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INTERNATIONAL NUCLEAR DATA COMMITTEE

IAEA Consultants' Meeting on Integral Cross-Section Measurements in Standard Neutron Fields

Vienna, 15 - 19 November 1976

SUMMARY REPORT

Conclusions and Recommendations

Edited by M.F. Vlasov
Nuclear Data Section
International Atomic Energy Agency

March 1977

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FOREWORD

This document contains the summary report of the Consultants Meeting on Integral Cross Section Measurements in Standard Neutron Fields for Reactor Dosimetry, convened by the IAEA Nuclear Data Section in Vienna, 15-19 November 1976.

The meeting constitutes one step of the IAEA Programme on Benchmark Neutron Fields Applications for Reactor Dosimetry, described in INDC(SEC)-54/L+Dos, published in July 1976.

The need for application of benchmark neutron fields, particularly for validation and improvement of neutron data required for reactor dosimetry, was recognized by the IAEA Consultants Meeting on Nuclear Data for Reactor Neutron Dosimetry, September 1973 [INDC(NDS)-56/U], and supported by the Agency's Working Group on Reactor Radiation Measurements and International Nuclear Data Committee.

The importance and usefulness of this approach was well demonstrated by the US Interlaboratory LMFBR Reaction Rate (ILRR) programme [Nuclear Technology 25, no. 2, Feb. 1975]

The main results of the meeting are as follows:

- a comprehensive survey of benchmark neutron fields available at present for reactor dosimetry applications and their classification in three categories;
- review of the methods used at present for spectral characterization of neutron fields: direct spectrometry, activation, analytical calculations, and of results obtained with these methods;
- review of the present status of integral and differential neutron cross-section data for reactor dosimetry and new classification of the reactions in two categories;
- discussion of methodology for validation and adjustment of differential neutron data on the basis of integral data;
- better understanding has been reached between scientists working in the fields of integral and differential data measurements.

The Proceedings of the Meeting will be issued as an IAEA Technical Report in June 1977.

I. INTRODUCTION AND OVERVIEW

1. Importance of Neutron Dosimetry - The importance of well-understood, firmly established and standardized neutron dosimetry methods has become more evident since the IAEA Consultants' Meeting on Nuclear Data for Reactor Neutron Dosimetry (Vienna, 10 - 12 September 1973)*. The interest in dosimetry for fast reactor applications, which was already substantial, appears to have further increased; a growing realization of the importance of dosimetry is obvious for reactor vessel surveillance and for other safety-related applications. More requirements for more accurate dosimetry come from several issues connected with the fuel cycle. Dosimetry is an essential part of the various shielding problems which are receiving general attention for all types of reactors and which have given rise to a programme of coordinated evaluation and benchmark experiments (also promoted by the I.A.E.A.)** which is parallel to, and has many interfaces with, the present dosimetry benchmark programme. Controlled thermonuclear applications call for exacting dosimetry measurements in order to investigate crucial material problems; interpretation of actual or projected damage measurements and extrapolation to fusion reactor environments rely heavily upon dosimetry to correlate effects in very different neutron spectra.

2. Status of Dosimetry Data - Some substantial improvements in neutron cross-sections and other dosimetry data have been achieved since the 1973 Consultants Meeting. However, the situation remains far from satisfactory: important gaps and discrepancies are still present, and new ones have been identified, so that a continuation of the dosimetry benchmark programme appears fully justified.

3. Consistency - The importance of arriving at a consistent cross-section set for the validation of reactor physics calculations and for spectrum unfolding is enhanced by the opportunity of putting together information derived from various sources when expensive experiments are involved, such as for instance in material irradiation programmes. This necessity was identified, among others, by the recent IAEA Specialists' Meeting on Radiation Damage Units (Harwell, 2 - 3 November 1976).

* further referred to as 1973 Consultants' Meeting.

** see for example Proceedings of Techn. Committee Meeting on Differential and Integral Nuclear Data Requirements for Shielding Calculations, Vienna, 10-15 October 1976, to be published as IAEA Technical Report.

4. International Cooperation - International cooperation, both on the basis of bi-lateral or multi-lateral programmes, and through international organizations, has been effective in this first period of implementation of the recommendations of the 1973 Consultants' Meeting. For instance, the Euratom Working Group on Reactor Dosimetry has entirely adopted these recommendations and worked for their implementation; the programme has been extensively reviewed at the First ASTM-Euratom Symposium on Reactor Dosimetry (Petten, September 1975). Coordinated programmes of measurements and evaluations on benchmark neutron spectra have involved the N.B.S.*/, the P.T.B.**, the Imperial College,*** CEN/SCK+ Mol, the Romanian ITN++ and the US laboratories involved in the ILRR+++ programme. It is important that this kind of international cooperation be continued and extended in the future, and that it involves exchange of information, data, codes, detectors, instruments and personnel so as to improve the quality and the reliability of the experiments and of their evaluation.

5. Purpose of Benchmark Experiments - Dosimetry benchmark neutron fields serve three general objectives, which had already been identified at the time of the 1973 Consultants' Meeting:

a) validation and/or calibration of experimental techniques;

b) validation and/or improvement of cross sections and other nuclear data needed for proper application of experimental techniques;

c) validation and/or improvement of analytical methods needed to extrapolate dosimetry data from a monitoring or surveillance position to the location of interest.

Although all of these objectives are important, the present programme is particularly focused on the second.

The way in which the benchmark programme may be instrumental in reaching these aims has been further investigated and will be discussed later.

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*** Imperial College of London University
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++ Institute for Nuclear Technology, Bucharest
+++ Interlaboratory LMFBR Reaction Rate Programme.

6. Reference Set of Cross-Sections - The ENDF/B-IV Dosimetry File has been made generally available, as recommended at the 1973 Consultants Meeting. This has proved very valuable in providing one reference set of cross sections that has made the intercomparison of results and predictions possible on a unified data basis. This library has in fact been extensively used throughout the world for the analysis of dosimetry experiments. It is hoped that this will in turn produce a valuable feedback of information to the ENDF/B evaluators in terms of data testing and indications for future improvements.

The aim of arriving at a generally accepted, internally consistent and extended dosimetry data file based on the ENDF/B specifications remains one of the fundamental objectives of this programme.

7. Cross-Section and Spectrum Processing - Even when the data base is common, some differences can be introduced by the method which is used to collapse or interpolate the data to a given group structure in order to use them in unfolding procedures or to calculate reaction rates. Although these uncertainties are less important for reaction cross sections than in other cases (particularly in the procedure of calculating the flux density spectrum itself) it is recommended that the cross-section processing method which is used be clearly specified when reporting results; in particular, if a weighting spectrum has been employed, it should be explicitly indicated.

8. Accuracies required - The target accuracies for dosimetry methods depend on the accuracies required for the integral quantities of final interest (such as radiation damage, activations, fuel burn-up etc). In most applications these last accuracies typically range from 5 to 20% (1σ)*. In some cases, required accuracies have recently been re-evaluated to more stringent specifications, partly also as a consequence of improved understanding of the damage functions. These requirements are reflected in target accuracies to be set for flux-fluence-spectral determination for the three categories of benchmark fields (see point II-1), depending on their intended use (a, b or c of point 5.). At the 1975 Petten Symposium, these accuracy requirements were stated to be in the $\pm$ 2 to 5% (1σ) range for LMFBR and somewhat less stringent for LWR and CTR applications.

(*) σ here stands for a standard deviation resulting from a combination of random and systematic uncertainties (uncertainties of corrections) assuming these have been assessed or estimated accordingly.

Present state-of-the-art accuracies are estimated to be in the range of ± 2 to 30% (1σ), depending on the particular spectral parameter and benchmark category. Although the ± 2 to 5% (1σ) goal objective may be considered ambitious for some applications, it is nevertheless reasonable. It is likely that, at least on the long term, most reactor fuels and materials development programmes will not accept an uncertainty greater than ± 5% (1σ). In order to achieve such an accuracy routinely, however, it is necessary to work towards a better level of accuracy, namely 2 to 5%.

9. Sensitivity Studies - The importance of sensitivity studies to correlate the target accuracies for the benchmark experiments with the accuracies required for the integral quantities of final interest had been identified at the 1973 Consultants' Meeting; however, very few investigations of this type have been reported since. All the theoretical and calculational tools to perform such a sensitivity analysis now appear to be available, and the importance of comprehensive and possibly intercompared sensitivity calculations for dosimetry is re-iterated. Notice has been taken of the extensive sensitivity calculations which are being carried out in the frame of the shielding benchmark programme.

10. Implementation - Important as it is to develop better dosimetry methods and to improve the accuracy of those presently available, one should bear in mind that this is of little value if it is not accompanied by a timely application of what is already available for the solution of everyday problems. It is a fact that nuclear programmes often do not make full use of already well-established and reliable dosimetry methods, but still employ or rely upon old methods and data that introduce appreciable uncertainties and consequent economic penalties. An important effort should be made towards the end of making all the interested people aware of the possibilities and advantages offered by the best dosimetry methods and data now available and by international cooperation in this non-proprietary field. Progress in this regard is being furthered by a series of ASTM-Euratom International Symposia on Reactor Dosimetry, the first one of which was held in Petten, September 22-26, 1975, and a second one is being planned for 3-7 October 1977 in the USA.

