International Atomic Energy Agency

INDC(NDS)-101/LF

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INTERNATIONAL NUCLEAR DATA COMMITTEE



# IAEA Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology

Vienna, 11-15 December 1978

## SUMMARY REPORT

Edited by

A. Lorenz and D.W. Muir
Nuclear Data Section
International Atomic Energy Agency

May 1979

IAEA NUCLEAR DATA SECTION, KÄRNTNER RING 11, A-1010 VIENNA

Reproduced by the IAEA in Austria
March 1979
79-4322

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Abstract

This Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology was convened by the IAEA Nuclear Data Section, at IAEA Headquarters in Vienna, Austria, from 11-15 December 1978. The meeting was attended by 34 representatives from 15 Member States and 3 international organizations.

The main objectives of this meeting were to determine specific nuclear data requirements for fusion reactor technology, to assess the adequacy of available data in relation to these requirements, and to formulate recommendations for future activities needed to remedy the identified data deficiencies.

# I. SUMMARY OF THE MEETING

## A. Introduction

The Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology was convened by the IAEA Nuclear Data Section at IAEA Headquarters in Vienna, Austria, from 11-15 December 1978. The meeting was attended by 34 scientists from 15 Member States and 3 international organizations. The list of participants is given in Appendix 1.

## B. Objectives and Organization

The main objectives of this meeting were to determine specific nuclear data requirements for fusion reactor technology, to assess the adequacy of available data in relation to these requirements, and to formulate recommendations for future activities needed to remedy the identified data deficiencies. In order to achieve these objectives, two Working Groups were formed during the meeting to assess the nuclear data used in studies of (1) neutron transport and gamma-ray production phenomena and (2) radiation damage and other nuclear effects.

The Adopted Agenda is given in Appendix 2 and the list of the Introductory and Review Papers presented at the meeting by the participants is given in Appendix 3. These original papers, prepared specifically for the meeting, are planned to be published as a separate report.

## C. Organization of this Report

Section II contains the set of general recommendations which this Advisory Group directed to the IAEA. Section III and Section IV contain the reports of the two Working Groups concerned with the specific nuclear data needs associated with neutron transport and radiation effects, respectively.

## II. RECOMMENDATIONS TO THE IAEA

### A. Dissemination of Nuclear Data Information

The Advisory Group recommended that the IAEA Nuclear Data Section be responsible for disseminating this report, maintaining and updating it as needed and considering it as one of the basic documents for review at future meetings in this field. Based on the results of future sensitivity studies and design needs, recommendations on accuracy and energy ranges should be made and priorities assigned to data requests according to the then current direction of conceptual studies. It was recommended that all nuclear data requests relevant to fusion continue to be entered also in the world request list WRENDA.

The Advisory Group recommended that the Nuclear Data Section, in co-operation with the other international data centers, continue its extensive services in the dissemination of numerical data. Further, the meeting participants felt that the nuclear data needed for fusion studies should be fully included in the performance of this service.

### B. IAEA Coordination of Required Nuclear Data Measurements

The meeting participants recognized the value and relative ease of 14-MeV cross section measurements on a wide range of isotopes not only in providing activation cross section data for materials envisaged for fusion reactors, but also for checking nuclear model calculations.

The Advisory Group therefore recommended that the IAEA establish a coordinated research programme with the aim of improving the accuracy of 14-MeV activation cross sections by intercomparing the results obtained in different laboratories under identical experimental conditions. Consideration should also be given to the measurement of required secondary particle distributions at 14 MeV. Special attention should be paid to research facilities located in laboratories in developing countries in order to encourage the participation of the scientists of these countries in the field of fusion nuclear data. The Advisory Group noted with gratitude the offer of the Institute of Experimental Physics at Debrecen to host the first meeting of the participants in this programme.

It was also suggested that the IAEA investigate the feasibility of establishing a complementary internationally coordinated programme devoted to integral measurements of neutron and gamma-ray energy spectra and/or the spatial dependence of reaction rates, for the purpose of checking evaluated nuclear data and the way they are prepared for their use in transport calculations.

### C. Future Meetings

There was a general consensus among the Advisory Group that another meeting to review the status of nuclear data for fusion reactor technology should be convened by the IAEA in three years.

The Working Group on neutron transport and gamma-ray production felt that at some future date, estimated at 2-3 years time, significant progress will have been made in the evaluation of covariance data and in the application of methods for sensitivity and uncertainty analysis and that a valuable purpose will be served in calling a specialists' meeting in this field. The Working Group therefore recommended that such a meeting be convened under IAEA auspices. The aim of this meeting would be to assess the results obtained and formulate recommendations to the nuclear data community based on them to remedy data shortcomings (including covariances) and to plan further development of methods for sensitivity and uncertainty analysis and their future application.

Independent of these recommendations the Nuclear Data Section informed the meeting participants that an IAEA Advisory Group Meeting on Radiation Damage Data for Fission and Fusion Reactors is planned to be held during 1981.

## III. REPORT OF WORKING GROUP ON NEUTRON TRANSPORT AND GAMMA-RAY PRODUCTION

| | |
|---|---|
| Constantine, G. | Perey, F.G. |
| Csikai, J. | Prillinger, G. |
| Cvelbar, F. | Pronyaev, V.G. |
| Dudziak, D.J. (Chairman) | Rusch, D. |
| Gervaise, F. | Seeliger, D. |
| Head, C. (Secretary) | Seki, Y. |
| Kushneriuk, S.A. | Verschuur, K.A. |
| Liskien, H. | Vonach, H.K. |
| Muir, D.W. | Wielding, T. |

### A. Introduction

#### 1. Goals

The general goals of this Working Group were to (1) identify and list specific nuclear data requirements for neutron transport and gamma-ray production; (2) determine the availability of nuclear data to satisfy these requirements; (3) identify measurements or theoretical nuclear model calculations needed to satisfy unfulfilled requirements; and (4) formulate recommendations for future data activities.

