Reactor Dosimetry:

12th International Symposium

STP 1490

Editors:
David W. Vehar
David M. Gilliam
James M. Adams

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David W. Vehar,
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and
James M. Adams, editors

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Foreword

The Twelfth International Symposium on Reactor Dosimetry was held in Gatlinburg, Tennessee, USA, May 8–13, 2005. This Symposium was jointly sponsored by ASTM International, the European Working Group on Reactor Dosimetry (EWGRD), and the Atomic Energy Society of Japan (AESJ). It was organized by ASTM Committee E10 on Nuclear Technology and Applications and the EWGRD. The Local Organizing Committee was chaired by Douglas L. Selby of Oak Ridge National Laboratory (ORNL). Co-sponsors were Sandia National Laboratory, UT-Battelle (ORNL), ThermoElectron/RMD, Canberra Industries, the National Institute of Standards and Technology, and the U.S. Department of Energy.

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IN MEMORIAM

Masaharu Nakazawa, 1944–2006

We lost our friend and colleague Prof. Masaharu Nakazawa, who died of heart failure on March 10, 2006. From 1967 until his death, Masaharu worked at Faculty of Engineering, the University of Tokyo, where he progressed from research associate to become Director of Research Center for Nuclear Science and Technology. For nearly 40 years, he had contributed to the establishment of nuclear engineering in Japan as one of the leaders in radiation measurement and dosimetry. His special expertise and accomplishments were in the neutron dosimetry, in particular, unfolding neutron energy spectra from foil activation detector and 3He proportional counter measurements, in the application of lasers and optical fibers to radiation measurement and reactor vessel surveillance, and in the development of superconducting X-ray detectors. Recently, he was also very enthusiastic about the spread of advanced medical and diagnostic applications of radiation in Japan.

Masaharu was well known to participants of the International Reactor Dosimetry Symposia. He was actively involved in the organization of the 10th Symposium held in Osaka in 1999, and also was a member of the program committee of the 11th Symposium in Brussels in 2002. He was always loved and respected by his colleagues and students in Japan and elsewhere for his originality, foresight, good humor and constant dedication to research and education.

Francis Kam, 1929–2005

Francis Kam, known to many of us as Frank, died November 15, 2005 at age 76. He was a researcher at Oak Ridge National Laboratory for 33 years starting in 1961. During that time period, he was deeply involved in and made significant contributions to ASTM E10 and the field of nuclear dosimetry. Frank was involved in the development, documentation, and application of several computer codes used for neutron transport analysis, including the O5R Monte Carlo Code. His publication list in the area of dosimetry included 19 journal articles, 4 book chapters and an assortment of conference publications and reports. Although retired, he was able to attend the 12th International Symposium on Reactor Dosimetry in May of 2005 where he was recognized for his lifetime achievements. Frank is clearly one of those people where it can honestly be said that he made a difference and he will be missed by many.

Harry Farrar IV, 1935–2007

Harry Farrar IV will be long remembered for his contributions to ASTM and to many of the past symposia on reactor dosimetry. Born in England, he emigrated at an early age with his family to Canada. After receiving his PhD from McMaster University, he joined Rockwell International, where he developed a helium mass spectrometer system that formed the basis for a number of dosimetry applications. These include the Helium Accumulation Fluence Monitor, which received an IR-100 award in 1978. Harry participated in early efforts to resolve discrepancies in neutron fluence measurements, starting with the Inter-Laboratory Reaction Rate Program in the early 1970s.

Harry was a contributor to the First ASTM-Euratom Symposium on Reactor Dosimetry in 1975, and continued to serve this symposium series in various capacities, including several terms as chairman. Harry also initiated and chaired several ASTM international workshops on radiation dosimetry. In 1984, Harry formed a task group “Radiation Dosimetry for Food Processing”, which was later expanded to include dosimetry standards for all forms of radiation processing. In 1988 this group became ASTM E10.01, “Dosimetry for Radiation Processing.” Under Harry’s leadership, it became one of the most successful activities of Committee E10. He was also instrumental in a pioneering effort to have these ASTM standards accepted internationally as ISO standards. Harry has held several ASTM Committee E10 offices, including two terms as chairman. His contributions have been recognized with numerous E10 awards, as well as the ASTM Award-of-Merit in 1992.

