International Atomic Energy Agency

INDC(NDS)-65/L+N

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

IAEA PANEL

ON

FISSION PRODUCT NUCLEAR DATA

Bologna, 26-30 November 1973

Summary

Observations, Conclusions and Recommendations

of the Panel

Edited by

M. Lammer

Nuclear Data Section

International Atomic Energy Agency

Vienna, Austria

March 1975

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

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S u m m a r y

OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS OF THE PANEL

In view of the complexity of the topics discussed at this Panel meeting, the observations, conclusions and recommendations on different major subjects are grouped together in the following seven chapters:

Chapter 1: Introduction (General observations, conclusions and recommendations).

Chapter 2: International cooperation in the exchange and dissemination of FPND information.

Chapter 3: FP inventory and decay heat.

Chapter 4: FP yield data.

Chapter 5: FP decay data.

Chapter 6: Delayed neutron data.

Chapter 7: Neutron cross-sections.

A summary of the important recommendations is given in Chapter 8. Comparisons of user requirements and data status for individual FPND are presented in Appendices A1 - A5:

Appendix A1: FP chain yields.

Appendix A2: Independent and cumulative fission yields.

Appendix A3: FP decay data.

Appendix A4: Neutron reaction cross-sections.

Appendix A5: FP decay heat.

1. INTRODUCTION

1.1 Scope

The Panel achieved a first review of requirements, status and availability of fission product nuclear data (FPND) important for various fields of practical applications. The topics discussed by the meeting are reflected by the titles of the review papers. The scope of the Panel was limited to these topics, as discussed in Review Paper 1a (but see also 1.2.1-(iv)).

The FPND considered by the Panel were of the following categories:

A. Yields (cumulative and independent)

B. Decay data

C. Delayed neutron data

D. Neutron reaction cross-sections

These categories included also integral FPND such as the total decay energy released after reactor shutdown (B) and total absorption of lumped FP (D).

This was the first meeting where users and producers of FPND met to compare required FPND accuracies with the status of available FPND and to discuss further experimental and evaluation work needed and measures for an improved communication between FPND users and producers. Apart from their own experience, the Panel participants relied on the background information supplied by the review papers. These review papers were internationally coordinated incorporating contributions from many experts in the field in order to provide a broad spectrum of opinions and to include also most recent experimental results.

The observations, conclusions and recommendations issued by the Panel are intended to stimulate coordinated activities in various laboratories whose results should be reviewed in a follow-up meeting of the same kind.

1.2 General observations and conclusions

1.2.1 User requirements

(i) The FPND and their accuracies required by users as observed by the Panel are discussed in chapters 2-7 and summarized in the Appendices A1-A5, together with the status of required FPND. These

appendices represent a first broad picture of the present knowledge of FPND requirements.

The Panel noted, however, that, with some exceptions, the requirements were not sufficiently supported by sensitivity studies relating requested FPND accuracies to those needed for the prediction of relevant technological parameters, and that a more thorough assessment based on the available experimental evidence was generally also lacking. It also noted that other users not present at this meeting might have different requirements.

Therefore the Panel wishes to emphasize the preliminary nature of the presently compiled requirements, but expresses the hope that they will stimulate critical comments and more detailed investigations and thus help to pave the way towards a better screened true "international FPND request list" (see recommendation in chapter 2).

(ii) The discussions on FPND requirements were generally limited to applications already in use. While the Panel recognized the importance of experimental studies of specific problems and the development of new methods in application fields, not all of these topics could possibly be covered at this meeting.

(iii) Review paper no. 6 discusses in detail the role of FPND in nuclear materials safeguards. In summary, the methods in safeguards that need FPND are not used routinely but only in special cases. These methods, although already used in test cases, need further development and detailed investigations of their applicability. Therefore FPND requirements for safeguards have low priority compared to other user needs and further sensitivity studies are necessary (see (i) above).

(iv) The scope of the Panel was limited to the discussion topics of the review papers. However, the Panel considered three more topics to be worth discussing during the meeting:

- Photoneutrons are of importance, especially in reactors containing heavy water or Be. A significant number of photoneutrons is produced in these reactors from high energy bremsstrahlung and γ-rays produced in FP decay, as well as from fission and capture γ-rays. This topic was discussed only briefly and the individual FP's in question have not yet been identified, but general statements on the relevant FPND are included in chapters 4 and 5.

- Fuel element design was briefly discussed during the meeting. R.H. Flowers, an expert in this field, supplied the Panel with background information and data requirements, which are reproduced in chapter 3.