11. <u>Interactions with other IAEA programmes</u> - Both the development and the implementation of the recommended dosimetry benchmark programme would benefit from increased interactions with other IAEA programmes, in addition to those directly sponsored by the Nuclear Data Section. In particular:

a) Cooperation with the IAEA-NEA-EURATOM sponsored shielding benchmark programme. It would be desirable that the dosimetry used in that programme were based on the present recommendations, and conversely that the dosimetry programme could use the results of the shielding benchmark experiments and of the sensitivity calculations.

b) Increased cooperation with the IAEA's Research Programme on Irradiation Embrittlement of Pressure Vessel Steels is desirable. The excellent work in this programme would benefit from improved dosimetry techniques.

c) There is naturally a close connection between the Dosimetry Benchmark Programme and some of the activities sponsored by the International Working Group on Reactor Radiation Measurements, such as the recommendations on radiation damage units and the intercomparison of unfolding codes.

d) The IAEA Programme on Intercomparison of Peak Analysis for Ge(Li) Detectors is interesting for dosimetry methods.

e) Prospective users of dosimetry methods should be informed of the views expressed by this Consultants' Meeting and asked for their comments, which could help for a better orientation of future dosimetry activities. These users are represented, among others, by the International Working Group on Fast Reactors, by the International Fusion Research Council, the International Working Group on Reactor Radiation Measurements and other appropriate committees.

II. DEFINITION OF BENCHMARK NEUTRON FIELDS

1. Categories of benchmark neutron fields - The rather broad and open definition of dosimetry benchmarks given at the 1973 Consultants' Meeting has been more exactly qualified. Three types of benchmark neutron fields for reactor dosimetry have now been identified and defined as follows:

   Standard: a permanent and reproducible neutron field with neutron flux intensity, energy spectra and angular flux distributions characterized to state-of-the-art accuracy. The main characterizations must be verified by interlaboratory measurements and calculations.

   Reference: a permanent and reproducible neutron field, less well characterized than a standard but accepted as a measurement reference by a community of users.

   Controlled Environment: a neutron field, physically well-defined and with some spectrum definition, employed for a restricted set of validation experiments.

2. Standard fields -At the moment, in some of the most important standard fields, discrepancies still appear to be present in the reaction rate measurements for some of the best known dosimetry reactions. The list of standard fields has therefore been limited to those contained in Table 1. It is considered important that more fields be added to the list; in particular it is recommended that an important effort of better qualification and of reaching consistency with reaction rate measurements be done on the short term at least for the 235-U fission spectrum, the $\Sigma\Sigma$-type facilities and the ISNF.

3. Reference fields - The reference fields identified on the basis of presently available information are listed in Table 2. This list should be periodically updated as new information becomes available. In particular it is hoped that neutron fields covering the high energy region of importance for Controlled Thermonuclear Reactors (CTR) and other radiation damage work, based on harder-than-fission spectra, should qualify for this category of benchmarks.

TABLE 1. STANDARD NEUTRON FIELDS FOR REACTOR DOSIMETRY

Neutron Field	Average Energy	Energy Range for Data Testing	Status of Group-Flux Spectrum Characterization
Thermal Maxwellian	0.025 eV	< 0.4 eV	± 2-5% theory of thermal equilibrium, and spectrometry
Epithermal-1/E	0.75 MeV	0.4 eV to 0.1 MeV	
^{252}Cf spontaneous fission	2.13 MeV	0.1 to ∿ 18 MeV	± 13%, E < 0.25 MeV; ± 2%, 0.25 < E < 8 MeV; ± 9%, 8 < E < 12 MeV *differential spectrometry ± 10%, 12 < E < 15 MeV, multiple foils

*The NBS recommended spectrum shape based on an evaluation of differential spectrometry results reported up to 1974 is recognized as an acceptable spectrum description for practical applications. See paper by Grundl and Eisenhauer, this meeting.

TABLE 2. REFERENCE NEUTRON FIELDS FOR REACTOR DOSIMETRY

Neutron Field *	Av. Energy (MeV)	Energy Range for Data Testing and Calibration (MeV)	Status of Group Flux Spectrum Characterization
^{235}U thermal fission	1.97	0.1 to ∿ 18	± 15%, E < 0.25 MeV (differential spectrometry) ± 2-5%, 0.25 < E < 8 MeV (differential spectrometry) ± 5%, 8 < E < 12 MeV (differential spectrometry) ± 10%, 12 < E < 15 MeV, multiple foil
Sigma Sigma (ΣΣ)	0.76	0.01 to ∿ 18	± 15%, E < 0.1 keV, multiple foil ± 5%, 0.1 keV < E < 2 MeV, spectrometry and computation ± 5%, E > 2 MeV, multiple foil
ISNF	0.80	0.008 to ∿ 18	± 5%, E < ∿ 2 MeV, computation ± 2-5%, 2 < E < 12 MeV, computation and spectrometry (fission spectrum)
BIG TEN **	0.58	0.01 to ∿ 18	± 5%, 0.05 < E < 2 MeV, computation and spectrometry ± 5%, E > 2 MeV, multiple foil and computation
CFRMF **	0.76	0.01 to ∿18	± 15% (E < 0.01 MeV) Multiple foils and computations; ± 5% (0.01 MeV < E < 2) Spectrometry and computations; ± 5-10% (E > 2 MeV) Multiple foils and computations.

* References or reference information for these neutron fields are given in the various individual papers presented at this meeting. Particular reference is made to the papers by Grundl et al. and McElroy et al.

** Central core position.

TABLE 2. REFERENCE NEUTRON FIELDS FOR REACTOR DOSIMETRY
(continued)

Neutron Field	Av. Energy (Mev)	Energy Range for Data Testing and Calibration (MeV)	Status of Group Flux Spectrum Characterization
APFA-III **	1.5	0.01 to 18	± 5-20% (0.01 MeV < E < 10 MeV) Spectrometry and computations; ± 5-20% (0.01 MeV < E < 18 MeV) Multiple foils and computations
TAPIRO **	1.5	0.01 to 18	± 5-20% (0.01 MeV < E < 10 MeV) Spectrometry and computations ; ± 5-20% (0.01 MeV < E < 18 MeV) Multiple foils and computations.
YAYOI **	1.5	0.01 to 18	± 5-20% (0.01 MeV < E < 10 MeV) Spectrometry and computations; ± 5-20 (0.01 MeV < E < 18 MeV) Multiple foils and computations.
YAYOI (Lead intermediate column)	1.5	10^{-7} to 2	± 5-20%, spectrometry, multiple foils, computations
Borated Graphite with Electron Linac (1/E spectrum in keV region) Japanese Facility.		10^{-6} to 10	± 5 - 10%, time-of-flight and computations.
Fe BLOCK (shielding benchmark)		0.01 to 1	± 10% or better, Spectrometry, multiple foils, several interlaboratory calculations and measurements.
Na BLOCK (shielding benchmark)		10^{-6} to 5	± 10% or better, Spectrometry, multiple foils, several interlaboratory calculations and measurements.

** Central core position

TABLE 2. REFERENCE NEUTRON FIELDS FOR REACTOR DOSIMETRY
(continued)

Neutron Field	Av. Energy (MeV)	Energy Range for Data Testing and Calibration (MeV)	Status of Group Flux Spectrum Characterization
ANL-Tandem $^{9}Be(d,n)$ reaction		Tailored distributions with mean energies: ∿1, ∿2, ∿3, up to ∿8 MeV.	$> \pm$ 10–30% (0.1 MeV $< E <$ 18 MeV) Spectrometry and theory; $> \pm$ 10–30% (0.1 MeV $< E <$ 18 MeV) Multiple foils and theory.
UC-Davis Cyclotron $^{9}Be(d,n)^{10}B$		Tailored distributions with mean energies, as above, up to ∿15 MeV.	$> \pm$ 10–30% (0.1 MeV $< E <$ 30 MeV) Spectrometry and theory; $> \pm$ 10–30% (0.1 MeV $< E <$ 30 MeV) Multiple foils and theory.

4. Controlled environments - A preliminary and incomplete list of controlled environments can be found in Table 3. These fields can play an important role in dosimetry applications, and a better characterization and fuller documentation should be encouraged.

5. Survey of benchmark fields - An international survey has been initiated to compile information on existing and proposed neutron fields that may qualify as dosimetry benchmarks. This survey has been based on the wide distribution of an extensive questionnaire covering all the relevant characteristics of the fields. It is recommended that full answers are promptly provided to the questionnaire by all those who have not yet done so. Physical description that allows interlaboratory calculation of the benchmarks should be supplied , as well as spectra in tabular or analytical form, and a suggested interpolation procedure.

6. Compendium - The answers so far received to the questionnaire have been compiled in a first compendium that is part of Grundl's and Eisenhauer's paper, this meeting.