Harry was a world traveler, an award-winning amateur photographer, and a man of many other accomplishments. He had an uncanny knack for making friends and creating a warm environment wherever he went. Harry led an amazing life and shared it with all of us.

Overview

The papers in this volume were presented at the Twelfth International Symposium on Reactor Dosimetry, and subsequently published in the Journal of ASTM International (JAI) following peer review. Eighty-seven participants from twenty countries attended the meeting.

Several trends are evident in the papers presented at this symposium. As operating nuclear power reactors have aged and continue to operate on extended operating licenses, new pressure vessel surveillance techniques have been required. In many cases, the original loadings of metallurgical surveillance specimens and their dosimeters have been completely used up. Innovative retrospective dosimetric techniques based on stable isotope transmutation or in-vessel gamma spectrometry are being developed and applied. Eastern European PWR's (especially those of the VVER-440 type) continue to have greater concerns about steel embrittlement, because of higher neutron radiation exposures than most Western European and US reactors. Accordingly, broader dosimetry studies are being made on the VVER reactors through retrospective dosimetry, ex-vessel dosimetry, and careful re-analysis of previously reported data. Vastly improved computer capabilities, international cooperation in nuclear data evaluations, maturation of analytic and adjustment software, and new data from "autopsies" of old decommissioned reactors have all contributed to greater reliability of reactor performance and materials calculations. Throughout the industry and regulatory bodies, there appears to be greater reliance on calculations in place of traditional methods of dosimetry and associated quality assurance.

The opening and keynote session included two papers, one on the very large new Olkiluoto 3 reactor under construction in Finland and one on the new Spallation Neutron Source under construction at Oak Ridge National Laboratory, the host laboratory.

There were seven plenary oral sessions of five or six papers each, and two poster sessions of about twenty-four papers each. In addition, there were two tutorials in parallel, and three workshop sessions with two parallel topics during each session.

The tutorials focused on materials science—one on radiation effects on materials, and one on materials science experiments based on neutron scattering.

Both the oral and poster sessions included the topics Power Reactor Surveillance; Test Reactors, Accelerators, and Advanced Systems; Benchmarks and Intercomparisons; Cross Sections, Nuclear Data, and Damage Correlations; Transport Calculations; Adjustment Methods and Reactor Dosimetry; and Experimental Techniques. In these proceedings, no distinction is made between the poster and oral papers, other than the notation of the awards for best poster papers.

The workshop sessions emphasized a discussion format rather than formal presentations. Workshop topics were LWR Surveillance and Retrospective Dosimetry; Dosimetry for Irradiation Facilities at Test and Research Reactors; Cross-Section Files and Uncertainties; Fusion and High Energy Neutrons; Adjustment Methods and Uncertainties; and Radiation Damage Correlations.

Best poster-paper awards were presented to Desislava Kirilova for "Validation of the Neutron Fluence on the VVER-440 RPV Support Structure," *K. Ilieva, S. Belousov, D. Kirilova, B. Petrov, E. Polk*, and to Mike Luker for " Application of a Silicon Calorimeter in Fast Burst Reactors," *S. M. Luker, K. R. DePriest, P. J. Griffin, D. B. King, G. E. Naranjo, A. J. Suo-Anttila*.

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WORKSHOP SUMMARIES

Mary Helen Sparks (White Sands Missile Range), ASTM Workshops Chair
Wim Voorbraak (ECN, Petten), EWGRD Workshops Co-Chair

Six workshops were held during the Symposium with the intent of providing an informal exchange of information on a selected variety of topics. The topics were approved by EWGRD and ASTM committees in advance of the meeting. A concerted effort was made to schedule concurrent workshops to allow maximum participation.