- In fast reactor dosimetry fission yields are required for measurements using ^{232}Th, ^{235}U, ^{236}U, ^{238}U, ^{237}Np and ^{239}Pu as fluence monitors. Needs for the LMFBR and FTR programme at Hanford (USA) were presented to the Panel by R.E. Schenter and are included in Appendix A1, Table A1-III. U. Farinelli summarized the conclusions of the IAEA Consultants Meeting on Nuclear Data for Reactor Neutron Dosimetry, held in Vienna from 10-12 September 1973. ("Others" in Appendix A1, Table A1-III).

1.2.2 Status of FPND

Reviewers of the status of FPND had the task of surveying existing evaluations supplemented by recent experimental results. The Panel noted that the assignment of uncertainties by evaluators was not always satisfactory, in some cases even missing, particularly for FP decay data.

On the basis of the Panel discussions FPND uncertainty figures were compiled from selected evaluations. They are listed in Appendices A1-A5 to allow a comparison with user requirements. The Panel discussed and suggested improvements of evaluations in general which are outlined in section 1.2.3. Special requirements pertaining to evaluations of specific FPND are included in chapters 4 to 7.

1.2.3 Evaluation

First the Panel recalled that the essential task of the evaluators is to critically review available experimental data and provide users with a set of "best" values. However, in order to enable the user to judge the quality of an evaluation and rely on the values recommended, it is important that the evaluator documents in detail the experimental data basis, the method and the results of his work. The presently available evaluations of FPND fall partly short of this ideal.

The experimental data considered in the evaluation, the physical conditions under which they were obtained, sources of statistical and systematic errors and discrepancies between the data are often not documented and probably not satisfactorily investigated; the Panel noted, however, a few exceptions where evaluators had been able to correct original data and thus

resolve discrepancies between them. Furthermore FPND evaluators sometimes do not assign properly assessed uncertainties to their recommended data (and sometimes cannot do so because of the inadequacy of the experimental data); such uncertainties are often very important to the user and will influence his choice of an evaluation. In this context the Panel observed that evaluators, in order to cope satisfactorily with these tasks, should be able to judge experimental results adequately. This would be easier if the experimenters would describe their measurements in sufficient detail and, in particular, perform a satisfactory error analysis separating random and systematic errors.

The above mentioned shortcomings are some of the reasons why different evaluations of FPND usually show different results. Other reasons consist in differences in the experimental data basis available to the evaluator, in unresolved discrepancies between different experimental data and justifiable differences in the evaluators' judgement and methods of analysis of the experimental data. Also the objective of an evaluation and the time and effort an evaluator is allowed to spend on an individual task have an influence on the final result and its quality.

These observations led the Panel to express concern not to aim at the establishment of only one standard FPND library, which some users would find convenient, but to pursue several independent evaluation efforts: The users should not have to rely on the results of one evaluation only but be able to choose among different evaluations and to select the one best fitting their purposes. The adoption of a standard format for data, as discussed later, is a key step in making this approach workable.

1.2.4. FPND user-producer communication

It was the impression of the Panel that the simultaneous presence of measurers, evaluators and users of FPND at one meeting stimulated fruitful discussions resulting in a better understanding of each others' problems. Closer contacts in the future should be established by improved ways of communication as suggested by the panel and outlined in chapter 2.

1.3. General Recommendations

(i) The Panel recommends that users of FPND perform sensitivity studies to enable a better specification of their requirements.

(ii) FPND evaluation work should continue to be performed at different places.

(iii) Evaluators are requested to publish all pertinent details of their work. They should attempt to identify systematic errors and resolve discrepancies. They should assess random and systematic errors separately, assign uncertainties to their recommended data and warn users in cases of unresolved discrepancies. Recognizing the magnitude of the work which is implied in these requirements and its importance to FPND users the Panel recommends that in future stronger support be given to FPND compilation and evaluation.

(iv) Measurers are requested to publish all details on experimental conditions, corrections applied and error analysis required for an adequate comparison with other measurements. A recommendation to improve the intercommunication between measurers and evaluators in this matter is included in chapter 2.

(v) A follow-up panel should be convened in about three years to review the progress in FPND measurement and evaluation, and sensitivity studies stimulated by the present meeting. Discussion topics should again be covered by review papers in order to provide background and save time for discussion. It is to be hoped that this follow-up meeting will be in a position to set up a final list of user requirements based on sensitivity studies.