The Working Group addressed itself to all available basic data and not just those available in evaluated data files. Nuclear data needs were considered for fusion reactors ranging from the proposed IAEA International Tokamak or the U.S. Engineering Test Facility, through demonstration commercial power reactors. Thus, the direct application of the nuclear data considered will extend over the next several decades. Although near-term projects with extremely low neutron fluences (e.g., JET, TFTR) were not considered, many of the identified data needs are already urgent for two reasons. First, some are required for the design of irradiation facilities and analysis of neutron fields in these facilities. (See Section 4 below.) Second, nuclear data uncertainties could affect conclusions concerning the feasibility of particular reactor concepts (especially those with marginal breeding capability) and thereby affect the direction of fusion research programmes.

Attention was fixed exclusively on D-T burning systems. Both magnetic and inertial confinement routes were considered.

An important emphasis was placed upon facilitating communication between the fusion reactor technologists (users) and the nuclear data community (providers). An attempt is made by means of this report to inform the providers of data as to the form in which the data is most useful for transport calculations (e.g., neutron-emission cross sections). Nevertheless, the Working Group recognized that many needs will be fulfilled by measurements or nuclear model calculations of partial cross sections, where the motivation may be more for basic nuclear physics information than for technological applications. Consequently, the Working Group strongly encouraged such research.

While fusion reactor spectra will extend from about 16 MeV down to thermal energies, the Working Group focussed most attention on the region from 16 MeV down to the lower MeV energy range, below which most data needs are already met by the work on fission reactors.

2. Integral Experiments

The group recognized the value of integral experiments in checking

(1) the quality of nuclear data,

(2) the correctness of multigroup cross-section processing, and

(3) the adequacy of the simplifications and approximations adopted in transport calculations.

However, care should be taken in the planning and analysis of such experiments, so that the origin of discrepancies can be correctly identified.

The group also specifically recommended that additional integral experiments be carried out, with materials such as

(1) stainless steel, and

(2) lithium alloys and compounds (LiAl, $Li_4Pb$, LiC, $Li_2O$, $LiAlO_2$).

Integral experiments in the resonance energy region, such as self-indication measurements, were also considered to be useful.

3. Hybrid Systems

Nuclear data specific to hybrid fusion-fission systems were considered in this study, insofar as many of the materials conceived are common to both the pure D-T fusion and hybrid reactors where they serve as neutron multipliers. In particular it is to be noted that the $^{238}U$ and $^{232}Th$ data requirements associated with hybrid transport problems at lower energies are, for the most part, already met by the data used for fission reactor development.

4. Material Test Facility Considerations

Mr. Head from the U.S.A. identified in his Introductory Paper presented at this meeting nuclear data needs for energies up to 50 MeV for use in designing and upgrading the Fusion Materials Irradiation Test (FMIT) facility, and for dosimetry data to be used in interpreting the results of FMIT testing.

While the Working Group recognized the short time available to produce data which will affect FMIT construction, more time is available for acquisition of data for use in FMIT upgrades or operation. Considering the international importance of the results expected from FMIT, the Working Group emphasized the desirability of filling the FMIT nuclear data requests listed in Mr. Head's paper, to be published in the proceedings of this meeting. These requests also have been submitted for incorporation in WRENDA 79/80.

B. Data Status Assessment

1. Data Breakdown

As a means of identifying all required materials and the corresponding data requirements for fusion reactor design calculations, the Working Group adopted the list of material uses given in Table IA. These categories of material uses, which break down a fusion reactor into its major components were chosen for convenience in identifying the wide variety of data needs for neutron transport and gamma-ray production calculations. The types of data required to characterize each of the material uses are also given in Table IA. Table IB identifies the specific elements which are expected to be used in each of the material use categories. Table IC identifies the nuclear data required for each element for transport calculations and the status of the data. These three tables are provided to facilitate use and updating of the data.

2. Comment on Table IC

It must be strongly emphasized that the assignment of status for the data in Table IC is by necessity based mostly on qualitative judgements. Thus, it is expected that as information on covariances of the data become available and are incorporated in sensitivity studies, the data status will be refined. This will lead to the necessity for periodic updating of the table. Also, an assignment of a satisfactory (S) category should not be misinterpreted so as to discourage further measurements of any particular cross section, because such additional measurements may be valuable in determining cross-section covariance data. It cannot be over-emphasized that covariance data are as essential to the uncertainty analyses as are the cross-section data themselves

C. Recommendations

The Working Group participants felt that early consideration of the following recommendations by the INDC would be appreciated.

1. The Working Group felt concerned that its classification of the state of various cross section data for a large number of candidate materials for fusion reactor use was not at this stage consistently derived from the standpoint of user needs. It is emphasized that changes in this status, including requests for higher accuracy where data is described herein as adequate, may be necessary in the light of future sensitivity studies and design needs. In order to speed this process the following courses of action are recommended:

a. Attention should be directed to extending sensitivity theory to solve the problems of adequately specifying accuracy in secondary energy and angular distribution data.

b. The provision of covariance data by evaluators should be strongly encouraged, even while recognizing the magnitude of such an undertaking.

c. The use of these covariance data by designers in carrying out sensitivity studies should be encouraged, leading in turn to reassessment of the adequacy of the data as described here and, if necessary, the initiation of measurements and/or evaluations.

d. The Working Group strongly urged the wider dissemination and use of sensitivity and uncertainty analysis methods.

2. A fusion-related evaluated nuclear data file free from the limitations of existing data files is an ultimate goal. However, the group, being well aware of the problems associated with the realization of this goal recommended as an interim measure the introduction of two new data types into the existing data files. The first of these is the double-

differential total neutron-emission cross section $\sigma_{n,nem}(E_n', \theta_n')$ and the second is the differential total gamma-ray-emission cross section $\sigma_{n,\gamma em}(E_\gamma)$. Both $\sigma_{n,nem}$ and $\sigma_{n,\gamma em}$ are required as a function also of the incident neutron energy.