TABLE 3 *) CONTROLLED-ENVIRONMENT BENCHMARKS FOR DOSIMETRY DATA DEVELOPMENT AND TESTING

Benchmark	Approximate Major Data Testing Energy Range (MeV)	Status of Group Flux Spectral Characterization
<u>Thermal Type</u>		
a) HFIR	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
b) BSR	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
c) BR2-Cd Loops	4×10^{-7} to 18	±5 to 30%, Multiple-foils and computations.
d) HFR	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
e) KUR	10^{-10} to 18	± 5 to 30 %, Multiple foils, ^{6}Li and ^{3}He Sandwich counters, and computations.
f) Etc.		

* From the report by McElroy et al. this meeting. Some references or reference information for these neutron fields are also given in the various individual papers presented at this meeting.

TABLE 3 (Continued)

Benchmark	Approximate Major Data Testing Energy Range (MeV)	Status of Group Flux Spectral Characterization
LWR-Surveillance		
a) ILR-PV Mockup	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
b) Japanese-PV Mockup	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
c) Browns Ferry* #3 (BWR)	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
d) McQuire 1* (PWR)	10^{-10} to 18	±5 to 30%, Spectrometry and multiple-foils, computations.
e) BR3 (PWR)*	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
f) ORR-PV Mockup*	10^{-10} to 18	±5 to 30%, Spectrometry and multiple-foils, computations.
g) Etc.		

* Planned measurements, computations, and/or spectrometry.

TABLE 3 (Continued)

Benchmark	Approximate Major Data Testing Energy Range (MeV)	Status of Group Flux Spectral Characterization
FAST Reactor Type		
a) ECEL Core 14-13	$\sim 10^{-6}$ to 18	±5 to 30%, Spectrometry, computations, and multiple-foils.
b) ECEL Core 16	$\sim 10^{-6}$ to 18	±5 to 30%, Spectrometry, computations, and multiple-foils.
c) EMC-FTR	$\sim 10^{-6}$ to 18	±5 to 30%, Spectrometry, computations, and multiple-foils.
d) EBR-II 31F Run	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
e) EBR-II 50H Run	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
f) EBR-II 75D Run	10^{-10} to 18	±5 to 30%, Multiple-foils and computations.
g) FTR-IRT*	10^{-10} to 18	±5 to 10%, Spectrometry, computations, and multiple-foils.
h) VIPER	10^{-4} to 10	±5 to 15%, Spectrometry, compilations and multiple foils.
i) STEK Cores	$\sim 10^{-6}$ to 18	±5 to 30%, " " "
j) etc.		

* Planned tests in a cooled in-reactor-thimble (IRT) in the Fast Test Reactor central core region.

TABLE 3 (Continued)

Benchmark	Approximate Major Data Testing Energy Range (MeV)	Status of Group Flux Spectral Characterization
<u>CTR Type</u>		
a) HENRE- $^{3}H(d,n)^{4}He$	10^{-2} to 16	±5 to 30%, Spectrometry, computations, and multiple-foils.
b) RTNS $^{3}H(d,n)^{4}He$	10^{-2} to 16	±5 to 30%, Spectrometry, computations, and multiple-foils.
c) CTR BLANKET MODEL LOCATIONS (D-T Reaction)	10^{-4} to 16	$\geq \pm$ 5 to 30%, Computations and multiple-foils.
d) etc.		

III. DETERMINATION OF NEUTRON FLUX-SPECTRA

A. Summary

Comments and Conclusions:

1. A major conclusion from recent and current data testing work is that spectrum averaged cross section data for dosimetry reactions as measured in standard and reference benchmark neutron fields depart from computed ones, not only because of absolute total flux level normalization and evaluated energy-dependent cross section inadequacies, but also because the spectra of most of these benchmarks are often inaccurate in the energy ranges not covered or poorly covered by differential neutron spectrometry techniques.

2. While the most precise determination of the spectral shape for some standard and reference fields will be accomplished by spectrometry and computations, in other cases, a combination of calculations, neutron differential spectrometry, and integral measurements will be required. For the standard and reference benchmark fields identified in the papers of this conference, Tables 1 and 2 , the total flux value and broad energy group spectral shape uncertainties for the more important energy regions are currently estimated to be in the $\pm$ 2 to 5% (1σ) and $\pm$ 4 to 15% (1σ) range, respectively. For a number of important controlled environments, Table 3, the uncertainties are considerably greater, in the $\pm$ 5 to 15% (1σ) and $\pm$ 5 to 30% (1σ) and higher ranges, respectively.

3. In considering the resolution of the problems and the achievement of higher accuracies, item 1 and 2 above, the following conclusions and/or recommendations are offered.

   a) **Flux-level Normalization**

   In addition to the documentation and reporting of the experimenters' own absolute value of total flux, a value should be established through a flux transfer from a Cf-252 neutron source*/.

*/ see paper by Grundl and Eisenhauer, presented at this meeting.

This flux transfer or normalization, using the ^{239}Pu (n,f) reaction, is rather direct and its accuracy is of the order of ± 2% (1σ) or better for certain classes of benchmark fields. If a reaction other than ^{239}Pu (n,f) is used, the uncertainty will be somewhat higher.

b) Spectrum Shape Determination

No single differential spectrometry method allows the determination of the entire spectrum shape to the goal accuracy of ± 5 to 10% (1 σ), or better. The (n,p), ^{6}Li (n,α)T and ^{3}He(n,p)T spectrometers have attained a stage of development that allows spectral measurements in the range of 10 keV to ~ 6 MeV, to approach the above goal accuracy. This accuracy can be obtained, however, only if the results of several experimenters and measurement techniques are combined.

Except for a few standard and reference neutron fields (such as thermal, 1/E, and the Intermediate-energy Standard Neutron Field (ISNF), no calculational method allows the determination of the spectrum shape to the goal accuracy of ± 5 to 10% (1 σ), or better.

The required level of accuracy for spectral shape determination in some benchmark fields will necessitate the combined use of data obtained from differential spectrometry, analytical calculations, and integral measurements. The development of new and/or improved unfolding codes to handle and combine simultaneously the results of these three techniques is desired. The success of such techniques, however, will depend on the availability of data and analytical methods for handling errors and their correlations, not only on the cross section data files, but also on the spectrometry and reaction rate data.

In the range above approximately 2 MeV, new spectrometry measurements by independent and/or new techniques are needed, such as nuclear emulsions, track recorders, ^{4}He recoil spectrometry, and organic proton recoil scintillators wherever applicable.

Recommendations: It is recommended that available codes that will handle the combined results of calculations, spectrometry, and integral measurements be applied to the simultaneous analysis of the data obtained in the best known benchmark fields.

B. Analytical Calculations

Comments and Conclusions:

1. Uncertainties in analytical computations are of two general types:

   a) Nuclear Data

   Errors related to uncertainties in the cross sections, fission spectra and angular distributions of neutrons for the materials in the system.

   b) Modeling

   Errors arising from the approximations necessary to perform the computations, including geometrical representation, multi-group energy structure and material changes due to burnup, etc.

   Uncertainties in the nuclear data can be quantified, but this has not been generally done and constitutes a major undertaking. Modeling approximations can be estimated by parametric studies.

2. One-dimensional geometries studied with fine energy group structures and high order expansions are the only ones, in practice, for which precise calculations are available. In such instances, the accuracy of the spectral determination is limited by the accuracy of the nuclear data.

3. Very often, systems with complicated geometries are analyzed with low-dimensional and/or synthesis techniques. In such cases, geometrical approximations are responsible for additional uncertainties.

4. Perturbation of nuclear data used in transport calculations to provide consistency, in a maximum likelihood sense, with reaction rate data can be identified as a potentially powerful method which can be applied in a few important cases (see McCracken's paper at this meeting).

Recommendations

1. It is recommended that sensitivity analyses be performed for dosimetry standard and reference neutron fields, and in some cases controlled environments. An effort to extend the ENDF/B cross section error file to dosimetry data and associated sensitivity codes should be undertaken.

2. For systems where modeling errors are significant, the generation of spatial importance functions should be considered in order to provide insight into ways of reducing the number of compromises made in the calculations.

3. The use of calculated flux spectra, either by themselves or in combination with experimental results, in data testing can only be recommended in cases where errors have been estimated by means of careful sensitivity studies. Such methods as ANISN-SWANLAKE are now widely available and should be generally used for calculations for the standard and reference fields.

C. Spectrometry Measurements

Comments and Conclusions:

1. Substantial progress has been made during the last few years in the characterization of the standard fission neutron spectra of ^{235}U and ^{252}Cf using differential methods.

The recent evaluation of J. Grundl et al. gave average fission neutron energies of 1.970 ± 0.014 MeV and 2.130 ± 0.027 MeV for the ^{235}U and ^{252}Cf fission neutron spectra, respectively. The average departure of the experimental spectrometry data from a reference Maxwellian is less than 5% in the energy range from 0.25 to 8 MeV. Due to necessary corrections for secondary interactions of fission neutrons in the ^{235}U target samples, the ^{235}U fission neutron spectrum appears to be somewhat harder (2.017 ± 0.015 MeV) compared to the recently evaluated value.