(vi) Surveys of user requirements of FPND should be completed and distributed to reviewers of the status of FPND well in advance of the follow-up panel, so as to give the status reviewers sufficient time to prepare lists of uncertainties for the required FPND.

2. INTERNATIONAL COOPERATION IN THE EXCHANGE AND DISSEMINATION OF FPND INFORMATION

2.1. Observations and conclusions

(i) The Panel noted in general that a regular exchange and dissemination of information in the field of FPND is lacking.

(ii) The list of FPND compilations and evaluations provided by Valente from NEA/CCDN (review paper 1b) to the meeting was found most valuable by the Panel participants.

(iii) The Panel observed that, in spite of the large number of existing FPND compilations listed in Valente's review paper, evaluated FPND are only partially included in the most widely used computer files of evaluated nuclear data.

(iv) The recent inclusion of FP yield and decay data in the US ENDF/B library was considered a great step forward. FPND data types and associated physical quantities foreseen in the ENDF format are specified in Annex 1 to this chapter. Some critical remarks concerning these specifications are given in Annex 3.

(v) One of the main difficulties encountered in the comparison and mutual conversion of different evaluated nuclear data files are the differences in physical content associated with certain classes of data. Such differences should be avoided when new classes of data are introduced and should, where possible, be eliminated for data already existing in files.

(vi) During the meeting it was frequently observed that the communication between the measurers, evaluators and users of FPND is still unsatisfactory:

- sources of available evaluated FPND are not sufficiently well known to users;
- users and evaluators have no means to inform FPND measurers about their requirements, except in the field of neutron induced reaction data, where WRENDA exists.
- the communication channels between FPND measurers, evaluators and users via presently existing publishing media are too slow, thus affecting also the efficient planning and coordination of experimental and evaluation work;
- at present there exist no convenient means of informing those interested in FPND about observed discrepancies.

2.2. Recommendations

(i) The Panel recommends that the list of FPND compilations and evaluations as provided by Valente from NEA/CCDN to this meeting be kept up-to-date and published at annual intervals.

In order to enhance the value of the list, it is recommended that future issues should contain short comments by the authors to each reference concerning its content, up-to-dateness, application area and a specification of the availability in computer medium of the data concerned including the computer format.

The first updated list should be published not later than one year after the panel. The Panel participants leave it to the discretion of NEA/CCDN, IAEA/NDS and other nuclear data centres to decide which centre will publish the list in the future. Until such decision is taken it is recommended that Valente from NEA/CCDN act as contact. The nuclear data centres concerned should explore the most suitable ways of obtaining the information to be included in the list and of channelling it to the publishing centre on a regular basis.

In addition to the participants in this meeting, the list should be given a wide distribution particularly among users and producers of FPND.

To determine the distribution of the list outside the Panel the assistance of participants in this Panel should be solicited as well as of the Members and Liaison Officers of INDC, EANDC and other regional and national nuclear data committees. Until further notice all information in this respect should be sent to Valente.

(ii) It is recommended that an international newsletter on activities in the field of compilation and evaluation of FPND be developed as soon as possible. This newsletter should be published in regular intervals of 4-6 months. For each group or individual concerned it should list available manpower, names and addresses and contain a concise description of work finished, underway and planned and of recent publications and computerized data files with a brief indication of their format. Discrepancies in important FPND should be stated and also brought to the attention of the INDC Subcommittee on Discrepancies.

Noting that the international exchange of evaluated data is still restricted, the Panel proposes that as soon as possible, this recommendation be approved by INDC and brought to the attention of EANDC and other regional and national nuclear data committees.

The Newsletter should preferably be compiled and published by IAEA/NDS. It is however, left to the discretion of IAEA/NDS, NEA/CCDN and other nuclear data centres to decide upon this in the shortest possible delay after approval by INDC.

The newsletter should be distributed particularly to compilation and evaluation centres, and to groups and scientists working in the field of nuclear data, especially FPND.

(iii) It is recommended further that another separate international newsletter be developed covering measurement activities directly or indirectly related to FPND. Form and content of this newsletter should follow the model of the neutron capture γ-ray newsletter edited by G.A. Bartholomew and co-workers at Chalk River, Canada. For each experimental group it should contain a concise description of available facilities and manpower, of experimental work finished, underway and planned; it should list recent and forthcoming publications and give names and addresses of the scientists involved; it should also point to data discrepancies and specify standards used if suitable.