Both cross sections, which contain information needed for rigorous transport calculations, will complement rather than replace the existing data. In addition, the covariance matrices can be given more reliably when these data emerge directly from experiments. The present practice is to construct partial cross sections with individual covariances. However, because of approximations and simplifications, this may degrade the original covariance information. Additionally, the requirements for the accuracies of the partial cross sections are unduly raised by the present practice, if a given target accuracy of neutron fluxes is to be met. For the gamma-ray-emission cross-section the emergent angular distribution may be approximated for fusion applications as isotropic.

The Working Group strongly recommended the preservation of available differential information in both types of differential cross-sections. For example, neutron induced gamma-ray-emission cross sections should be compiled as a function of $E_\gamma$, together with the cross section integrated over $E_\gamma$.

3. The group strongly emphasized the importance of nuclear theory, especially of nuclear reaction models, for obtaining and evaluating nuclear data for fusion reactors. Important next steps in this direction are:

- inclusion of angular dependence of emitted particles into the nuclear reaction codes,

- development of treatments of nuclear structure effects within the framework of theoretical nuclear reaction models,

- further compilations and evaluations of nuclear model parameters (optical model parameters, level densities, gamma-ray strength functions etc.).

By limiting the request for data to below 16 MeV the group did not want to impede measurements above this energy for the purpose of nuclear physics. It was felt that the nuclear models should be tested over a wider energy range, but specification of experimental data needs for this purpose could not be addressed by this Working Group.

4. For deep-penetration problems as well as back-scattering the existing differential data in the MeV range are generally insufficient. New techniques have to be developed for the measurement of these data. For example, monoenergetic neutron generators have to be upgraded to higher instantaneous yield (e.g., $10^5$ neutrons per pulse in 2ns) in order to allow a higher time-of-flight resolution than presently obtainable.

5. The Working Group recommended that full documentation of measurements, and in particular evaluations, be published in the open literature and not only in internal reports. Such internal reports are issued in a timely manner but are often not easily available. Few journals will accept publication of documentation for evaluations with the details required for applications. "Atomic and Nuclear Data Tables" will consider publication of such comprehensive documentations.

Table IA

Material Uses versus Data Required for Transport Calculations

| | $\sigma_{TOTAL}$ | $\sigma_{n,nem}(E_n',\theta_n')$ | $\sigma_{n,2n}$ | $\sigma_{n,3n}$ | $\sigma_{n,\gamma}$ | $\sigma_{nf}$ | $\sigma_{n,em}(E\gamma)$ |
|---|---|---|---|---|---|---|---|
| Internal First Wall Protection | X | X | X | | X | | X |
| Neutron Multipliers | X | X | X | X | X | X | X |
| Breeding Materials | X | X | X | | X | | X |
| Structural Materials | X | X | X | | X | | X |
| Magnet Conducting Materials | X | X | X | | X | | X |
| Reflectors and Moderators | X | X | X | | X | | X |
| Shielding | X | X | X | | X | | X |
| Coolants | X | X | X | | X | | X |

Table IB

Material Uses versus Materials

| Element or Isotope | Internal First Wall Protection | Neutron Multipliers | Breeding Materials | Structural Materials | Magnet Conducting Materials | Reflectors and Moderators | Shielding | Coolants |
|---|---|---|---|---|---|---|---|---|
| H | | | | | | X | X | X |
| D | | | | | | X(1) | | |
| T | | | | | | X(1) | | |
| He | | | | | | | | X |
| $^{6}Li$ | | | X | | | | | X |
| $^{7}Li$ | | | X | | | | | X |
| Be | X | X | | | X | X | | X |
| $^{10}B$ | | | | | | X | X | |
| $^{11}B$ | | | | | | X | X | |
| C | X | | | X | | X | X | |
| N | | | | | | | | X |
| O | X | | | | | X | X | X |
| F | | | | | | | | X |
| Na | | | | | | | | X |
| Al | X | | | X | X | | | |
| Si | X | | | X | | | X | |
| K | | | | | | | | X |
| Ca | | | | | | | X | |
| Ti | | | | X | X | | | |
| V | | | | X | X | | | |
| Cr | | | | X | | | X | |
| Mn | | | | X | | | | |
| Fe | | | | X | | X | X | |
| Ni | | | | X | | | X | |
| Cu | | | | | X | | | |
| Ga | | | | | X(2) | | | |
| Zr | | | | X | | | | |
| Nb | | | | X | X | | | |
| Mo | X | | | X | | | | |
| Sn | | | | | X(2) | | | |
| W | X | | | | | | X | |
| Pb | | X | | | | | X | X |
| $^{232}Th$ | | X | X | | | | | |
| $^{238}U$ | | X | X | | | | | |

(1) Significant moderation occurs in compressed D-T inertial-confinement pellets.

(2) Ga and Sn are listed here for completeness, but are not discussed further since the amounts present are judged to be too small to affect transport calculations.

Table IC

Materials versus Transport-Calculation Data Needs and Status

| | $\sigma_{TOTAL}$ | $\sigma_{n,nem}(E_n', \theta_n')$ | $\sigma_{n,2n}$ | $\sigma_{n,3n}$ | $\sigma_{n,\gamma}$ | $\sigma_{nf}$ | $\sigma_{n,\gamma em}(E_\gamma)$ |
|---|---|---|---|---|---|---|---|
| H | S | S | | | | | |
| D | S | U | | | | | |
| T | S | U | | | | | |
| He | S | S | | | | | |
| $^6$Li | S | U | | | | | |
| $^7$Li | S | A | | | | | S |
| Be | S | A | A | | | | |
| $^{10}$B | S | U | | | | | S |
| $^{11}$B | S | U | | | | | U |
| C | S | U5,S | | | | | S |
| N | S | S | S | | | | S |
| O | S | S | | | | | A |
| F | S | U | S | | | | S |
| Na | S | U | S | | | | S |
| Al | S | S | | | | | S |
| Si | A2,S | A | | | | | S |
| K | S | U | | | | | U |
| Ca | S | U | | | | | S |
| Ti | S | U | U | | | | S |
| V | S | U | U | | | | S |
| Cr | U2,S | U1,A | U | | | | S |
| Mn | S | S | S | | | | S |
| Fe | S | U1,5,A | S | | | | S |
| Ni | U2,S | U1,A | U | | | | S |
| Cu | S | U4 | S | | | | S |
| Zr | S | U3 | A | | | | |
| Nb | S | S | S | | | | S |
| Mo | A | U | U | | S | | S |
| W | A | U | U | | S | | S |
| Pb | S | U | U | | | | S |
| $^{232}$Th | S | U6 | U | U | | S | S |
| $^{238}$U | S | U6 | A | A | | S | S |