Whether the slopes of the spectra are better described by a Maxwellian or Watt function can finally be determined only on the basis of an evaluation which considers not only the statistical errors but also contributions due to uncertainties in backgrounds, detector efficiency, energy resolution, secondary processes in the samples, etc.

The largest uncertainties in the knowledge of the fission neutron spectra still exist in their low and high energy ends, which contain about 6% of the total neutrons. In certain cases, however, these energy tails are of importance and therefore their knowledge should be improved.

2. The neutron spectrum is one of the most important characteristics of a benchmark neutron field. Its determination should be unique, i.e. only subject to changes in the material and physical characteristics of the field. The closest approach to this ideal situation is actually given by differential neutron spectrometry where the derived spectrum characteristics, generally, depend only upon a single well-known cross section. The applicable energy range, resolution, and estimated accuracy of a number of spectrosoopy methods are given in Table 4.

3. For neutron spectrometry in some fast neutron spectrum fields, a ^{3}He proportional counter and a double scintillator time-of-flight method are also applicable (see paper by SEKIGUCHI et al. at this meeting).

   a) ^{3}He proportional counter $\sim$10% 0.1 - $\sim$2 MeV

   b) double scintillator time-of-flight method: $\sim$10% $5x10^{-2}$ - $\sim$10MeV

Table 4: Comparison of Selected Differential Reactor Neutron Spectroscopy Methods.

Method	E_L [a)]	E_u [b)]	Resolution	Accuracy % (1σ) [c]
1. (n,p) Emulsions				
- Collimated Source	5×10^{-1}	20	Fair	5 - 10% $0.5 < E < 10$ MeV 10 - 20% $10 < E < 20$ MeV
- Non-Collimated Source	5×10^{-1}	10		10 - 15% $0.5 < E < 3$ MeV 15 - 25% $3 < E < 10$ MeV
2. (n,p) Proportional Counters	1×10^{-3}	2.5	Good	10 - 50% $0.001 < E < 0.02$ MeV 5 - 10% $0.02 < E < 1.0$ MeV 10 - 25% $1.0 < E < 2.5$ MeV
3. $^6Li(n,t)\,^4He$ [d]	1×10^{-2}	6.5	Fair	5 - 10% $0.01 < E < 0.15$ MeV 10 - 20% $0.15 < E < 0.3$ MeV 5 - 10% $0.3 < E < 0.8$ MeV 5 - 15% $0.8 < E < 4.0$ MeV 15 - 25% $4.0 < E < 10.0$ MeV
4. Time-of-flight (TOF)				10 - 15% $0.00001 < E < 0.001$ MeV
- $^3H(d,n)^4He$ Source	5×10^{-5}	0.2	Good	15 - 20% $0.001 < E < 0.02$ MeV 20 - 30% $0.02 < E < 0.2$ MeV
- LINAC Source	10^{-9}	10	Good	5 % $10^{-9} < E < 10^{-3}$ MeV 10 - 20% $10^{-3} < E < 1$ MeV 20 % $1 < E < 5$ MeV

a) Approximate lower energy limit of applicability, MeV.

b) Approximate upper energy limit of applicability, MeV.

c) Typical accuracies for coarse group structures.

d) The current accuracy of $^6Li\,(n,t)^4He$ spectroscopy is mainly dominated by the uncertainty in the angular and total reaction cross sections.

4. For the establishment of clean Maxwellian standard thermal neutron fields, it is desirable to measure the thermal neutron spectrum by a chopper time-of-flight method. The superiority of using heavy water as a moderator for a thermal neutron facility compared with a crystalline material such as graphite is shown by the chopper measurements of Kanda et al., reported at this meeting

Recommendations

1. In-core neutron spectrometry is complex and expensive. Experimental planning of neutron spectrum measurements should at least consider two independent techniques.

2. The experimental spectral data, the cross sections and response functions used and the nuclear characteristics of the benchmark field in which the measurement was performed, should be available upon request.

3. Experimental differential spectral results in the benchmark fields must be intercompared and the spectrum reevaluated by taking into account the latest reliable results.

4. Differential neutron spectrometry data should be introduced into unfolding codes as are the integral data.

5. (n,p) spectrometry: Nuclear emulsions should be used in benchmark fields.

6. Techniques covering the higher MeV region ($\sim$2 to 50 MeV) must be further developed, especially keeping in mind the needs of CTR reactor development programs.

7. ^{6}Li (n,α)T spectrometry: cross section improvement is needed for
   a) σ (n,α) for En $>$5 MeV, and
   b) $\frac{d\sigma}{d\Omega}$ for En $<$100 keV.

8. In order to intercalibrate methods of neutron spectrometry, it would be helpful if IAEA would promote some international intercomparisons. (IAEA might supply some transfer instruments with established unfolding techniques, as the Bureau International des Poids et Measures (BIPM) does for the international intercalibration of fast neutron fluence).

D. Integral Measurements

Comments and conclusions:

1. Since 1973 the importance of intercomparing neutron spectrum unfolding programs has been emphasized by experts at the first ASTM-Euratom Symposium on Reactor Dosimetry and by members of the International Working Group on Reactor Radiation Measurements.

2. It is recognized that some activities in this field are initiated and supported by the IAEA. Valuable information on general unfolding techniques is now available in the Proceedings of a Seminar Workshop on Radiation Energy Spectra Unfolding, held at Oak Ridge, April 1976 (see report ORNL/RSIC-40).

3. At the present meeting further results of intercomparison studies have been reported (see contribution by Zijp). Also some new approaches on simultaneous unfolding of data from different spectrometry techniques have been communicated (see contribution by MacCracken, Najzer, Williams and Hannan.)

Recommendations

1. The merits of some promising unfolding codes like SAND-II, RFSP-JUL and CRYSTAL BALL should be studied further.
The IAEA is requested to make these programs available to interested laboratories upon request.

2. For more specific recommendations on unfolding, reference is made to the results of a workshop on unfolding at the First ASTM-Euratom Symposium on Reactor Dosimetry at Petten, September 1975.

3. When in practical dosimetry applications, in the absence of spectrum information, the concept of equivalent fission neutron fluence is used, one should apply those values of average fission neutron cross sections which result from integral experiments in a ^{235}U fission neutron spectrum (see paper by Fabry et al., Session III).

E. Cross-Section and Spectrum Processing

Comments and Conclusions:

Even when the data base is common, some differences can be introduced by the method which is used to collapse or interpolate the data to a given group structure in order to use them in unfolding procedures or to calculate reaction rates. For measured spectral data even the adoption of a common group structure is questionable: the most adequate group widths and boundaries being dependent on such parameters as experimental resolution, bin width and on the spectrum itself.

Recommendations:

1. When spectral data are given it would be highly advisable to specify the interpolation scheme or to agree on a common one. Attention should also be paid to error propagation.

2. It is recommended that the cross-section processing method which is used be clearly specified when reporting results. In particular, if a weighting spectrum has been employed, it should be explicitly indicated.

IV. INTEGRAL MEASUREMENTS IN BENCHMARK NEUTRON FIELDS

A. Comments and Conclusions:

1. The data development and testing approach first applied to the development of the SAND-II cross section file, and subsequently recommended by the 1973 Consultants' Meeting has been further validated for establishing accepted reference sets of evaluated energy-dependent cross sections for dosimetry applications.

2. Using the above approach, some specific recommendations for further study of reactions in the ENDF/B-IV file have been delineated. (See paper by A. Fabry et al., Session III.)

3. A few sustained inconsistencies still exist and a vigorous and well-planned, coordinated international interlaboratory effort will be required to resolve them. More specific information is provided in the paper by Fabry et al., this meeting, Session III.

B. Recommendations

1. Reaction rate measurements form the backbone of reactor neutron dosimetry. Such measurements must be done with accuracies in the 2-5% (1σ) range, depending on the reaction. Past evidence suggests that systematic errors are best identified and minimized through interlaboratory comparisons, preferably involving independent techniques. It is thus recommended that such inter-comparisons continue to be done on as large a basis as possible and be considered mandatory in the case of fundamental reaction rate measurements in standard and reference radiation fields; this requirement may be somewhat relaxed in the study of controlled environments. It is, however, essential that careful documentation of the measurements be provided by the experimenters.

2. Discrepancies up to 10% exist between absolute average cross section measurements in the U-235 fission neutron spectrum. In order to investigate these discrepancies, an interlaboratory experiment is being organized under the sponsorship of the IAEA; it involves the transfer of a fission spectrum assembly and of irradiated detectors */ between Mol (Belgium), Osaka (Japan), the Seibersdorf Laboratory (Austria) and laboratories participating in the US Interlaboratory LMFBR Reaction Rate (ILRR) program. It is recommended that the scope of this experiment be enlarged so as to encompass as many as possible contributions from other interested laboratories.

3. Inconsistencies between measured and computed average cross sections in the fission neutron spectrum of U-235 have decreased significantly in the past three years but continue to be an issue of relevance in terms of international standardization of dosimetry, in particular because the high energy ($\geq$ 2.5 MeV) tails of the reactor core neutron spectra are often close to fission neutron spectra.