The number of workshops was reduced to six with two concurrent meetings on three consecutive days. Two co-chairmen, one each from ASTM and EWGRD, organized each workshop, defined the scope of the meeting and kept the meetings to a workshop atmosphere rather than additional oral session.

The attendance and participation at the workshops was most rewarding. The summaries of each workshop follow.

I-A. LWR SURVEILLANCE AND RETROSPECTIVE DOSIMETRY
Chaired by: E. P. Lippincott and S. Zaritsky

The workshop on LWR Surveillance and Retrospective Dosimetry was attended by 30 participants representing 13 countries. The workshop encompassed discussions on three major topics: surveillance dosimetry, fluence determination, and retrospective dosimetry measurements.

The importance of surveillance dosimetry measurements was emphasized by many of the participants. Of special importance are the dosimetry measurement programs for the VVER reactors. The measurement needs were summarized by J. Hogel as follows:

<u>VVER 440</u>

More (as good as possible) information is needed about the radiation exposure of RPV materials for the lifetime extension of VVER 440 reactors. Reasons for this are:

- The neutron flux during irradiation is significantly higher than for western PWRs, as well as for the VVER 1000 vessels.
- The standard surveillance program (SP) was not good enough.

Experimental tools include:

- New extended SP with well designed neutron dosimetry enabling the neutron fluence in each specimen to be determined. The large lead factor in these plants allows enough time to obtain the necessary specimen exposure levels.
- Continuous ex-vessel monitoring will provide necessary results for the SP dosimetry evaluation.
- Measurement of Nb activation in scraping samples from the inner cladding of the RPV provides evaluation of the neutron fluence for the whole time of operation. Combined with the ex-vessel dosimetry, the attenuation factor through the vessel wall could be obtained.

VVER 1000

All new units are equipped with the new type of surveillance program (e.g. Temelin and Kola 3). The use of reconstituted surveillance specimens (which occupy 1/4 of the space of regular specimens) enables a large number to be irradiated. It is also possible to use "guest" reactors for the irradiation of materials from the older generations of power plants.

B. Osmera added comments on the role of benchmark experiments (such as mock-up experiments in the LR-0 reactor) for decreasing systematic uncertainties. The experiments on VVER 440 and VVER 1000 mock-ups can significantly improve the reliability of surveillance programs and pressure vessel dosimetry results.

Discussion was also held on the need for surveillance dosimetry in the fourth-generation reactors to be built in the future. It was concluded that surveillance programs will still be needed for these reactors to address future questions that may arise. In addition, new requirements may arise for measurements in other environments such as high intensity spallation sources. Additional data may be needed to establish accurate methods for assessment of fluence of higher energy neutrons. Future needs may also include more accurate fluence determinations at reactor locations not presently deemed important for damage considerations, especially to satisfy life extension requirements.

Fluence determination in high flux regions in reactors appears to be in good shape, with estimated uncertainties of 15% or better. Some improvement in fluence assessment may result when systematic discrepancies are investigated in detail. For example, new thickness measurements of reactor components using radiography or other measurement techniques may help resolve differences from plant to plant between measurement and calculation of reactor cavity flux levels. This could reduce the spread in C/M ratios that Stan Anderson indicated presently has a standard deviation of 7.5% for Westinghouse PWRs.

The discussion on retrospective dosimetry centered on its usefulness for determination of exposure in reactor geometries where no measurement data otherwise exist. The limitations of retrospective dosimetry are important. These include the small number of reactions available for measurement and the lack of accurate characterization of the materials to be analyzed. In some cases the uncertainty in the position of the samples adds a significant error contribution.

In the case of some VVER surveillance capsules, retrospective dosimetry using samples from specimens has made a significant reduction in the fluence uncertainty. S. Zaritsky mentioned the new proposal for using diamond detectors for neutron fluence retrodosimetry of VVER 1000 surveillance specimens. These detectors are located in each surveillance container as irradiation temperature monitors, and after corresponding calibration can also be used as fluence monitors by precise measurement of the extension of the diamond crystal lattice caused by the irradiation. Since the diamond integrates the fluence over the entire irradiation history, information about the global and local power history is not required. Thus, the diamond detectors have the potential to be a useful alternative fluence integration tool.