Legend

Blank: no data needed.
S - present data seem satisfactory.
A - acceptable data are anticipated soon.
U - Uncertain; either data are not adequate, or the Working Group was uncertain of any work in progress.
1,2,etc... - numbers following the letters refer to the notes below. (For example U1,5,A means that the data covered by this entry are uncertain for the reasons given in Notes 1 and 5, but otherwise acceptable data are anticipated soon.)

Notes for Table IC:

1. These $\sigma_{n,nem}(E_n', \theta_n')$ data are inadequate for forward scattering angles ($\theta < 25^o$) for deep penetration shielding applications.

2. These $\sigma_{TOTAL}$ data are uncertain due to the existence of "windows" or local minima in the cross sections.

3. If Zr is used only as an alloying agent, the amount used is too small to require improvement of existing nuclear data. However, if Zr is used as a clad/structure for fissionable or fertile material, more data is needed.

4. $\sigma_{n,nem}(E_n', \theta_n')$ for Cu is well known at 14 MeV incident neutron energy, but additional data is needed at other energies.

5. $\sigma_{n,nem}(E_n', \theta_n')$ data for C and Fe is adequate except for backscattering emission uses. Fe data and theory for backscattering are also inconsistent.

6. For $^{232}$Th and $^{238}$U, the emission-spectrum includes contributions from fission, as well as inelastic, (n,2n) and (n,3n) reactions.

## IV. REPORT OF THE WORKING GROUP ON RADIATION EFFECTS

| | |
|---|---|
| Abdou, M.A. | Marsicanin, B. |
| Arcipiani, B. | Matthes, W. |
| Behrens, H. | Münzel, H. |
| Bhat, M.R. | Nascimento, I.C. |
| Jarvis, O.N. (Secretary) | Osterhage, W. |
| Kotov, V.V. | Qaim, S.M. (Chairman) |
| Lorenz, A. | Reffo, G. |

### A. Introduction

The Working Group on Data for Radiation Effects in D-T Reactors discussed the nuclear data needs related to radiation damage, nuclear heating and activation. Both near-term needs (Priority I) and long-term needs (Priority II) were considered. A distinction was drawn between the basic nuclear cross-section measurements which are required and the data representations which are used by reactor designers. The important contribution made by nuclear model codes in supplementing the experimental data was stressed. The detailed considerations and recommendations of the working group are presented in the following paragraphs.

### B. General Data-Requirement Considerations

The Working Group began its deliberations by identifying the materials, reactions and energies considered of importance to fusion reactors in relation to radiation effects before moving on to a consideration of specific topics. Table IB, provided by the Working Group on Neutron Transport and Gamma-Ray Production, lists the materials likely to be employed in a fusion reactor by function. This list is comprehensive and includes the possibility of using the refractory structural alloys based on Nb and Mo as well as the more conventional materials, and allows for the possibility of hybrid reactor construction. The Working Group on Radiation Effects adopted Table 5 of Review Paper A5 (Shielding, Safety and Environmental Considerations, by M.A. Abdou) as a guide-line for data measurement requirements for near-term fusion reactor designs. This table, listing detailed reaction cross-section requirements by nuclide and qualified by energy range, accuracy and relative priority is reproduced in this report as Table IIA.

#### 1. Materials

Priority I materials include: the iron- and nickel- based alloys (Fe, Ni, Cr, Mn); lithium and its compounds; coil stabilizing materials (Al, Cu) and coil structure (stainless steel, Al); insulators (Mg, Al, Y, Yb as oxides); and shielding materials ($B_4C$, stainless steel, W, Pb). Priority II materials are more extensive, and include: structural alloys of Ti, V, Zr, Nb and Mo; Pb as a neutron multiplier; Sn, Si, C, O; shielding materials (e.g., the constituents of concrete with regard to activation); and the breeding materials $^{238}$U and $^{232}$Th for hybrid systems.

#### 2. Nuclear Reactions

a. Information on all reactions energetically possible with neutrons up to 16 MeV is needed, but with accuracies dependent upon the response function being investigated. Sensitivity and uncertainty analysis can ultimately be valuable when complete data bases (including covariances) become available. At present extreme care must be taken not to draw unwarranted conclusions from partial uncertainty studies.

b. Neutron elastic and inelastic scattering cross sections can be calculated with reasonable accuracy for mass numbers $A > 20$, for all energies up to 14 MeV. For higher energies improved calculational methods are needed and experimental verification is essential. For these high energies proton scattering data should prove of great value but this has yet to be explored in the detail necessary.

c. The (n,2n), (n, charged particle) and (n,n' charged particle) reactions have a weak data base, especially in relation to energy and angular distributions of secondary particles. Multi-step Hauser-Feshbach codes provide guidance in this area but much experimental data is required to assist in code development and finally to validate the predictions.

d. For light elements ($A < 20$) the optical and statistical model codes are not applicable and comprehensive experimental data is required.

e. Tritium production in lithium is of vital importance for fusion reactor design but was not discussed in detail as there are experiments currently being performed to improve the $^{7}$Li(n,n'$\alpha$)T data. It is noted, however, that a target accuracy of between 2 and 5% is needed for both $^{6}$Li and $^{7}$Li reactions.

f. For breeding fissile materials in hybrid reactors the available data in the 5-10 MeV energy range is very poor for $^{238}$U(n,$\gamma$) and $^{232}$Th(n,$\gamma$), and target accuracies of about 5% should be aimed at.

g. Dosimetry reactions and reference neutron spectra have been considered in the November 1978 IAEA meeting on nuclear data for reactor dosimetry. The recommendations relevant to fusion of that advisory group are endorsed.