On the other hand, consistency is observed for the Cf^{252} spontaneous fission neutron spectrum, but very few measurements have been performed so far in this benchmark.

A critical appraisal of this situation leads to the following recommendations:

3.1. The neutron flux spectral shapes of the U-235 and Cf-252 fission neutron spectra should be compared directly

a) by spectrometry techniques **/

b) by means of double reaction rate ratio ***/ measurements, which are extremely sensitive to spectral shape differences.

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*/ Reactions ^{235}U (n,f) F.P., ^{238}U(n,f) F.P., and $^{58}Ni(n,p)$ ^{58}Co.

**/ Work along such line is in progress at PTB; experts from CEN-SCK, Mol, Belgium, have volunteered to supplement this effort by performing ^{6}Li (n,α) spectrometry at the PTB facilities, if the experimental conditions are adequate.

***/ It has been suggested that such measurements could be performed at NBS.

3.2. Laboratories operating ^{252}Cf sources should be encouraged to perform detector exposures to a certified fluence and distribute the detectors to outside laboratories for reaction rate measurements.
Particular emphasis should be placed upon the $^{58}Ni(n,p)^{58}Co$ reaction.

4. Measurements of cross sections for non-threshold reactions in fast and intermediate-energy neutron fields involve self-shielding corrections that may be substantial. There is a need for additional measurements of these corrections and for confrontation with their computed values. In this context, total cross sections for non-threshold reactions should be included in dosimetry files.

5. New resonance integral measurements are necessary for the reactions $^{45}Sc\ (n,\gamma)^{46}Sc$; $^{58}Fe\ (n,\gamma)^{59}Fe$; $^{63}Cu\ (n,\gamma)^{64}Cu$; $^{6}Li\ (n,\alpha)^{3}H$; and $^{10}B\ (n,\alpha)^{7}Li$.

6. When data are reported from reaction rate measurements in standard or reference neutron fields it is essential that sufficient information be given to allow interpretation of the data according to alternative normalization schemes. To achieve this we recommend that errors be quoted separately for measured absolute reaction rates on the one hand and normalizing parameters on the other. These remarks apply especially to average cross section and spectral index data. In general it is desirable that systematic errors be identified and presented separately from each other and from random errors.

7. Reaction rate traverse measurements performed in shielding benchmark experiments, well characterized by means of spectrometry, could help to establish energy-dependent cross section trends. Results of such well documented experiments should be applied to dosimetry data testing.

8. The IAEA has already established an important programme on irradiation embrittlement of pressure vessel steels (coordinated Research Programme on Irradiation Embrittlement of Pressure Vessel Steels, IAEA-176, 1974). It is desirable to promote the study of pressure vessels in benchmark experiments (for example work at JAERI, CEN/SCK and ORNL) and in operating power reactors. The IAEA should promote international intercomparison of both experimental and theoretical results in connection with the above programme of already established work.

9. Fission rate measurements in standard and reference neutron fields are usually performed by means of absolute fission chambers. Consistently applied solid state track recorder methods can valuably supplement the fission chamber results and should be applied more systematically. $^{6}Li\ (n,\alpha)$ and $^{10}B\ (n,\alpha)$ reaction rate measurements techniques using nuclear emulsions and solid state track recorders need to be developed and applied in standard and reference neutron fields to provide good data for comparison with the total helium production method.

   C.E.N./S.C.K. will start in MOL- ΣΣ the $^{10}B/^{6}Li$ spectral index measurement, for comparison with the total helium production data, by using their ^{10}B and ^{6}LiF BCMN deposits, positionned in front of fine grain nuclear emulsions.

10. The use of fission detectors requires a knowledge of yields for selected fission products from several fissile nuclides as a function of the energy of the neutrons inducing fission. The nuclear cross section data and decay schemes for such fission products are also required.

   - The fissile nuclides of main interest in dosimetry are ^{235}U, ^{239}Pu, ^{238}U, ^{237}Np.

   As had already been stated at former meetings, the yields of the fission products ^{95}Zr, ^{97}Zr, ^{103}Ru, ^{131}I, ^{132}Te, ^{137}Cs, ^{140}Ba and ^{148}Nd should be known to an accuracy of $\approx$ 2% (1σ) for the fast breeder programmes, and between 2 and 10% for other reactor programmes.

- The accuracies (1σ) to which "fast reactor fission yields" are known can be assumed to be

  1.5% for ^{235}U fission
  1 to 2 % for ^{239}Pu fission
  1.5 to 3 % for ^{238}U fission
  5 to 10% for ^{237}Np fission.

  - There is still a need to evaluate the energy dependence of the fission yields for the thermal to fast reactor-neutron range, especially for those fission products for which the difference between thermal and fast reactor neutron-yields is considerable (^{103}Ru, ^{131}I, ^{132}Te, ^{140}Ba). Similarly, it seems that for CTR applications fission yields for mean energies up to about 20 MeV may be required.

11. Calibrations of detector sets in standard neutron fields (when available), reduce the relative errors in reaction rate determinations between different foil materials. The influence of the two main sources of error - the reaction rate determination and the cross section - is minimized in this way. Relative errors in reaction rate determination may be reduced to one or two percent. The results (fluence or spectra) are then relative to the standard spectrum measured so that the error then depends upon the precision to which the standard (fluence or spectrum) is known.

    It is recommended that this dosimetry approach be implemented whenever possible and that standard neutron fields be consequently made available to any interested user.

12. Materials used as neutron dosimeters must be accurately defined and contain a minimum of impurities. Enriched isotopes are sometimes required. A pool of such materials including fissionable materials should be established, possibly by the IAEA at its Seibersdorf Laboratory. The Agency should promote the establishment of a close working relationship between different centres which fabricate and provide such detector materials.

The pool of these materials should be open to Member States. This cooperative effort should establish the necessary procedures that are needed to maintain a uniform level of overall standardization of the necessary physical and chemical properties of the materials and fabrication of the detectors.

13. For the radioisotopes resulting from important dosimetry reactions a list of recommended values for decay parameters (γ-intensities, half-lives) should be prepared and distributed by the IAEA.

14. The dosimetry reactions have been classified in two categories. Category I reactions are defined as reactions,

    a. whose differential-energy cross section is well known over their response range in standard neutron fields;

    b. which are consistent with integral measurements in the standard neutron fields.

The following reactions belong to Category I:

$^{197}Au(n,\gamma)^{198}Au$, $^{239}Pu(n,f)$ F.P., $^{237}Np(n,f)$ F.P., $^{238}U(n,f)$ F.P., $^{56}Fe(n,p)^{56}Mn$, $^{27}Al(n,\alpha)^{24}Na$, $^{63}Cu(n,2n)^{62}Cu$(*) and $^{58}Ni(n,2n)^{57}Ni$(*).

A number of other reactions are considered Category I candidates:
$^{235}U(n,f)$ F.P., $^{59}Co(n,\gamma)^{60}Co$, $^{238}U(n,\gamma)^{239}U$, $^{115}In(n,n')^{115m}In$, $^{58}Ni(n,p)^{58}Co$, $^{32}S(n,p)^{32}P$, $^{54}Fe(n,p)^{54}Mn$, $^{59}Co(n,\alpha)^{56}Mn$, $^{103}Rh(n,n')^{103}Rh^{m}$.

All other reactions used for dosimetry are Category II reactions.

It is recommended that caution be exercised when using the Category II reactions for neutron spectrum adjustment or unfolding.

(*) For the very high energy range, accuracies of the order of $\pm$ 10 % are presently acceptable.

V. DIFFERENTIAL MEASUREMENTS AND EVALUATIONS

1. The development of consistent sets of cross section data for a selected group of dosimetry reactions has not turned out to be an easy task. The current accuracy goal of better than $\pm$ 5% (1σ) has not been achieved with the possible exception of a few "Category I" reactions. It is clear that an international effort is desirable in order to achieve the stated goal and that it will have to involve investigation of decay schemes and a variety of "benchmarks" integral experiments as well as of differential (monoenergetic) measurements. A first step has been taken by adoption of the ENDF-B-IV dosimetry evaluated data file as the reference library of differential cross sections. This file represents the best available set to date. It appears that the uncertainty in the experimental data included in evaluated files cannot be expected to become less than 4 - 7% with the exception of a few special cases. The major source of uncertainties come from the neutron fluence determination.

2. For threshold reaction cross sections used in reactor dosimetry, the energy range of main interest is from threshold up to 4-6 MeV above it: the range of 20% reaction response in fission spectrum. Differential measurements are encouraged to be done especially in this energy range.

3. The problem of error files was not addressed in the ENDF/B-IV dosimetry file. In many applications such as neutron spectrum unfolding by multiple foil activation techniques, error files are important (e.g. error propagation calculations). It is recommended therefore that evaluators of energy-dependent cross section data provide confidence statements for successive energy regions specifying where possible the random and systematic contributions. It is further recommended that practical procedures are developed to account for propagation of errors in cross section data.