The newsletter should be published every 6 months and given a wide distribution particularly among measurers, but also compilers and evaluators of FPND. The aforementioned nuclear data committees and the participants in this panel should help to determine a suitable distribution. Also this newsletter should be published preferably by IAEA/NDS.

The approval of INDC for this newsletter should be sought as soon as possible and EANDC and other regional and national nuclear data committees should be informed of its decision. After INDC approval the nuclear data centres involved should decide who is to publish the newsletter. and its first issue should be published as soon as possible.

The Panel participants considered it suitable if, in addition to direct contacts, the Members and Liaison Officers of INDC would help to make sure that the contributions of their countries to the newsletter are provided regularly and on time to the publishing centre. For the time being IAEA/NDS will be the point of contact in all matters concerning this newsletter.

(iv) In order to improve the communication between users and producers of FPND it is recommended that the INDC at its next meeting in October 1974 discuss and approve the development of an international request list for FPND.

In order to assure that the list represent a realistic picture of the FPND requirements the Panel recommends that FPND requests should be justified by appropriate sensitivity studies and critically screened on the national scale before being submitted for international publication. These requests should be consistent with the Panel's findings, which emerged from discussion between users, measurers and evaluators of FPND.

In the compilation and publication of the list the existing WRENDA computer formats and intercentre cooperation should be used. The list should be updated and published by IAEA/NDS in annual intervals. The first issue should be published as soon as feasible after approval by INDC. The list should be given a wide distribution, particularly among nuclear physicists and measurers of FPND.

(v) In order to avoid a proliferation of computer formats the Panel recommends that the formats of FP yield and decay data as developed for the ENDF/B library and specified in Annex 1 with due regard of the deliberations presented in Annex 3 be adopted as the standard formats for the exchange of such data; for this purpose (A,Z) ordering should be used. For those institutions wishing to simplify that data for their own use some suggestions are given in Annex 2.

(vi) It is recommended that FP group cross sections (see Annex 2) be included in evaluated nuclear data files, provided that energy groups and spectrum used for averaging are specified in the same file.

(vii) Following the general discussion about information on experimental details needed by evaluators (chapter 1) the Panel recommends to improve the intercommunication between measurers and evaluators and to initiate a circular which would list information on experimental details, corrections applied, error analysis etc. evaluators require from FPND measurers. IAEA/NDS is to send a questionnaire to evaluators of FPND, asking them to state the information they want to obtain from

measurers. After having received the replies from evaluators, IAEA/NDS is to draft the circular and send it to evaluators for comment. The final, approved, version of the circular will be distributed to measurers. In addition, the circular will be included in one of the two newsletters recommended above.

It is realized that the inclusion of lengthy information on experimental details in publications may not be accepted by editors of scientific journals. Therefore it may be more appropriate to publish such information in laboratory reports, or send an information sheet directly to evaluators for their use.

(viii) The Panel noted that many observations and recommendations resulting from this meeting are of direct concern to the specialists group on nuclear data for applications to be convened by IAEA/NDS in Vienna from 29 April - 3 May 1974. This group will have the objective to coordinate on an international scale the compilation, evaluation, exchange and dissemination of nuclear level scheme and decay data of importance for applications in science and technology. The Panel recommends that all relevant observations and recommendations resulting from the present meeting including the data scope of FPND be given suitable consideration in the work of the specialists' group.

Annex 1

Definition of quantities in the ENDF format for FP yield and decay data

A detailed description of ENDF formats can be found in ENDF-102, Vol. I (last edition: BNL-50274, October 1970), which is generally available. Revisions have been made recently and are included in the data specifications given below. ENDF/B processing codes are described in ENDF-110 and the documentation of data is given in ENDF-201; both are also generally available.

Data type	Data specifications	Remarks
FP independent yields		FP yield data are listed for each individual fissile nuclide.
	- fission product identifier	- ZA, integer or real
	- isomeric state flag	- integer or real
	- yield	$\sum_i y_i = 2$
	- neutron energy or	- as a parameter (eV)
	- neutron spectrum specification	- recommended to give an evaluated point-wise spectrum
Radioactive decay data	General information:	
	- original nuclide identifier	- ZA, integer or real
including: $\alpha, \beta^-, \beta^+, \gamma$ isomeric trans. delayed neutrons	- isomeric state flag	- integer
	- half life of original nuclide	- in seconds
	- uncertainty of half life	- evaluated relative error, 1 standard deviation
	- number of average decay energies given	- integer
	- average decay energy for radiation x ($\bar{E}_x$)	- in eV; given in the order β, γ, α; delayed neutrons are presently included as β-decay
	- uncertainty of $\bar{E}_x$	- in eV

Annex 1 (cont'd.)

