections are considered to be well known, particularly at energies below 100 keV, it appears that adjustments to each, and also to other standards such as the ^{235}U (n,f) cross section, may be required to get consistency. Adjustments in the best estimate of the benchmark neutron spectrum may also be required. Results from EBR-II, described in Section V, also support the need for some cross section adjustments. It is expected that further analyses of the integral data will result in an improved knowledge of the ^{10}B and ^{6}Li cross sections, and will increase the accuracy of application of these reactions for fluence determination.

With perhaps one or two exceptions, other helium production cross sections can be measured only in higher fluence environments, which are not as well characterized as the standard and reference neutron fields. This means that validation and calibration of these reactions must be tied back to the benchmarks through radiometric results. Although this extra step contributes some additional uncertainty, the development of self-consistent cross section sets in this way will still produce accurate integral results. In fact, since many (n,α) reaction cross sections are not well known, integral measurements may add considerably to the knowledge of the cross sections in neutron energy regions important to fission and fusion applications. Integral normalizations have been especially important in the prediction of helium production rates in structural components for fast reactors, in particular for the (n,α) reactions for Ni, Fe, and Cr in stainless steel. For thermal and mixed spectrum reactor components containing nickel, the very large helium contribution that can result from the nickel two-stage thermal neutron reaction $^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$ has been studied extensively in this laboratory in cooperation with Oak Ridge National Laboratory.

VII. Conclusions

The value of helium accumulation fluence dosimetry has been demonstrated both in breeder neutron spectra and in fusion neutron test environments. The multiple foil technique with the inclusion of the boron and ^{6}LiF HAFM's, is being applied extensively to characterize fluence and fluence spectra in breeder reactor environments. It appears that the uncertainties in the resulting fluence values are dominated not by the reaction rate measurements but instead by uncertainties in the energy-dependent neutron cross sections and predicted neutron spectral shapes. These uncertainties are partly overcome by the use of monitors with overlapping energy response ranges.

Individual reaction ratios provide very useful and often accurate correlations as shown in Figure 1, even though the absolute comparisons of the reaction rates with cross sections have these additional uncertainties. In the case of the ^{10}B and ^{6}Li EBR-II results, the measured ratio of the ^{10}B and ^{6}Li reactions agrees much better with SAND-II calculated values than do the specific values for the two reactions. This difference is due to uncertainty in the SAND-II spectrum, arising from errors in calculated input spectrum shape and in the cross sections of the multiple foil reactions, and to cross section errors in ^{6}Li and ^{10}B relative to the reactions included in the multiple foil unfolding process.

This points to the need to continue to obtain more accurate energy dependences of all applicable dosimetry cross sections. For fusion reactor applications, even less is known of the energy dependent neutron cross sections of potential radiometric and helium accumulation reactions in the 10 to 40 MeV energy range. It is also very important, from the

dosimetry point-of-view, to integrally test the same reactions in as many different neutron spectra as possible. Until more accurate energy dependent data are available, the best evaluations of existing data, normalized wherever possible by integral measurements, must be used.

Acknowledgements

The authors wish to acknowledge contributions to this work by D. W. Kneff, M. M. Nakata, and J. F. Johnson of Atomics International and by W. N. McElroy and J. A. Ulseth at HEDL. We also wish to express our thanks to J. W. Lewellen, P. B. Hemmig, T. C. Reuther, Jr., and K. M. Zwilsky of the U.S. Department of Energy (DOE) for their continued interest and support of this work.

This work was sponsored under DOE Contract Nos. EY-76-C03-0824 and EY-76-C-03-0701 at AI, and EY-76-C-14-2170 at HEDL.

References

1. H. FARRAR IV, E. P. LIPPINCOTT and W. N. McELROY, "Dosimetry for Fluence Applications" *Proc. First ASTM-EURATOM Symposium on Reactor Dosimetry,* Petten, Netherlands, September 22-26, 1975, Report EUR 5667, Part I, 675 (1977).

2. W. N. McELROY, D. G. DORAN, R. GOLD, E. P. LIPPINCOTT, J. O. SCHIFFGENS, R. L. SIMONS, W. C. MORGAN, J. A. GRUNDL, E. D. McGARRY, F. B. K. KAM, J. H. SWANK and G. R. ODETTE, "Standardization of Dosimetry and Damage Analysis Work for U.S. LWR, BR and MFR Development Programs," *Proc. Second ASTM-EURATOM Symposium on Reactor Dosimetry: Dosimetry Methods for Fuels, Cladding and Structural Materials,* Palo Alto, California, October 3-7, 1977.

3. F. J. RAHN, C. Z. SERPAN, A. FABRY, W. N. McELROY, J. A. GRUNDL and J. DEBRUE, "Trends in Light Water Dosimetry Programs," and other papers included in the Workshop on Dosimetry for Light Water Reactor Pressure Vessel Surveillance Programs, *Proc. Second ASTM-EURATOM Symposium on Reactor Dosimetry: Dosimetry Methods for Fuels, Cladding and Structural Materials,* Palo Alto, California, October 3-7, 1977.

4. G. C. MARTIN, Jr., "Dosimetry Method for Light Water Reactors," *Proc. Second ASTM-EURATOM Symposium on Reactor Dosimetry: Dosimetry Methods for Fuels, Cladding and Structural Materials,* Palo Alto, California, October 3-7, 1977.