   The proposal to carry out a detailed analysis of the variance/covariance estimates of the ^{235}U fission cross section by the task force*) and the covariance subcommittee of CSEWG should be monitored closely to determine the feasibility of use with dosimetry files.

4. In principle it is possible to intercalibrate absolute fission detectors used in some integral measurements with those used in differential measurements. It is recommended that this possibility be investigated for use.

5. The large discrepancy between integral and differential data for the ^{63}Cu (n,α) ^{60}Co reaction may be resolved by two new experiments: measurement near threshold (5 - 6 MeV, low resolution is acceptable) and a new 14 MeV measurement (where an accuracy of 5% (1σ) or better is needed).

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*) M. Bhat NEANDC/NEACRP Specialists Meeting on Fast Neutron Fission Cross Section of ^{233}U, ^{235}U, ^{238}U and ^{239}Pu. NEANDC(US)-199/L, ERDA-NDC 5/L, ANL-76-90, Ed. Poenitz & Smith.

6. Integral data testing of the ENDF/B-IV dosimetry file suggests that for a number of threshold reactions, existing inconsistencies can be explained by flux scale normalization errors in differential-energy cross section measurements. The suggested normalization factors+ are as follows:

^{232}Th (n,f): 1.15
^{47}Ti (n,p): 0.825*
^{54}Fe (n,p): 0.967*
Ti (n,x) ^{46}Sc:1.128
^{59}Co (n,α) ^{56}Mn: 0.98

It is recommended that evaluators of differential-energy cross sections examine whether such renormalizations are acceptable.

7. It is recommended that differential cross section measurements be undertaken for:
^{45}Sc (n,γ) in the energy region .5 eV - 1 MeV,

^{93}Nb (n,n') ^{93}Nb^{m}
^{199}Hg (n,n')^{199}Hg^{m} from threshold to 10 MeV.

8. With a view towards application of dosimetry for radiation damage studies, it is recommended that differential cross section data for helium production in reactor structural materials be performed. (See recommendations of I.A.E.A. Specialists Meeting on Radiation Damage Units, Harwell, 2-4 Nov.1976).

9. The List of reactions of interest to reactor neutron metrology** is given below.

The table is arranged as follows:

Category:

The dosimetry reactions have been classified in two categories. Category I reactions are defined as reactions:

a. for which the energy dependent cross sections are well known over their response range in standard neutron fields;

b. for which calculated reaction rates in the standard neutron fields are consistent with the measured reaction rates.

+ A. Fabry (Session III paper).

* A new evaluation by C. Philis, D. Smith and A. Smith, reported by B.A. Magurno at this meeting (preliminary results), should solve the discrepancy for Ti(n,α)^{46}Sc; however, the discrepancy for ^{47}Ti(n,p) remains.

** submitted by W.L. Zijp, Petten.

All other reactions used for neutron metrology are category II reactions. However, some of them, denoted with II*, are considered category I candidates. They will reach the status of category I after removal of some inconsistencies between integral measurements and differential evaluations, at least as concerned the ^{235}U fission neutron spectrum, the $\Sigma\Sigma$ spectrum and the ISNF spectrum.

Reaction:

This column lists the reactions of interest in order of increasing proton number. The first part of the table contains the non-threshold reactions. The second part lists the threshold reactions.

Response remarks:

The information refers for the (n,γ) reactions to the energy E_r of the main resonance, and for the other reactions to the energy range comprising 90% response in a Watt fission neutron spectrum. For some reactions the information was not readily available.

Evaluations and compilations:

This column contains some relevant recent general literature references, described below the end of the table.

Applications:

Here indications are given of the field of applications. The code used is as follows:

a. Often used for flux density determinations (here a knowledge of integral cross sections and decay scheme data is required).

b. Often used in triple foil ("Sandwich") techniques (here a knowledge of resonance activation integral and decay scheme data is required, and also supplementary data to calculate self-shielding factors).

c. Often used for fluence determinations (here a knowledge of integral cross sections and decay scheme data is required).

d. Often used in spectrum unfolding techniques using computer codes like SAND-II and SPECTRA (here a knowledge of energy dependent cross section data is required).

e. Useful in measurements for CTR applications.

Special remarks:

Where it seemed appropriate, some special comment is given.

Non-threshold reactions:

category	reaction	response remarks	evaluations and compilation	applications	special remarks
II	$^{6}Li(n,\alpha)^{3}H$		1 6 7		total He production of particular importance
II	$^{10}B(n,\alpha)^{7}Li$		7		
II	$^{23}Na(n,\gamma)^{24}Na$	E_r = 2850 eV	2 6 7	b d	
II	$^{30}Si(n,\gamma)^{31}Si$		2 6		
II	$^{45}Sc(n,\gamma)^{46}Sc$		6 7	d	
II	$^{51}V(n,\gamma)^{52}V$	E_r = 4162 eV	2 6	b	
II	$^{55}Mn(n,\gamma)^{56}Mn$	E_r = 337 eV	2 6	b d	
	$^{58}Fe(n,\gamma)^{59}Fe$		2 6 7	c d	
	$^{58}Co^{m}(n,\gamma)^{59}Co$				Important to derive burn-up correction for nickel as fast neutron detector.
II	$^{58}Co(n,\gamma)^{59}Co$				
II*	$^{59}Co(n,\gamma)^{60}Co$	E_r = 132 eV	1 2 6 7	a b c d	σ_0, I and $\sigma(E)$ of particular importance
II	$^{63}Cu(n,\gamma)^{64}Cu$	E_r = 580 eV	2 6 7 8	a b d	
II	$^{64}Ni(n,\gamma)^{65}Ni$		2 6		
II	$^{71}Ga(n,\gamma)^{72}Ga$	E_r = 95 eV	6	b	
II	$^{75}As(n,\gamma)^{76}As$	E_r = 47 eV	6	b	
II	$^{80}Se(n,\gamma)^{81}Se$	E_r = 1965 eV	6	b	
II	$^{81}Br(n,\gamma)^{82}Br$	E_r = 101 eV	6	b	
II	$^{93}Nb(n,\gamma)^{94}Nb$		4		Suggested as possible long term fluence detector
II	$^{98}Mo(n,\gamma)^{99}Mo$	E_r = 12 and 480 eV	2 6	b	
II	$^{100}Mo(n,\gamma)^{101}Mo$	E_r = 97.3 and 364 eV	6	b	
II	$^{103}Rh(n,\gamma)^{104}Rh$	E_r = 1.257 eV	6	b	
II	$^{108}Pd(n,\gamma)^{109}Pd$	E_r = 2.96 eV	6	b	
II	$^{109}Ag(n,\gamma)^{110}Ag^{m}$		3 6	c d	Together with $^{59}Co(n,\gamma)$ important in double foil technique to determine fluence of thermal and intermediate neutrons. Long $T_{\frac{1}{2}}$ replacement for $^{197}Au(n,\gamma)^{198}Au$.
II	$^{114}Cd(n,\gamma)^{115}Cd$	E_r = 120 eV	6	b	
II	$^{115}In(n,\gamma)^{116}In^{m}$	E_r = 1.46 eV	2 6 7 8	a b d	
II	$^{121}Sb(n,\gamma)^{122}Sb$		6	b	
II	$^{133}Cs(n,\gamma)^{134}Cs$	E_r = 5.9 eV	6	b	
II	$^{139}La(n,\gamma)^{140}La$	E_r = 72.4 eV	2 6	b	
II	$^{152}Sm(n,\gamma)^{152}Sm^{m}$	E_r = 8.01 eV	6	b	
II	$^{151}Eu(n,\gamma)^{152}Eu^{m}$		2 6		
II	$^{164}Dy(n,\gamma)^{165}Dy$		2 6	a	
II	$^{175}Lu(n,\gamma)^{176}Lu$		2 6		
II	$^{176}Lu(n,\gamma)^{177}Lu$		2 6		
II	$^{181}Ta(n,\gamma)^{182}Ta$		6	d	Long $T_{\frac{1}{2}}$ replacement for $^{197}Au(n,\gamma)^{198}Au$
II	$^{186}W(n,\gamma)^{187}W$		2 6	b	
	$^{197}Au(n,\gamma)^{198}Au$	E_r = 4.90 eV	1 2 6 7 8	a b d	
	$^{232}Th(n,\gamma)^{233}Th$		6 7		
II*	$^{235}U(n,f)$**	0.19...5.1 MeV	123 5678	a c d	
II*	$^{238}U(n,\gamma)^{239}U$		1 2 6 7		Of particular importance
I	$^{239}Pu(n,f)$**	0.27...5.1 MeV	1 2 6 7 8	a c d	

* category I candidate.