3. Energies

Energies in the range 0-16 MeV should be covered for fusion reactor applications, with highest accuracy in the energy regions most emphasized by the response function being investigated. Extension of certain classes of data to energies between 16 and 50 MeV will be required for assessing damage experiments performed with the proposed d-Li sources. Considerable reliance must be placed at present on theoretical calculations for supplying data in this higher energy region.

## C. Specific Radiation-Effects Considerations

### 1. Displacement Damage

For calculations of primary knock-on atom (PKA) spectra, the most important reactions are elastic and inelastic scattering, with (n,2n) reactions and processes involving charged-particle emission providing significant contributions. The neutron data files currently available generally contain insufficient data for constructing reliable PKA spectra: not only are the reaction cross-sections for (n,2n) and charged particle emitting reactions required, but also the energy and angular distributions of the emitted particles are needed to permit energy and momentum balancing when calculating PKA spectra.

In conjunction with any PKA spectrum it is necessary to provide a guide to its accuracy. Further studies will be needed to assign priorities and meaningful accuracies.

The final requirement is for a PKA data file containing data for elements or alloys. Any file produced in the future should be made available to the international community (perhaps several for intercomparison purposes) through the IAEA.

2. Gas Production

Three techniques are used for gas production measurements: activation, mass spectrometry and charged-particle emission analysis. Isotopic data are required if nuclear physics information is to be deduced from the results and also to assist with energy interpolation problems. Integral measurements for elements and alloys are needed to confirm the more basic data. Experiments at both discrete energies and with broad neutron spectra are needed. Calculational procedures are becoming very good for (n,p) and (n,$\alpha$) reactions but improvement is needed for (n,n'p), (n,n'$\alpha$) reactions, etc. (See section 5 for discussion of theory.) The final requirement is for gas-production data to an accuracy of 15-20%, for elements and alloys.

It would be desirable to have the ENDF/B gas-production data file made available to the international community through the IAEA.

3. Nuclear Heating

KERMA* factors for nuclear heating calculations are currently processed from basic data in ENDF/B format. The energy and momentum-balance calculations necessary for estimating KERMA factors require knowledge of individual reaction cross sections, Q-values, and energy and angular distribution of emitted particles and photons. At present, basic data files such as ENDF/B do not meet all these requirements. The following observations and recommendations can be made:

a. Gamma-production data are extremely important for nuclear heating calculations (for predicting both neutron and gamma-heating). The increased availability of gamma-production data for many materials in the past three years has reduced considerably the neutronics data requirements. For gamma production the highest priority requirements are for total gamma-production cross sections and for energy distributions of emitted gamma rays as a function of incident neutron energy.

   With a few important exceptions (e.g., the isotopes of lithium and boron and the fertile isotopes) these gamma-production data are required only for elements.

b. Because of the isotope dependence of the nuclear energy release (Q-value) of nuclear reactions, individual neutron reaction cross sections must be known by isotope.

c. Care must be taken to provide a sufficiently accurate representation of the data that reliable estimates of total energy deposition can be made. Problems of data representation are currently most noticeable with energy and angular distributions of secondary particles.

d. Local energy deposition is sensitive to charged-particle producing reactions and some effort must be devoted to providing data for these reactions.

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* KERMA = Kinetic Energy Released in MAterials.

For near-term devices the target accuracy for nuclear heating will be ±10 to 20%; for later devices improved precision will be needed. Integral experiments are required to confirm the accuracy of nuclear heating predictions. The final requirement of the users is for a KERMA factor library, containing comprehensive uncertainty estimates. This library file should be made available to the international community through the IAEA.

4. Transmutation (other than gas production)

The data required for transmutation calculations is expected to be provided in the context of other nuclear data requirements; it was considered unnecessary to consider it here. Moreover, the predicted effects will frequently be minor compared with other radiation damage consequences unless very long component life-times become possible.

5. Activation

At the present time most of the needs could be met by the application of a state-of-the-art multi-step Hauser-Feshbach code. Ideally, calculations should be run for all nuclides likely to be encountered in a fusion reactor, including certain stable and unstable reaction products. The cross sections for all energetically possible reactions are required, for neutron energies up to 16 MeV. Although libraries of input data for fission product and structural material nuclides ($A > 35$) have been prepared already, this project will necessitate collecting and/or evaluating an extensive set of additional input data (e.g. level densities, optical model parameters, Q-values, $\gamma$-decay widths, etc). Consideration should be given to estimating the accuracy of these calculations. Accuracies required will be about ±25% at best. Many data measurements (e.g., at 14 MeV) will be needed to check and to normalize the calculations.

Any data library resulting from this effort should be made fully available to the international community through the IAEA. In the meantime, the IAEA was requested to look into the acquisition and dissemination of the activation file being assembled for ENDF/B-V.

Photonuclear activation is not of great importance in the blanket and shield, but may be of interest for plasma diagnostics (e.g., electron acceleration processes).

Decay data is generally available from the ENSDF library, but a convenient tabulation of averaged $\beta$-energies and other relevant data in machine-readable form would be very useful.