I-B. DOSIMETRY FOR IRRADIATION FACILITIES AT TEST AND RESEARCH REACTORS
Chaired by: A. Hawari and W. Voorbraak

The workshop was attended by 27 participants. After an introduction round, where everyone could express his/her interest, several topics were discussed in a good atmosphere. All participants were willing to exchange experience with each other, contacts were made for further discussions after the workshop. Discussion centered around the following topics:

Active (on-line) monitoring: SNL is experienced in various counting techniques for neutrons as well as gamma rays, e.g. self powered neutron detectors (SPNDs), fission chambers, ionization chambers, diamond photo conducting detectors (PCD) and silicon PIN diodes (see paper 2.01). CEN Saclay has a lot of experience with calorimeters based on graphite and with SPNDs based on Ag and Rh. Today there are few limitations on the availability of good electronic equipment. The challenge is the discrimination between the signal component in a mixed field in which one is interested and other components that may contribute as much as 70%. There is a need to distinguish between thermal and epithermal neutrons. There are also other irradiation-time-dependent effects, such as activation of the detector and noise generated in signal cables. There are very few suitable benchmark fields in which to test the detectors.

High temperature detectors: There are many activation detectors that can be used between 1000 and 1500 °C, needed for use in Generation IV (e.g., the VHTR) and space reactor applications. NRG has had good experience up to 1100 °C with encapsulation in quartz. The quartz tube fixed the volume of the detector during melting. Such detectors will be measured after irradiation inside the quartz tube. Quartz may be brittle in certain atmospheres. In case of doubt, use extra iron encapsulation or consult a specialist in the application of quartz. Helium Accumulated Fluence Monitors/detectors (HAFM) may be an alternative for temperatures close to 1000 °C.

Determination of gamma-ray spectra, e.g. from a reactor beam may be done by measuring a small part of the beam with a Ge detector using a pencil collimator or a part of the beam that is deflected. The opinion was expressed that this will not be easy, as modern electronics will have serious problems with count rates $>$60k/sec. An extra barrier directly after the beam exit could help. Dependence on gamma ray energy could be investigated using computer (e.g., MCNP) simulations.

There is a growing concern for the continued operation of small reactors. Possible uses include biological applications such as Boron Neutron Capture Therapy, and use of activation analysis as a forensic tool. For example, NIST exposes paintings for the Smithsonian Museum. After exposure, different photographic films successively cover the painting. These films absorb gamma rays from the radiated painting, starting with the reaction products with the shortest half-lives. This provides information on the images from deeper layers, and therefore about the way that the painting has been created. NRG Petten has also applied this technique for a few old Dutch paintings. In addition to the classic approach of neutron radiography based on Gd and photographic film, CCD devices and ZnS screen are being used to digitize the images.

Reactors in the US are beginning to offer on-line reactor laboratory courses. An extensive program has been started between North Carolina State University and the University of Tennessee in this area. Information can be distributed in real time via the internet during an exercise, including reactor parameters such as power, temperature, control rod positions, etc., and experimental results, such as neutron images.

Computer codes such as MCNP, DORT and TORT are used to perform calculations prior to new experiments and changes in reactor cores. Each code has its advantages and disadvantages related to precision and computer time. Fuel burn-up is taken into account as part of the core modeling. The consequences of conversion to low enriched uranium fueled reactors have also been discussed.