** the yields for the fission products ^{95}Zr, ^{137}Cs, ^{140}Ba and ^{148}Nd belong to the second category.

Threshold reactions:

category	reaction	response remarks	evaluations and compilation	applications	special remarks
II	$^{19}F(n,2n)$		6	e	Threshold ~11.8 MeV
II	$^{23}Na(n,2n)^{22}Na$				Very high threshold = 12.5 MeV
II	$^{24}Mg(n,p)^{24}Na$	6.5...11.5 MeV	2 5 6 8	d	
II	$^{27}Al(n,p)^{27}Mg$	3.5... 9.3 MeV	1 2 3 5 6 7 8	d	Of particular importance
I	$^{27}Al(n,\alpha)^{24}Na$	6.4...11.9 MeV	2 3 4 5 6 7 8 9	a d e	
II	$^{28}Si(n,p)^{28}Al$	5.4...10.1 MeV	6		
II	$^{31}P(n,p)^{31}Si$	2.2... 7.0 MeV	2 3 4 5 6 8 9	d	
II*	$^{32}S(n,p)^{32}P$	2.5... 7.5 MeV	2 3 4 5 6 7 8 9	a d	
II	$^{34}S(n,\alpha)^{31}Si$	5.1...10.4 MeV	6		
II	$^{35}Cl(n,\alpha)^{32}P$	3.2... 8.0 MeV	6		
II	$^{46}Ti(n,p)^{46}Sc$	3.4... 9.1 MeV	2 3 4 5 6 7 8 9	a c d	Particular interest in $Ti(n,x)^{46}Sc$
II	$^{47}Ti(n,p)^{47}Sc$	2.1... 7.0 MeV	2 3 4 5 6 7 8 9	d	
II	$^{48}Ti(n,p)^{48}Sc$	6.6...12.8 MeV	2 3 4 5 6 7 8 9	d	
II	$^{55}Mn(n,2n)^{54}Mn$		2 3 4 5 7 8 9	d	Possible long term fluence monitor
II*	$^{54}Fe(n,p)^{54}Mn$	2.3... 7.8 MeV	1 2 3 5 6 7 8	a c d	Of particular importance
I	$^{56}Fe(n,p)^{56}Mn$	5.5...11.0 MeV	2 3 4 5 6 7 8	d	
II	$^{59}Co(n,p)^{59}Fe$		6		Might be of interest
II*	$^{59}Co(n,\alpha)^{56}Mn$		2 3 4 5 6 7 8 9	e	
II	$^{59}Co(n,2n)^{58}Co$		6 7		
II*	$^{58}Ni(n,p)^{58}Co$	2.1... 7.0 MeV	1 2 3 5 6 7 8	a d	Includes $^{58}Ni(n,p)^{58}Co^{m}$
II	$^{58}Ni(n,\alpha)^{55}Fe$		1 2 5 6		Of particular importance
I	$^{58}Ni(n,2n)^{57}Ni$	13.2...17.0 MeV	6 7 8 9	e	Very high threshold
II	$^{60}Ni(n,p)^{60}Co$	2.7... 9.6 MeV	6 7		
II	$^{63}Cu(n,\alpha)^{60}Co$	6.1...11.3 MeV	1 2 3 5 6 7 8 9	a c d	Of particular importance
I	$^{63}Cu(n,2n)^{62}Cu$	11.9...16.4 MeV	1 2 3 5 6 7 8 9	e	
II	$^{65}Cu(n,p)^{65}Ni$		6	d	
II	$^{65}Cu(n,2n)^{64}Cu$		2 3 5 6		
II	$^{64}Zn(n,p)^{64}Cu$	2.3... 7.8 MeV	2 3 5 6 8	d e	
II	$^{64}Zn(n,2n)^{63}Zn$		6		
II	$^{90}Zr(n,2n)^{89}Zr$	12.5...16.7 MeV	6 8 9	d	
II	$^{93}Nb(n,n')^{93}Nb^{m}$		1 2 5 6		Low threshold of particular importance
II	$^{93}Nb(n,2n)^{92}Nb$		2 3 4 5 6 8 9		
II	$^{92}Mo(n,p)^{92}Nb$		2 5 6		
II	$^{94}Mo(n,p)^{94}Nb$				Possible long term fluence monitor
II*	$^{103}Rh(n,n')^{103}Rh^{m}$		1 2 3 5 6 8		Low threshold; of particular importance
II*	$^{115}In(n,n')^{115}In^{m}$	1.2... 5.8 MeV	1 2 3 5 6 7 8	a d	Low threshold; of particular importance
II	$^{127}I(n,2n)^{126}I$	10.0...14.6 MeV	2 3 5 6 7 8	a d e	High threshold
II	$^{199}Hg(n,n')^{199}Hg^{m}$				Recently suggested
II	$^{232}Th(n,f)$	1.5... 7.2 MeV	1 2 3 5 7 8	d	Of particular interest; fission product activities contain information on irradiation history
I	$^{238}U(n,f)$**	1.5... 6.7 MeV	1 2 3 5 7 8	a c d	
I	$^{237}Np(n,f)$**	0.69...5.6 MeV	1 2 3 5 7 8	a c d	

* category I candidate

** the yields for the fission products ^{95}Zr, ^{137}Cs, ^{140}Ba and ^{148}Nd belong to the second category.

Literature references, quoted in column 4:

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VI. USE OF INTEGRAL EXPERIMENTS

1. High priority should be given to the establishment of important fields and reactions as Standard Fields and Category I reactions respectively; in particular discrepancies between measured and calculated reaction rates of several important reactions in the U-235 fission spectrum should be investigated.

2. The choice of reactions to be used in a given environment will be limited by practical considerations, but there may still remain a large choice. It is desirable to focus attention on a more limited number of reactions which might be of particular importance in Multiple Foil Analysis. It is recommended that the feasibility of identifying such reactions by means of a sensitivity study be investigated.

   In order to predict accurately the reaction rates and their variances in Standard Neutron Fields and Reference Neutron Fields evaluators of both should be encouraged to provide an approximate correlation function for the evaluated spectra. Where this is not possible details of the calculations and measurements (with a full list of estimated uncertainties) used to evaluate the field should be supplied.

3. For the same reason evaluators of cross-sections used in dosimetry should be encouraged to provide an estimate, however approximate, of the cross-section correlation function.

4. The establishment of more extreme Reference Neutron Fields is desirable to give knowledge of the performance of reactions important to dosimetry in the energy ranges not being considered at present.

VII. SUMMARY OF CONCLUSIONS

1. The most significant advances in the dosimetry benchmark programme since September 1973 are the following:

   - The availability of the ENDF/B-IV Dosimetry File and its wide use as a reference set,

   - an improved characterization by measurements and calculations of the benchmark neutron fields,

   - the collection and compilation of information on benchmarks,

   - a number of consistent applications of benchmark measurements to spectrum and/or cross-section validation or correction.

2. The most significant conclusions reached at this meeting are:

   - The identification of a limited number of standard neutron fields (thermal, 1/E, ^{252}Cf spontaneous fission) and of Category I dosimetry reactions (^{197}Au(n,γ)^{198}Au; ^{237}Np (n,f) F.P.; ^{238}U(n,f) F.P.; ^{56}Fe(n,p)^{56}Mn; ^{27}Al(n,α)^{24}Na; ^{63}Cu(n,2n)^{62}Cu; ^{58}Ni(n,2n)^{57}Ni). Reaction rate measurements of Category I reactions in the standard field yield results consistent with calculations using ENDF/B-IV cross-sections and the recommended representations of the standard spectra.

   - The agreement on the principles of a procedure to use measurements in benchmark fields to improve the knowledge of the reference fields and controlled environments and/or of Category II reaction cross-sections.

3. Some of the most important recommendations coming from the meeting are:

   - ENDF/B-IV dosimetry cross-sections and agreed representations for the standard spectra should be used, at least in parallel with other cross-sections and representations.

- Efforts should be made to remove inconsistencies between integral measurements and differential evaluations at least as concerns the ^{235}U fission spectrum, the $\Sigma\Sigma$-type facilities and the ISNF, and the cross-sections for $^{58}Ni\ (n,p)^{58}Co$; $^{235}U(n,f)$ F.P., $^{59}Co(n,\gamma)^{60}Co$; $^{115}I(n,n')^{115}In^{m}$, $^{54}Fe(n,p)^{54}Mn$; $^{103}Rh(n,n')^{103}Rh^{m}$ and some others, see page 29, so as to qualify them as standard spectra and Category I reactions, respectively.

- Some assessment of errors and of correlations should be made for the dosimetry cross-sections.

- Further efforts should be made to arrive at a better characterization of benchmark neutron fields, including interlaboratory measurements and calculations; it is important that some indications on the confidence to assign to fluxes and spectra are reached.

- Efforts to improve the knowledge of Category II reactions should be focused with first priority on a restricted number of reactions of primary interest for dosimetry applications.

- Simultaneous analysis of measurements of several reactions in different benchmark fields appears the most promising way to arrive at physically meaningful results; such analyses should be carried out in several laboratories and the results compared.

- The necessity of a limited number of new differential measurements and evaluations of dosimetry cross-sections has been identified; for all the other reactions of interest for dosimetry, the improvement of cross-sections is expected to be derived from a combination of integral and differential measurements, when available, which should yield internally consistent data.

- International cooperation is essential in reaching these goals; closer links should be established between the present programme and other programmes sponsored by the IAEA and by other international organizations, so that the full variety of available and identified benchmark fields is employed.