Data type	Data specifications	Remarks
	Decay mode information:	given for each mode of decay
	- total number of decay modes given	- integer
	- decay mode identifier	- real, included are γ,β^-,β^+,IT,α, delayed ns
	- isomeric stage flag for daughter nuclide	- integer or real
	- total decay energy (Q)	- in eV, Q-value available in corresponding decay process
	- uncertainty in Q	- in eV
	- decay branching (BR)	- fractional; given for radiation x
	- uncertainty of BR	
	Radiation spectra:	given as function of radiation energy for every decay mode
	- decay mode identifier	
	- number of spectra	- integer
	- radiation energy (E)	- in eV
	- uncertainty of E	- in eV
	- intensity of radiation (I)	- relative intensity, arbitrary units
	- uncertainty in I	- same units as I
	- internal conversion coefficient (ICC)	
	- uncertainty of ICC	
	- normalization factor (F)	- = ratio absolute intensity/relative intensity
	- uncertainty of F	- same unit as F
	- total number of energy points	

Annex 2

Specifications of FPND for applications

Data type	Application	Data specifications	Remarks
FP group cross section $\int(n,\gamma)$ or others $\int$ (also for pseudo-FP)	burn-up long-range dynamics inventory calculation*	- Specification of group system, spectrum and method of averaging - Nuclide identifier - cross section type indicator - group cross sections - uncertainties of the group cross sections	) once for all FP - ZA, integer or real - integer - relative error
Independent yields of a FP nuclide	burn-up, long--range dynamics, decay heat inventory calculation*	- FP nuclide identifier - Identifier of fissionable nuclides having this FP - yields - neutron energy or - spectrum specification	- ZA, integer or real) ZA, integer or real - as a parameter (eV) - recommended to give an evaluated point-wise spectrum

- cont.

Annex 2
(cont.)

Data type	Application	Data specifications	Remarks
Decay constants	long-range dynamics inventory calculation*	- Daughter nuclide identifier - Identifier of nuclides decay of which leads to the above daughter nuclide - decay constants	- ZA, integer or real) ZA, integer or real - sec^{-1}
x-decay data ($x=\alpha,\beta,\gamma$)	shielding design, safeguards, decay heat	- Nuclide identifier - Total decay energy (Q) - Uncertainty of Q - Average energy of radiation($\bar{E}x$) - uncertainty in $\bar{E}_x$ - Point-wise spectrum - energy of radiation $x(E_x)$ - uncertainty of E_x - intensity of radiation $x(I_x)$ - uncertainty of I_x - Normalization factor (F) - uncertainty of F	- ZA, integer or real - eV - relative error - eV - relative error - eV - relative error - relative - relative error - ratio absolute/relative intensity - relative error

Annex 2
(cont'd.)

Data type	Application	Data specifications	Remarks
Delayed neutron precursor data (Note: in ENDF delayed neutron precursor data are part of the decay data)	Reactor kinetics, safeguards fuel failure detection reactor operation	- Identifier of precursors - total decay constants - uncertainty of decay constant - cumulative yields of precursors - probability of neutron decay(Pn) - uncertainty of Pn - point-wise spectrum - delayed neutron energy (En) - uncertainty of En - incident neutron energy or - spectrum specification	- ZA, integer or real - sec. $^{-1}$ - relative error - fractional, absolute values - relative error - eV - relative error - as a parameter (eV) - recommended to give an evaluated point-wise spectrum

* As applied in shielding, reactor safety operation, fuel element endurance, etc.

Annex 3

Format Requirements for a library of evaluated FPND

A library of evaluated FPND has to contain:

i) FP yields;
ii) half-lives or the equivalent decay constant for the radioactive FP;
iii) beta and gamma ray intensities, energies and branching ratios for each FP;
iv) cross sections for each FP.

We shall discuss each item in detail, but first a few general comments are in order.

1. The data may be arranged either by FP nuclide, giving for each in turn yields, half-lives, decay data and cross-sections; or in blocks giving first all the yields then all the half-lives, then all decay data and finally all cross sections; or in some intermediate arrangement. Putting the data in blocks makes revision much easier as data from, say, a new evaluated fission yield library may be incorporated without much effort. Consequently, some blocking is recommended: certainly yields should be separate, and there are advantages in complete blocking.