Table IIA

Nuclear Data Needs for Fusion Reactors

(from M.A. Abdou)

| Reaction | Type of Measurement | Incident Energy (MeV) | Accuracy Goal (%) | Priority [a] | Comments |
|---|---|---|---|---|---|
| $^{6}$Li elastic scattering | $\sigma_{n,n}$, $d\sigma/d\Omega$ | 2–16 | 10 | 2 | Reaction is important for good interpretation of other reactions. |
| $^{6}$Li inelastic scattering | $\sigma_{n,n'}$, $d\sigma/d\Omega$ | 2–16 | 10–20 | 2 | |
| $^{6}$Li neutron emission | $\sigma^{+}_{n,em.}$ | 3–16 | 5 | 2 | |
| $^{7}$Li inelastic scattering | $\sigma_{n,n'}$ | 2–16 | 10–20 | 2 | |
| $^{7}$Li neutron emission | $\sigma^{+}_{n,em.}$ | 2–16 | 5 | 1 | |
| $^{6}$Li(n,α)T | $\sigma_{n,\alpha}$ | 0.2–16 | 2–5 | 2 | |
| $^{6}$Li(n,2n′) | $\sigma_{n,2n'}$, $P\left(E_{n'}\right)^{*}$ | 6–16 | 10–20 | 2 | Source of helium and hydrogen production. |
| $^{6}$Li(n,n′p), $^{6}$Li(n,n′α) | $\sigma_{n,n'p}$, $\sigma_{n,n'\alpha}$ | 5–16 | 30 | 4 | Cross sections may be small but need to be examined. |
| $^{6}$Li(n,n′d) | $\sigma_{n,n'd}$, $P\left(E_{n'}\right)$ | 3–16 | 10–20 | 2 | |
| $^{7}$Li(n,n′t) | $\sigma_{n,n't}$, $P\left(E_{n'}\right)$ | 3–16 | 2–5 | 1 | |
| $^{7}$Li elastic | $\sigma_{n,n}$ | 2–16 | 10 | 2 | Elastic scattering is essential to interpreting important reactions such as (n,n′t). |
| $^{9}$Be neutron emission | $\sigma_{n,em.}$ | 1.8–16 | 10 | 3 | |
| $^{9}$Be(n,2n) | $\sigma_{n,2n}$ | 1.8–16 | 10 | 3 | |
| B elastic scattering | $\sigma_{n,n}$ | 6–16 | 5–15 | 2 | Isotopic values needed; reaction affects the interpretation of other reactions. |
| B neutron emission | $\sigma_{n,em.}$ | 6–16 | 10 | 1 | |
| B gamma production | $\sigma_{n,x\gamma}$, $P\left(E_{\gamma}\right)$ | $10^{-6}$–16 | 20 | 1 | |
| $^{10}$B(n,t) | $\sigma_{n,t}$ | 1.2–16 | 20 | 1 | |
| $^{11}$B(n,t) | $\sigma_{n,t}$ | 12–16 | | | |
| $^{10}$B(n,p) | $\sigma_{n,p}$ | 0.01–16 | 20 | 2 | |
| $^{10}$B(n,2n) | $\sigma_{n,2n}$, $P\left(E_{n'}\right)$ | 9–16 | 20 | 2 | $^{10}B(n,2n)^{9}B \rightarrow 2\alpha + p$ |
| $^{10}$B(n,n′p) | $\sigma_{n,n'p}$, $P\left(E_{n'}\right)$ | 7–16 | 30 | 2 | |
| $^{11}$B(n,α) | $\sigma_{n,\alpha}$ | 7–16 | 30 | 2 | The decay product is 2α. |
| $^{11}$B(n,2n) | $\sigma_{n,2n}$, $P\left(E_{n'}\right)$ | 12–16 | 30 | 2 | |
| C neutron emission | $\sigma_{n,em.}$ | 6–16 | 10 | 1 | |
| C(n,xα) | $\sigma_{n,x\alpha}$ | 6.5–16 | 10 | 2 | |
| C(n,α) | $\sigma_{\alpha_0}$, $\sigma_{\alpha_1}$, ... | 6.5–16 | 20 | 3 | Energy distribution of the charged particles is useful. |
| C(n,n′3α) | $\sigma_{n,n'3\alpha}$, $P\left(E'_{n}\right)$ | 8–16 | 10 | 1 | Total helium production, heating and neutron transport in carbon is very sensitive to this reaction. |

Table IIA (continued)