II-A. CROSS-SECTION FILES AND UNCERTAINTIES
Chaired by: P. J. Griffin and E. Zsolnay

A major topic of discussion was the release of the IRDF-2002 dosimetry library. This library was included in the symposium distribution to all participants along with the draft papers that were presented at this symposium. This new dosimetry cross section library was the result of a request by the community at the workshop during the 10th ISRD. The workshop participants welcomed this library release and expressed their thanks to the IAEA. Many participants had already used the library and reported on the experiences. The following observations were made:

- A problem was observed with the MN55G reaction covariance. The problem was traced to the LB=8 component of the covariance that resulted in a very large uncertainty in one energy bin. The IAEA was requested to resolve the issue by confirming the evaluator's intent to have this large of an uncertainty in the one energy group, correct the problem if it was the result of the reversal of two numbers, or provide guidance to the community on the recommended approach to treating this covariance in spectrum adjustments.
- There was a request to add cross sections to the library required to treat parasitic burnup reactions that might interfere with the interpretation of the Ag, Nb, and Co (n,γ) dosimetry reactions.
- There was a request to the general community and, in particular, to the national standards laboratories, to gather additional validation data for reactions in the ^{252}Cf spontaneous fission standard benchmark field. The experiment data is required to validate the dosimetry cross sections. Data was also requested for the ^{235}U reference benchmark field.
- A request was made to add carbon dpa to the damage cross sections in the IRDF-2002 library.
- A request was made to add proper covariance files for the ^{197}Au(n,γ) and ^{235}U(n,f) reference benchmark reactions. These data are expected to be available from the international cross section standards community within the year. The request was to issue a revision to the IRDF-2002 library as soon as the data became available.
- Several reactions in the library only have a diagonal covariance matrix. This suggests that the covariance was not properly evaluated. Requests were made to do a re-evaluation for these reactions.
- A request was made for some new evaluations. These requests will be transmitted to the WPEC. Specific requests were for a new evaluation of the MN55G reaction and the ^{nat}Cd absorption cross section in the resonance region.
- Several cases were cited where the IRDF-2002 library appears to have resonance integrals with large deviations from the recommended experimental values. An evaluation of the resonance parameters and a reconciliation of the recommendations was requested for these reactions.
- The community requested the IRDF-2002 library to add (γ,f) photofission and (γ,γ') photonuclear cross sections that might produce the same products as dosimetry reactions. Even if these reactions did not have covariance matrices, the use of standard recom-

mended cross sections would benefit the community in bounding the importance of the interference reactions.
- Additional gas production cross sections were also requested.
- The publication of the benchmark field validation testing of the library was requested. These data are desired for use in simultaneous field spectrum adjustments, e.g. in the LEPRICON methodology.
- Requests were made for the spectrum covariance in the reference and validation field testing. This request also highlighted the problem in including such data within the framework of the existing ENDF-6 file format. This issue will be pursued with the CSWEG community.

The discussion revealed that many users had problems in using the new data in their spectrum adjustment codes due to the lack of data processing tools and difficulty in format conversions. A request was made to also provide the library in a processed form that would be compatible with the commonly used spectrum adjustment codes. The requests included support for LSL, STAYS'L, SAND-II, and text format data. The text format should include full covariance matrices in order to facilitate ease of use with a variety of processing methods. The desire was expressed to have the nuclear data file as well as the cross sections and covariance matrices available in more human-readable format. Volunteers were found to provide conversions of the exiting library into these formats. The community will request that the IAEA post these format conversions on the IRDF-2002 web site so that the whole community could more easily benefit from the data.

II-B. FUSION AND HIGH ENERGY NEUTRONS
Chaired by: L. Greenwood and P. D'hondt

There was only one paper in this symposium directly related to the topic of fusion dosimetry, although irradiations of fusion materials are frequently performed in fission reactors. Techniques for dosimetry in simulated fusion reactor fields are very similar to those employed in fission reactors, with the main difference being the higher energy neutrons near 14 MeV. There was agreement that cross sections are generally not so well known in the 10-13 MeV energy range, as has been noted in cross section evaluations as well as experiments, such as the work with MUSE by M. Plaschy, et al. Some improvement is needed in this energy region to improve the accuracy of fusion dosimetry and radiation damage calculations.