2. It will be very useful to have some bibliographic information in the library, so that the sources of the data can be identified. Of course any user programme must then be able to read alphanumeric input.

3. One must always expect large amounts of data to have some punching errors, and often these may evade quite careful visual checking. In addition, faults and errors can occur on magnetic tapes during storage and use. To be able to detect such errors built-in checks are always desirable in large data libraries and suggestions for some will be made in the following sections.

Re (i): FP yields

Yields are needed for each fissile nuclide that is likely to be present in a reactor fuel, and either for several neutron spectra (e.g. thermal and fast power reactor) or at several specified neutron energies. In the latter case an interpolation scheme has to be assumed. For the input to an FP inventory programme, yields in reactor spectra are preferable but, for the exchange of data, specifying particular energies has the advantage of greater generality: but note that in this case the task of evaluation would be harder because most measurements of yields to date have been made in reactor spectra. Of course, a measurement in a reactor spectrum could be represented as a measurement at some suitable mean energy.

Either independent yields or chain yields and fractional independent yields may be stored. The latter alternative allows chain yields to be altered without having to re-punch fractional yields and permits extra checks to be made on the data: chain yields adding to 2 and fractional yields for each chain adding to unity. If independent yields are given they should sum to 2. Fractional independent yields for each chain of mass A may be expressed either explicitly for each Z or parametrically in terms of the most probable charge $Z_p(A)$ and the width $\sigma(A)$ of a Gaussian distribution: usually they are calculated from such a distribution.

Re (ii): Decay constants

Either half-lives or decay constants (in sec^{-1}) may be given. The former choice makes visual checking easier especially if each half-life is given in the most appropriate unit of time (sec, min, hour, day or year) with the rule that the unit be chosen so that the numerical value of the half-life is as small as possible but not less than 1. The unit could either be specified by a numerical code or by its initial letter: the latter allows easier checking but requires slightly more complicated programming. Although the ENDF format at present requires the half-life to be given in seconds, a blank field is available in which a unit indicator could be specified.

Re (iii): Decay schemes

The essential data are (i) average beta energies, (ii) gamma ray energies and intensities and (iii) branching ratios to alternative product nuclides or isomeric states. No existing programme calculates a beta energy spectrum for gross fission products and it is most unlikely that this will ever be needed, so that average beta energies are adequate. The French library gives beta end - point energies and probabilities, so the data have to be processed by an auxiliary programme to obtain the average energy. One small disadvantage of this refinement is that presumably all the transitions are assumed to be allowed, as no information is stored about the classification of each beta decay.

For gamma-rays a spectrum is needed, for use in shielding calculations. One can group gamma energies in "bins", or give individual energies: this latter more general convention seems preferable as the specification of the "bins" may need changing as photon transport codes become more powerful. Conversion electron and X-rays should be given in a special "bin" or line.

Intensities for individual transitions may be given either absolutely or relatively.

It is worth pointing out that none of the libraries available contains all the data available in a full decay scheme. This would involve giving, for each level of the product nucleus, its spin and parity and energy above the ground state and the probability of decay to it from the parent nucleus and of decay from it to each lower level. However, such extra-complexity would not give any extra useful information to FP inventory programmes.

It is necessary to have a rule for defining "isomeric state". The compilers of ENDF assume that no level with a half-life less than 0.1 sec. need be considered separately as an isomeric state: this limit appears quite adequate.

Re (iv): Cross sections

Inventory programmes need (n,γ) cross sections for thermal, resonance and fast groups. On the other hand, ENDF/B, being part of a larger library, gives only point cross-sections for all relevant reactions. However, few-group cross-sections will depend on reactor spectrum, and so it will be desirable to be able to change them easily. Consequently, if ENDF is adopted as standard, it is suggested the the FP library contain, as an additional separate block, well defined few-group capture cross-sections. The details of a proposed format can be discussed later.

Uncertainties

ENDF allocates space for uncertainties in half-lives, decay data and branching ratios. This is an interesting and potentially useful development, which is very much appreciated by FPND users. The inclusion of yield data uncertainties should also be developed for ENDF. For problems such as the calculation of the FP decay heat and its error, the Panel considers the knowledge of FPND uncertainties as indispensable.

Conclusions

ENDF fits the requirements better than the other formats and as it also has advantages in the international exchange of data, its use as standard is recommended. It may be possible to make a few changes in it to make it match up even better to the requirements.