| | | | | | |
|---|---|---|---|---|---|
| $^{16}O$ Neutron emission | $\sigma_{n,em.}$ | 5–16 | 10 | 2 | Insulators, solid breeders |
| $^{27}Al$ neutron emission | $\sigma_{n,em.}$ | 5–16 | 20 | 2 | |
| $^{27}Al(n,2n)$ | $\sigma_{n,2n}$ | 13.5–18 | 20 | 2 | Cross section for production of $^{26m}Al$ (6.3 sec positron emitter) is major concern for induced activation. |
| $^{27}Al(n,p)$ | $\sigma_{n,p}$ | 14–16 | 20 | 2 | |
| $^{40}Ar(n,2n)$ | $\sigma_{n,2n}$ | Threshold–16 | 20 | 2 | Reactor building atmosphere. |
| Ti total cross section | $\sigma_{tot}$ | 1–20 | 2 | 2 | |
| $^{46}Ti$ inelastic / $^{48}Ti$ scattering | $\sigma_{n,n'}$ | 4–16 | 10 | 2 | |
| $^{47}Ti(n,p)$ | $\sigma_{np}, \sigma_{p_0}, \sigma_{p_1},\ldots$ | 10–16 | 20 | 2 | |
| $^{47}Ti(n,\alpha)$ | $\sigma_{n\alpha}, \sigma_{\alpha_0}, \sigma_{\alpha_1},\ldots$ | $10^{-6}$–16 | 20 | 2 | |
| $^{47}Ti(n,2n)$ | $\sigma_{n,2n}, P(E_{n'})$ | 9–16 | 20 | 3 | |
| $^{48}Ti(n,2n)$ | $\sigma_{n,2n}, P(E_{n'})$ | 12–16 | 20 | 2 | |
| $^{48}Ti(n,\alpha)$ | $\sigma_{n\alpha}, \sigma_{\alpha_0}, \sigma_{\alpha_1},\ldots$ | Threshold–16 | 20 | 3 | |
| V inelastic scattering | $\sigma_{n,n'}$, angular and energy distributions | 7–16 | 10–20 | 3 | |
| V neutron emission | $\sigma_{n,em.}$ | 7–16 | 10–20 | 2 | Angular distribution is of interest. |
| V(n,p) | $\sigma_{np}, \sigma_{p_0}, \sigma_{p_1},\ldots$ | 2–16 | 20 | 3 | |
| V(n,α) | $\sigma_{n\alpha}, \sigma_{\alpha_0}, \sigma_{\alpha_1},\ldots$ | 3–16 | 20 | 3 | |
| V(n,2n) | $\sigma_{n,2n}, P(E_{n'})$ | 12–16 | 10 | 2 | |
| V(n,n'p) / V(n,n'α) | $\sigma_r, P(E_{n'})$ | 8–16 | 20 | 4 | |
| Cr neutron emission | $\sigma_{n,em.}$ | 8–16 | 10 | 1 | |
| Cr(n,xα) | $\sigma_{n,x\alpha}$ | Threshold–16 | 20 | 2 | |
| Cr(n,xp) | $\sigma_{n,xp}$ | Threshold–16 | 20 | 2 | |
| $^{52}Cr(n,p)$ | $\sigma_{n,p}, \sigma_{np_0}, \sigma_{np_1},\ldots$ | Threshold–16 | 30 | 2 | |
| $^{53}Cr(n,p)$ | | | | 2 | |
| $^{54}Cr(n,p)$ | | | | 4 | |
| $^{50}Cr(n,p)$ | | | | 4 | |
| $^{52}Cr(n,2n)$ | $\sigma_{n,2n}, P(E_{n'})$ | ~12–16 | 20 | 2 | |
| $^{52}Cr(n,d)$ | $\sigma_{n,d}, \sigma_{nd_0}, \sigma_{nd_1},\ldots$ | ~9–16 | 30 | 3 | |
| $^{55}Mn(n,2n)$ | $\sigma_{n,2n}$ | 12–16 | 20 | 2 | |
| $^{55}Mn(n,p)$ | $\sigma_{n,p}$ | 2–16 | 20 | 3 | |
| $^{55}Mn(n,\alpha)$ | $\sigma_{n,\alpha}$ | 1–16 | 20 | 3 | |
| $^{55}Mn(n,n',p)$ | $\sigma_{n,n'p}$ | 6–16 | 30 | 3 | |
| $^{55}Mn(n,n',\alpha)$ | $\sigma_{n,n'\alpha}$ | 8–16 | 30 | 3 | |

Table IIA (continued)

| | | | | | |
|---|---|---|---|---|---|
| Fe neutron emission | $\sigma_{n,em.}$ | 8–16 | 10 | 1 | |
| $^{54}$Fe, $^{56}$Fe(n,α) | $\sigma_{n,\alpha}$ | $10^{-6}$–16 | 20 | 2 | Energy distributions of emitted alphas are very useful. |
| | $\sigma_{\alpha_0}$, $\sigma_{\alpha_1}$, $\sigma_{\alpha_2}$,... | | 40 | 3 | |
| $^{54}$Fe(n,n′p) | $\sigma_{n,n'p}$, $P(E_{n'})$ | ~9.5–16 | 20 | 2 | |
| Ni neutron emission | $\sigma_{n,em.}$ | Threshold–16 | 10–20 | 2 | Angular distribution required where significantly anisotropic. |
| $^{58}$Ni inelastic scattering | $\sigma_{n,n'}$ | 4–16 | 10–20 | 2 | |
| (level and continuum) | Angular and energy distributions | 6–16 | 20–30 | | |
| $^{60}$Ni inelastic scattering | $\sigma_{n,n'}$ | 8–16 | 10–20 | 2 | |
| (level and continuum) | Angular and energy distributions | 6–16 | 20–30 | | |
| $^{58}$Ni(n,n′p), $^{60}$Ni(n,n′p) | $\sigma_{n,n'p}$, $P(E_{n'})$ | Threshold–16 | 20 | 1 | Current uncertainity ~200%. |
| $^{58}$Ni(n,2n) | $\sigma_{n,2n}$, $P(E_{n'})$ | Threshold–16 | 10 | 3 | Data currently available but there are some discrepancies at high energies. |
| $^{60}$Ni(n,2n) | $\sigma_{n,2n}$, $P(E_{n'})$ | Threshold–16 | 10 | 2 | Currently, no data. |
| $^{58}$Ni(n,α), $^{60}$Ni(n,α) | $\sigma_{n\alpha}$, $\sigma_{\alpha_0}$, $\sigma_{\alpha_1}$,... | $10^{-6}$–16 | 10 | 1 | |
| $^{58}$Ni(n,n′α), $^{60}$Ni(n,n′α) | $\sigma_{n,n'\alpha}$ $P(E_{n'})$ | 7–16 | 20 | 4 | |
| Cu neutron emission | $\sigma_{n,em.}$ | 2–16 | 10 | 1 | |
| Cu *gamma* production | $\sigma_{n,x\gamma}$, $P(E_{\gamma})$ | $10^{-6}$–16 | 20 | 1 | |
| $^{63}$Cu(n,p) | $\sigma_{n,p}$, $\sigma_{np_0}$, $\sigma_{np_1}$,... | 1–16 | 20 | 1 | |
| $^{63}$Cu(n,d), $^{65}$Cu(n,d) | $\sigma_{n,d}$, $\sigma_{nd_0}$, $\sigma_{nd_1}$,... | 10–16 | 30 | 2 | |
| $^{63}$Cu(n,n′p) | $\sigma_{n,n'p}$, $P(E_{n'})$ | 9–16 | 20 | 1 | |
| W inelastic scattering | $\sigma_{n,n'}$ | 1.5–4 | 10 | 4 | |
| W elastic scattering | $\sigma_{n,n}$, $d\sigma/d\Omega$ | 2–6<br>8–16 | 10 | 4 | |
| W neutron emission | $\sigma_{n,em.}$ | 4–16 | 20 | 3 | |
| W gamma production | $\sigma_{n,x\gamma}$, $P(E_{\gamma})$ | $10^{-6}$–16 | 20 | 1 | |
| Pb neutron emission | $\sigma_{n,em.}$ | 6–16 | 20 | 2 | |
| Pb(n,n′) | Discrete inelastic scattering | 8–16 | 20 | 2 | |

*$P(E_{n'})$ refers to the energy distribution of secondary neutrons.