- Substantial efforts should be undertaken, preferably by the IAEA Seibersdorf Laboratory, to create a pool of dosimetry materials (in particular fissionable isotopes) accessible to the whole dosimetry community.

Consultants' Meeting

on Integral Cross-Section Measurements

in Standard Neutron Fields for Reactor Dosimetry

Vienna, 15 - 19 November 1976

AGENDA

MONDAY, 15 NOVEMBER, morning session

Opening of the meeting by Dr. J.J. Schmidt, IAEA

SESSION I. OVERVIEW

Chairman: Dr. J.A. Grundl

1.1 Review:

1.1a 'Benchmark neutron fields for reactor dosimetry' (J.A. Grundl, NBS, Washington)

1.1b 'Power reactor pressure vessel benchmarks' (F. Rahn, EPRI, Palo Alto)

1.1c 'Remarks on terminology and symbols for physical quantities in neutron metrology" (S. Wagner, PTB, Braunschweig)

1.2 Contributed papers

1.2a 'One material experiments in the frame of power reactor pressure vessel benchmarks' (G.De Leeuw-Gierts, C.E.N.-S.C.K., Mol)

1.2b 'Spectrum characterization and threshold reaction rate measurements in the neutron field of VIPER' by M.H. McTaggart (J.G. Williams, London Univ.)

MONDAY, 15 NOVEMBER, afternoon session and TUESDAY, 16 NOVEMBER morning session

SESSION II. Spectral Characterization of Benchmark Neutron Fields

Chairman: Dr. W.N. McElroy

2.1 Review:

2.1a 'Spectral characterization by combining neutron spectroscopy, analytical calculations and integral measurements' (W.N. McElroy, HEDL, Richland)

2.1b 'A review of the standard fission neutron spectra of ^{235}U and ^{252}Cf' (H.H. Knitter, Geel)

2.1c 'In-pile neutron spectroscopy: status' (G. de Leeuw, CEN-SCK, Mol)

2.2 Contributed papers

2.2a 'Standards for thermal neutrons at the PTB' (S.Wagner, PTB)

2.2b 'Fast neutron standards at the PTB' (S. Wagner, PTB, Braunschweig)

2.2c 'A Californium-252 fission spectrum irradiation facility for neutron reaction rate measurements' by J.A. Grundl, V.Spiegel, C.M. Eisenhauer, H.T. Heaton, II, D. Guliam and J. Bigelow' (J.A. Grundl, NBS)

2.2d 'The IAEA Programme on intercomparison of the computer codes for neutron spectra unfolding by activation technique', Progress report (B. Cross, IAEA)

2.2e 'Comparison of neutron spectrum unfolding codes', by W. Zijp and H.J. Nolthenius (W. Zijp, ECN, Petten)

2.2f 'Spectral characterization of the NISUS neutron field' by J.G. Williams and A.H.M.A. Hannan (J.G. Williams, London University)

2.2g 'Studies of neutron standard fields in the fast source reactor 'YAYOI', by A. Sekiguchi et al. (I. Kimura, RRI, Osaka)

2.2h 'Thermal neutron field with a heavy water facility', by K. Kanda et al. (I. Kimura, RRI, Osaka)

2.2i 'The coupled fast reactivity measurements facility (CFRMF)' by J.W. Rogers, Y.D. Harker and D.A. Millsap. (A. Fabry, CEN-SCK, Mol)

2.2j 'The IAEA Intercomparison of methods for processing Ge(Li) γ-ray spectra', Progress report (R.M. Parr, IAEA)

2.3 Discussion and Recommendations for Sessions I & II.

TUESDAY, 16 NOVEMBER, afternoon, and WEDNESDAY, 17 NOVEMBER morning session

SESSION III. Integral Data in Benchmark Neutron Fields

Chairman: Dr. A. Fabry

3.1 Review

3.1a 'Review of microscopic integral cross section data in fundamental reactor dosimetry benchmark neutron fields' Part I, by A. Fabry et al., (for Part II: see agenda item 5.1c)
(A. Fabry, CEN/SCK, Mol)

3.1b 'Ratios of measured and calculated reaction rates for some known spectra' (W. Zijp, ECN, Petten)

3.2 Contributed papers

3.2a 'General remarks on the benchmark studies'
(W. Zijp, ECN, Petten)

3.2b 'Intercomparison of the intermediate energy standard neutron field at the NISUS and Mol-ΣΣ- facilities by means of absolute fission chambers', by A. Fabry, J.G. Williams and A.H.M.A. Hannan, D. Azimi-Garakani.
(J.G. Williams, London University)

3.2c 'Activation foil data for NISUS, ΣΣ-Mol and ^{235}U fission spectrum' by A.H.M.A. Hannan and J.G. Williams
(J.G. Williams, London University)

3.2d 'Integral cross section measurements with regard to the low and high energy part of the Californium-252 neutron spectrum'
(W. Mannhart, PTB, Braunschweig)

3.2e 'Spectrum averaged cross-section measurements in the fast neutron field of a uranium fission plate'
(D. Najzer, Ljubljana, Inst. J. Stefan)

3.2f 'Fission product yield ratios for ^{235}U fission by thermal and ^{252}Cf neutrons', by K. Debertin
(S. Wagner, PTB, Braunschweig)

3.2g 'Measurement and evaluation of threshold reaction cross sections in standard neutron fields'
(I. Kimura, RRI, Osaka)

3.2h 'Quality control and calibration of miniature fission chambers by exposure to standard neutron fields. Application to the measurement of fundamental integral cross section ratios'
(A. Fabry, CEN/SCK Mol)

3.2i 'Measuring of a few integral data in the $\Sigma\Sigma$ neutron field'
(I. Gârlea, INT, Bucharest)

3.2j 'Progress report on detector cross section benchmark measurements in the Tapiro reactor', by M. Martini, P. Moioli, and F. Sirito
(U. Farinelli, CNEN / CSN Casaccia)

3.2k 'Comparison of integral cross-section values of several cross section libraries in the SAND-II format'
(W.L. Zijp, Petten)

3.2l 'Comparison of DETAN-74 and ENDF/B-IV cross section data in 620 groups'
(W.L. Zijp, Petten)

3.2m 'Status of fission product yields used in fast reactor dosimetry'
(G. Lammer, IAEA)

3.3 Discussion and Recommendations for Session 3

WEDNESDAY, 17 NOVEMBER, morning and afternoon sessions

SESSION IV. Differential Cross-Section Data for Reactor Dosimetry

Chairman: Dr. B. Magurno

4.1 Review

4.1a 'Remarks concerning the accurate measurement of differential cross sections for threshold reactions used in fast neutron dosimetry for fission reactors', by D. Smith, ANL, Argonne
(M. Vlasov, IAEA)

4.1b 'Comments on excitation functions of threshold reactions used in reactor neutron dosimetry'
(M.Vlasov, IAEA)

4.1c 'Status of some activation cross sections for reactor neutron dosimetry in the range 13 - 15 MeV'
(H. Vonach, IRK, Vienna)

4.1d 'Status of the ENDF/B-V dosimetry file'
(B. Magurno, BNL)

4.2 Contributed papers

4.2a 'Cross-section requirements for reactor neutron flux measurements from the user's point of view' by M. Mas and R. Lloret (R. Lloret, CEN, Grenoble)

4.2b 'Evaluations of ^{27}Al $(n,\alpha)^{24}$Na, ^{27}Al$(n,p)^{27}$Mg and ^{58}Ni$(n,p)^{58}$Co cross sections', by T. Asami (I. Kimura, RRI, Kyoto Univ. Osaka)

4.3 Discussion and Recommendations for Session IV

THURSDAY, 18 NOVEMBER, morning session

SESSION V. Validation and Adjustment of Differential Cross Sections on the Basis of Integral Data

Chairman: Prof. U. Farinelli

5.1 Review

5.1a 'General proposals of methodology for cross-section validation and adjustment' (U. Farinelli, CNEN,CSN Casaccia)

5.1b 'Foil activation detectors - some remarks on the choice of detectors, the adjustment of cross-sections and the unfolding of flux spectra' (A.K. Mac Cracken, Winfrith)

5.1c 'Review of microscopic integral cross section data in fundamental reactor dosimetry benchmark neutron fields', Part II (for Part I see 3.1a) (A. Fabry, CEN/SCK, Mol)

5.2 Contributed papers

5.2a 'On the possibility of unfolding simultaneously data from multiple foil, proton recoil and other neutron spectrometers by the SAND-II type unfolding codes' (M. Najzer, Institute J. Stefan, Ljubljana)

5.3 Discussion and Recommendations for Session V

THURSDAY, 18 NOVEMBER, afternoon

Meetings of working groups.

FRIDAY, 19 NOVEMBER

SESSION VI. Conclusions and Recommendations to the IAEA

Chairman: Dr. J. Grundl

Scientific
Secretary: Dr. M. Vlasov

Review and finalization of conclusions and recommendations of the working groups.

Closing and adjournment of the meeting. (Prof. U. Farinelli,
Dr. J.A. Grundl)

IAEA Consultants' Meeting

on

Integral Cross-Section Measurements

in Standard Neutron Fields

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