Consideration of possible checking programmes should begin as soon as possible. A short list of checks that could be made follows:

a. Yields should add to 2.
b. $\bar{\nu}$ should be calculated, from the yields, for comparison with recommended values: in addition, the mean atomic number should equal $Z/2$, where Z is the atomic number of the fissile nucleus.
c. Partial decay energies should sum to the total available.
d. Branching ratios should add to unity.

3. FP INVENTORY AND DECAY HEAT

3.1. General subdivision of data requirements

3.1.1. Observations and conclusions

(i) FP inventory is the amount of individual and collective fission products present in a fuel element or part hereof, or in the reactor core, at any time during or after irradiation. FP inventories are required in nearly all areas connected with the nuclear fuel cycle, as covered by RP's 2-7 at this meeting. FPND required for the determination of inventory are:

- FP yields
- neutron absorption and - capture cross-sections
- half lives
- decay branching ratios

These data are referred to as "inventory data" in the following.

(ii) In some cases only the knowledge of certain bulk properties of mixed FP is required and the inventory of individual FP can be replaced by that of groups of FP, e.g.:

- total FP absorption: individual FP are replaced by pseudeo FP;
- delayed neutrons: the total delayed neutron yield or delayed neutron groups are sufficient in most cases;
- total FP energy release: the concept of pseudo FP needs further investigation

(iii) In some fields of application further decay data in addition to inventory data are required for the calculation of certain properties of a mixed FP source

- For the calculation of the total energy released by FP after reactor shutdown, either the average β- and γ-energy emitted per decay, or the effective decay energy of (important) individual FP is required.
- The knowledge of penetrating radiation emitted by FP is needed in shielding.

(iv) Finally, decay properties only are required for the measurement of individual FP.

- Properties of the characteristic radiations emitted by FP have to be known for their identification and for the determination of their content in a sample.
- A number of decay characteristics of radioactive species are required in all fields where the interaction of radiation with matter is important, such as life sciences, industrial and agricultural applications.

3.2. Needs for inventory data and bulk properties of FP

3.2.1. Observations and Conclusions

The Panel noted that in general accuracy requirements for bulk properties of FP, such as total FP absorption or energy release, or for the FP inventory have been well assessed in the review papers to this Panel. However, a great deal of more work is needed to assign accuracy requirements to individual FPND consistent with those for bulk properties. In particular, accuracies already achieved for available FPND should be taken into account.

(i) Environmental and exposure studies require a rather complete knowledge of FP inventories, starting from FP half lives as short as <1 s in cases of accidents and nuclear explosions. No studies have yet been performed to evaluate the accuracy to which the FP inventory is required. Since a vast number of FPND is involved in this field and a lot of information on these FPND is already available, it is the feeling of the Panel that

- theoretical studies should be performed as to which FP constitute an important hazard and to what accuracy the knowledge of their inventory is required;
- the needs for individual FPND should be evaluated in the light of the accuracy presently achieved;
- with respect to the importance of FP with yet unmeasured properties, limitations on the ranges of yields, half lives and Q values should be given on the basis of theoretical considerations.

(ii) The Panel endorsed the conclusions of J.G. Tyror (RP 3) that is is necessary to

- achieve a target accuracy of 2% in the prediction of the fuel reactivity life times due to fission products alone for thermal reactors;
- evaluate the effect of fission products in a typical fast breeder reactor to within 0.5% of reactivity, i.e. to within 10% accuracy in FP captures;
- evaluate the change of reactivity held by fission products due to the Na-void effect to within 0.2% of reactivity in fast reactors, i.e. to evaluate the change of FP captures to within 30%.

Tyror pointed out that his target accuracies for individual FPND, listed in Tables IV and VIII of RP 3, were obtained as one possible and economically justifyable solution among others for achieving the accuracy requirements for total FP capture quoted above. The Panel accepted these target accuracies, as reproduced in Appendices A1-A4, but recommends the study of other solutions based on the accuracies which may be obtained both from experiments and theoretical calculations.

(iii) For FP release and contamination of reactor components, the Panel, after some discussion, adopted C. Devillers' interpretation (RP 4) of R.H. Flowers' proposal of FPND requirements. These accuracy targets for the general case without using any knowledge of the presently available accuracy of the required FPND are (1 standard deviation):

inventory to $\pm$ 40%, comprising:

fission yields to $\pm$ 20%

half lives to $\pm$ 5%

neutron capture cross sections sufficiently accurate to allow a calculation of the term $(\lambda + \sigma\phi)$ to $\pm$ 5%.