For spallation neutron sources such as the ADS (Accelerator Driven Systems) in Europe or SNS (Spallation Neutron Source) in the US, more accelerator measurements are needed to improve dosimetry cross sections and radiation damage cross sections. In Europe, two programs have been performed for $E > 20$ MeV in the framework of the EC (European Commission), HINDAS and n-TOF programs. The results of these programs will be made available in the JEF files in the future. There were several papers at the conference from the US, all connected with LAMPF or SNS. A paper by F. Gallmeier, et al, discussed the extension of neutronics techniques up to GeV energies. A paper by P. Ferguson, et al, showed the development of radiation damage and gas production cross sections to GeV energies. Such efforts in the United States are somewhat limited at present, since the main application of spallation neutron sources is for cold neutrons for neutron scattering, and the SNS currently has no provision for irradiation of samples close to the target. Neutron experiments conducted close to spallation targets, but not directly in the beam, have neutron spectra that resemble fast reactors with the addition of a high energy tail up to the beam energy. Generally, neutrons above 20 MeV comprise only about 10% of such spectra. However, considerably more work is needed to expand the database of high energy cross sections for dosimetry, radiation damage, and gas production and other transmutation.

There was some discussion of whether there is any information available on gamma production at higher neutron energies and whether such data are needed for spallation or space applications. Some work in this area has been reported at previous symposia; however, the status of this work is not currently known. Space programs are thought to have similar nuclear data needs as for spallation sources regarding higher energy neutrons that may be present from cosmic rays. Much of the charged particle data currently used by spallation neutron sources was originally developed for astrophysical applications.

Finally, there was a discussion of active detectors that can be used at higher energies and whether such detectors could be used in higher temperature applications. F. Ruddy mentioned that SiC detectors are being tested for applications at higher neutron energies.

The workshop was attended by 15 participants.

III-A. ADJUSTMENT METHODS AND UNCERTAINTIES
Chaired by: W. Sallee and T. Serén

The current state of the technology and methodologies were discussed in some detail. Old and new codes were discussed with their liabilities and strengths. There are some promising new methods becoming available (a couple of which were discussed in papers presented at this meeting).

The addition of the IRDF 2002 library is very much appreciated by this community as these data underpin all of the adjustment methodologies.

Several key issues remain for most (not all) users. One is how to address the use of covers. This issue was discussed extensively and two approaches were mentioned on how to handle the uncertainty and covariance data correctly. However, no movement was made toward programmatically treating this persistent problem. Most users still use only simple exponential attenuation. T. Serén mentioned a code he is developing for adding degrees of anisotropy to this simplistic approach. This is currently under test and is only available as a replacement for the LSL-M2 "COVER" auxiliary code. It addresses only the cross section data, not how to adjust the attendant covariance data. The strictly correct procedure would be to model (e.g. with MCNP) the situations with and without covers as different, but highly correlated, neutron fields. This would also address downscatter into resonance energies, which occasionally leads to *higher* reaction rates with covers than without. Some problems related to covers also occur when treating self-shielding effects.

Several suggestions for simplifying the input streams for the various codes were made but not well received. There could be particular benefit in the development of a standard input format. However, it was not as clear what that actually would mean or how that might actually be accomplished.

The other major topic of discussion for the workshop was the issue of uncertainty and covariance information in transport calculations. The right way to do it was discussed, as were several "approximations." M. Plaschy described his use of repeated perturbations to generate uncertainty information. It was also pointed out that covariance matrices are being provided in the IRDF-2002 files for some standard and evaluated fields. These data were deemed better by most of the participants than the currently recommended method of fabricating a matrix when one is not available (e.g. using algorithms recommended in at least two ASTM standards). It would be highly desirable to have covariances available for a much larger collection of different neutron fields than those treated in the LEPRICON system. It was suggested that this topic or a subset that involves perturbation or sensitivity analysis be considered for a tutorial at a future meeting.