+ For all entries in the table, $\sigma_{n,em.}$ refers to the neutron emission spectra and angular distribution, $\sigma_{n,nem}(E_{n'}, \Theta_{n'})$, generally required at several angles with outgoing neutrons recorded down to a few hundred keV.

a. Priorities are assigned as follows: (1) Urgent, (2) important, (3) necessary, (4) desirable.

## Radiation Effects References

The following recent meetings and reviews on radiation effects pertinent to fusion reactor technology were noted:

1. "Radiation damage in metallic reactor materials", H. Ullmaier and W. Schilling, Int. Course on Physics of Modern Materials, ICTP Trieste, June 1978. Proc. to be published by IAEA.

2. NEANDC/NEACRP Specialists' Meeting on Neutron Data of Structural Materials for Fast Reactors, CBNM Geel, Belgium, December 1977. Proc. published by Pergamon Press, 1979.

3. First Topical Meeting on Fusion Reactor Materials, January 19-31, 1979, Miami Florida, USA. Proc. to be published by American Nuclear Society.

4. "Radiation Effects and Tritium Technology for Fusion Reactors", J.S. Watson and F.W. Wiffen, editors. Proc. of a conference at Gatlinburg, Tennessee, USA, October 1975, CONF-750989 (1976).

5. "Radiation Damage in Organic Insulators", C.A.M. van der Klein, RCN-240, Reactor Centrum Nederland (1975).

6. BNL-NCS-50681, proc. Symposium on Neutron Cross-Sections from 10 to 40 MeV, Brookhaven National Laboratory, (May 1977).

7. "Radiation Damage in Super-Conducting Materials", proc. 1978 Argonne National Laboratory meeting published in J. Nucl. Materials 72 (1978).

8. "The Effects of Radiation on Electrical Insulators in Fusion Reactors", D.C. Phillips, AERE-R-8923, Harwell, (June 1978).

9. "Electrical Insulator Requirements for Fusion Reactors", R.H. Condit and R.A. Van Konynenburg, Lawrence Livermore Laboratory, UCRL-52098 (1977).

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Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology

Vienna, 11 to 15 December 1978

## ADOPTED MEETING AGENDA

| | |
|---|---|
| Monday | Introductory Items |
| | - Opening and announcements |
| | - Selection of working group chairmen |
| | - Collection and distribution of papers |
| | Presentation of Part A Papers |
| | Chairman: H. Liskien |
| Tuesday | Presentation of Part B Papers |
| | Chairman: O.N. Jarvis |
| Wednesday and Thursday | Full day meeting of working groups |
| | - Working group on Neutron Transport and gamma-Ray Production. Chairman: D.J. Dudziak |
| | - Working group on Radiation Effects. Chairman: S.M. Qaim |
| Friday | Plenary session for the discussion and final approval of conclusions and recommendations of the working groups. Chairman: J.J. Schmidt |

Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology

Vienna, 11 - 15 December 1978

Introductory Paper

Nuclear Data Requirements of the Magnetic Fusion Power Program of the United States of America. (C. Head, DOE Washington, USA)

Review Papers

A. Nuclear Data Requirements for Fusion Reactor Design

1. Nuclear Data Requirements for Fusion Reactor Design - Neutronics Design, Blanket Neutronics and Tritium Breeding. (G. Constantine, AERE Harwell, UK)

2. Review of Nuclear heating in Fusion Reactors (Y. Seki, JAERI Tokai, Japan)

3. Nuclear Data Requirements for Transmutation and Activation of Reactor Wall and Structural Materials. (O.N. Jarvis, AERE Harwell, UK)

4. Nuclear Data Needs for Radiation Damage Studies Relevant to Fusion Reactor Technology. (S.M. Qaim, KFA Juelich, Federal Republic of Germany)

5. Nuclear Data Requirements for Fusion Reactor Shielding. (M.A. Abdou, Georgia Institute of Technology, Atlanta, USA)

6. Neutron Data for Hybrid Reactor Calculations. (Review written by D.V. Markovskii and G.E. Shatalov and presented by V.V. Kotov, all of Kurchatov Atomic Energy Institute, Moscow, USSR)

B. Status of Nuclear Data Required for Fusion Reactor Design

1. Cross-Section Sensitivity and Uncertainty Analysis for Fusion Reactors - A Review. (D.J. Dudziak, Los Alamos Scientific Laboratory, USA)

2. Theoretical Approach to Nuclear Data Required for Fusion Reactor Calculations. (D. Seeliger, Technische Universitaet Dresden, German Democratic Republic)

3. Evaluated Files of Nuclear Cross Sections for Fusion Reactor Calculations. (M.R. Bhat, Brookhaven National Laboratory, USA)

4. Neutron Reaction Data in the MeV Range. (H. Liskien, CBNM Geel, Belgium)

5. Neutron Total, Elastic and Inelastic Scattering and Gamma-Ray Production Data. (F.G. Perey, Oak Ridge National Laboratory, USA)

6. Status of 14 MeV Neutron Cross Section Data. (J. Csikai, Kossuth University, Debrecen, Hungary)

7. Data for Charged Particle Reactions with Heavier Nuclides. (H. Muenzel, KFZ Karlsruhe, Federal Republic of Germany)