5. HARRY FARRAR IV, D. W. KNEFF, R. A. BRITTEN and R. R. HEINRICH, "Fluence Mapping of RTNS-I by Helium Accumulation and Foil Activation Methods," *Proc. Symp. on Neutron Cross Sections from 10 to 40 MeV,* Brookhaven National Laboratory Report BNL-NCS-50681, July 1977.

6. R. R. HEINRICH, L. R. GREENWOOD, G. R. ODETTE, H. FARRAR IV, R. DIERCKX and R. GOLD, "Dosimetry Needs for the Magnetic Fusion Materials Program," *Proc. Second ASTM-EURATOM Symposium on Reactor Dosimetry: Dosimetry Methods for Fuels, Cladding and Structural Materials*, Palo Alto, California, October 3-7, 1977.

7. W. L. ZIJP, "Review of Activation Methods for the Determination of Neutron Flux Density Spectra," *Proc. First ASTM-EURATOM Symposium on Reactor Dosimetry*, Petten, Netherlands, September 22-26, 1975.

8. F. W. STALLMANN and F. B. K. KAM, "Review of Unfolding Methods for Neutron Flux Dosimetry," *Proc. First ASTM-EURATOM Symposium on Reactor Dosimetry*, Petten, Netherlands, September 22-26, 1975.

9. C. A. OSTER, "Review of Neutron Unfolding Methods Used in the U.S. and their Standardization for Dosimetry," *Proc. Second ASTM-EURATOM Symposium on Reactor Dosimetry: Dosimetry Methods for Fuels, Cladding and Structural Materials*, Palo Alto, California, October 3-7, 1977.

10. HARRY FARRAR IV, W. N. McELROY and E. P. LIPPINCOTT, "Helium Production Cross Sections of Boron for Fast Reactor Neutron Spectra," *Nucl. Technol.*, 25, 305 (1975).

11. W. L. ZIJP, J. H. BAARD and H. J. NOLTHENIUS, "Comparison of Some Neutron Spectrum Unfolding Codes" and other papers included in the Workshop on Computer Codes for Unfolding Neutron Spectra, *Proc. Second ASTM-EURATOM Symposium on Reactor Dosimetry: Dosimetry Methods for Fuels, Cladding and Structural Materials*, Palo Alto, California, October 3-7, 1977.

12. W. N. McELROY, S. BERG, T. CROCKETT, and R. HAWKINS,"A Computer-Automated Iterative Method for Neutron Flux Spectra Determination by Foil Activation, a Study of the Iterative Method," AFWL-TR-67-41, Vol.I, Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, NM (1967).

13. S. BERG and W. N. McELROY, "SAND-II (Spectrum Analysis by Neutron Detectors-II) and Associated Codes, A Study of the Iterative Method," AFWL-TR-67-41, Vol.II, Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, NM (1967).

14. S. BERG, "Modification of SAND-II," BNWL-855, Battelle-Northwest Laboratories, Richland, WA (1968)

15. C. R. GREER, J. A. HALBLEIB and J. V. WALKER, "A Technique for Unfolding Neutron Spectra from Activation Measurements," SC-RR-67-746, Sandia Laboratories, Albuquerque, NM (1967).

16. G. DiCOLA and A. ROTA, "Calculation of Differential Fast-Neutron Spectra from Threshold-Foil Activation Data by Least-Squares Series Expansion Methods," *Nucl. Sci, & Eng.*, 23, 344 (1965).

17. G. DiCOLA and A. ROTA, "RDMM - A Code for Fast Neutron Spectra Determination by Activation Analysis," EUR-2985.e, C.C.R. EURATOM, Ispra, Italy (1966).

18. L. STEWART, "Status of ENDF/B Special Applications Files," *Proc. Second ASTM-EURATOM Symposium on Reactor Dosimetry: Dosimetry Methods for Fuels, Cladding and Structural Materials*, Palo Alto, California, October 3-7, 1977.

19. A. FABRY, J. A. GRUNDL, W. N. McELROY, E. P. LIPPINCOTT and HARRY FARRAR IV, "Status Report on Dosimetry Benchmark Neutron Field Development, Characterization and Application," *Proc. Second ASTM-EURATOM Symposium on Reactor Dosimetry: Dosimetry Methods for Fuels, Cladding and Structural Materials*, Palo Alto, California, October 3-7, 1977.

20. J W ROGERS, D. A. MILLSAP and Y. D. HARKER, "CFRMF Neutron Field Flux Spectral Characterization," *Nucl. Technol.*, 25, 330 (1975).

21. E. J. DOWDEY, E. J. LOZITA and E. A. PLASSMANN, "The Central Neutron Spectrum of the Fast Critical Assembly BIG-10," *Nucl. Technol.*, 25, 381 (1975).

22. A. FABRY, G. DeLEEUW and S. DeLEEUW, "The Secondary Intermediate Energy Standard Neutron Field at the Mol-ΣΣ Facility," *Nucl. Technol.*, 25, 349 (1975).

23. J. H. REYNOLDS, "High Sensitivity Mass Spectrometer for Noble Gas Analysis," *Rev. Sci. Instr.*, 27, 928 (1956).

24. F. A. SMIDT, Jr. and A. G. PIEPER, "Studies of the Mobility of Helium in Vanadium," *J. Nucl. Materials*, 51, 361 (1974).