The final topic of discussion was correctly collapsing the IDRF 2002 cross sections to a smaller group structure. There appears to be differences between the FLXPRO and X333 processing codes when applied to the same data [specifically $^{58}Fe(n,\gamma)$, see paper A.14 by Serén & Wasastjerna]. The two codes have also been tested for $^{54}Fe(n,p)$ and $^{58}Ni(n,p)$, but in those cases the results agreed well. Obviously there can be pitfalls when using the processing codes as "black boxes" without further checking. The largest discrepancies between the two codes have been traced to incorrect use of keywords in FLXPRO (*I, *D and *P for integral, differential and point spectra, *I being the default). However, subtle differences still remain, possibly traceable to the use of single precision in the codes.

III-B. RADIATION DAMAGE CORRELATIONS
Chaired by: L. K. Mansur and D. A. Thornton

The workshop was attended by 23 participants who engaged in a lively and wide-ranging discussion on damage radiation effects and the correlation against exposure parameters. A brief introduction, given by Lou Mansur, proposed the objectives of the workshop and gave initial points to help focus the discussion. The participants introduced themselves and stated their interests, which included damage modeling and correlation, gamma radiation induced damage, electronic materials, determination of life-time exposure, computation transport calculations, reactor internals and prediction of life-limiting effects, and fission/fusion and spallation related applications.

The discussion began by considering the circumstances in which gamma radiation induced displacements might give rise to significant levels of damage. Lou Mansur reviewed the experience from HFIR in which a ratio of hard gamma radiation fluence to fast neutron fluence of order 10^4 was required for gamma induced damage to dominate the production of atomic displacements. Analyses describing the physical bases of this determination are described in reference [1]. As a corollary to this, analysts should begin to consider gamma radiation effects at hard gamma to fast neutron fluence ratios of order 10^2. Larry Greenwood cited work by Baumann on displacement cross-sections of gamma rays [2] and noted that the NRC had commissioned a study on the significance of gamma radiation induced damage in other reactors. It had concluded that displacements produced by gamma rays would not be significant in current LWR designs.

The discussion moved on to consider damage mechanisms within electrical and electronic materials. It was noted that the fluence ranges relevant to these effects are very much less than those considered in the assessment of structural materials. It is necessary to take account of ionization/excitation both by neutrons and gamma radiation in addition to displacement damage. Dean Thornton drew an analogy with graphite in which irradiation induces both corrosion, via ionization, and dimensional changes, via neutron damage. It was queried whether there is any prospect for the development of a coherent unified approach to correlation of these effects against ionization and displacement damage. Although special circumstances exist where this may be achieved, any broad based approach would prove very challenging.

Alain Alberman raised the question of new materials for Generation IV reactors. Such materials may include ceramics and metallic alloys for high temperature performance. It was agreed that it would be necessary to address the effects of ionization damage in ceramic materials, in addition to displacement damage.

Larry Greenwood reminded the participants that transmutation reactions induced by thermal neutrons should not be overlooked. Lou Mansur drew a parallel with the formation of transmutation products caused by high energy protons in the spallation targets of high energy proton accelerators. In both cases transmutation production can be substantially higher than what is typical for fast reactor neutrons.

Roger Stoller confirmed that there is now significant evidence for the existence of dose rate effects in pressure vessel steel embrittlement, and that analysts should take them into account. However, the magnitude of the effects is sometimes small if the dose rate range is not very large and may be influenced by the accumulated damage. An example of such a property is swelling, which is important to reactor internals. This property shows a clear dose rate effect where the temperature range at which maximum swelling occurs (for a given exposure) tends to shift depending on dose rate.

Displacement, gas production, and other transmutation cross-sections have been developed to the range of GeV for protons and neutrons, partially from measured cross-sections at low energies and calculated cross-sections at high energies. However, for spallation sources, it was felt that this range is only of primary importance for the target and that beyond the target, damage cross-sections below 20 MeV are more relevant.

At previous symposia, workshop participants have discussed the results of French experiments to determine most appropriate parameters for neutron exposure [3]. These have shown that use of dpa did not improve upon the correlation against fluence $>$1MeV. Participants continued to express surprise at this outcome. The potential role of thermal and epi-thermal neutron induced displacements within these experiments was discussed.

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