The last requirement should hold for fluxes of about 10^{14} and 5×10^{15} neutrons$\cdot$cm$^{-2}\cdot$sec^{-1} for thermal and fast systems, respectively. The Panel concluded that for stable FP 20% accuracy on the capture cross-section would be sufficient.

Individual figures again depend on the presently available accuracy of FPND. As can be seen in Appendix A3, the uncertainties of half lives are much less than 5% in most cases and can in fact be neglected compared to the 40% uncertainty required for the inventory. Thus the tolerable error of fission yields can be raised to about 40% provided that neutron capture is insignificant. The significance of capture cross sections, on the other hand, needs further investigation in some cases.

(iv) For failed fuel detection the Panel adopted the accuracy requirements presented in RP 4 for the general case (see Appendix A3). Again, half lives are generally known more accurately than required and accuracy targets should be reconsidered as said under (iii) above.

(v) Fuel element design was not foreseen to be included in any review paper, but data requirements were discussed briefly during the meeting. The technical background and FPND requirements are taken from a contribution to RP 4 by R.H. Flowers with additions from the Panel discussions:

In fuel element design, chemical and mechanical interactions arising from FP present in a burnt fuel element have to be considered, specifically:

- calculation of noble gas pressure within the fuel,
- calculation of oxygen potential changes due to replacement of U or Pu by FP,
- calculation of volume changes in fuel.

General ND requirements for FP with half lives > 1 day are (1 standard deviation):

- FP inventory: to $\pm$ 20% for FP with cumulative yields $\geq$ 1%,
  to $\pm$ 50% for FP with cumulative yields between 0.1 and 1%,
  within a factor 5 for FP with cumulative yields < 0.1%,
  comprising:
- FP cumulative yields from
  thermal fission of ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu and from
  fast fission of ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu
  to $\pm$ 15% for FP with cumulative yields $\geq$ 1%,
  to $\pm$ 50% for FP with cumulative yields between 0.1 and 1%,
  within a factor 5 for FP with cumulative yields < 0.1%;
- branching ratios sufficiently accurate to allow calculation of the cumulative yield of daughter products within the limits given above;
- half-lives and capture cross-sections: the term $(\lambda + \sigma\phi)$ should be known accurately enough to calculate the inventory within the limits given above. Neutron fluxes to be considered and arguments for splitting up accuracy requirements between T1/2 and σ are the same as those stated under (iii) above for FP release and contamination of reactor components. Accuracies of capture cross-sections of stable FP should meet requirements for inventory after burn-ups up to 90% FIMA.

Adequate calculation of the gas pressure within a fuel element due to noble gas FP requires more accurate data:

$\pm$ 10% are required for the inventory of stable rare gases, comprising
$\pm$ 5-10% for cumulative fission yields (= chain yields), and

± 5% for neutron capture cross-sections (if relevant)

The fission yield requirements listed are for thermal fission of ^{233}U, ^{235}U and ^{239}Pu and fast fission of ^{235}U and ^{239}Pu. Accuracy requirements are lower for other fissionable isotopes listed above.

FP half-lives exceeding 1 day are generally known accurately enough to be negligible against the other uncertainty limits given above. Thus the accuracy requirements for yields $\geq$1% can be raised to ± 20% if neutron capture is insignificant. Furthermore, for FP with half lives > 1 day total chain yields can be used together with branching ratios within the requested accuracy limits.

(vi) The Panel agrees that for fuel handling generally the total heat released by FP should be known to ± 5% or better from about 3 months onwards. In future, this accuracy should be reached already from about 1 month cooling time onwards as needed for Pu recycling of fast-breeder reactor fuel. Needs for energy released by FP are summarized in Appendix A5.

The Panel accepted for its present survey the FPND requirements presented in RP 7 which are based on more general considerations. It recommends, however, to re-evaluate accuracy requirements for individual FPND with the aid of Devillers' decay heat studies, using available FPND. These studies became available only after the Panel meeting and are included as appendix to RP 4 and presented graphically in Appendix A5.

Data requirements for FP constituting a potential hazard in fuel handling are generally agreed by the Panel.

(vii) Nuclear fuel burnup can be determined directly using long-lived stable FP as burnup monitors (destructive and non-destructive analysis), or indirectly (correlation studies) with the aid of ratios of the number of FP atoms (destructive analysis) or of FP activities (non-destructive analysis). Details are given in RP 5 and 6. Accuracy requirements for burnup determination presented to the Panel ranged from about 2% (USA, EURATOM) to 5% (France, UK, USSR). After some discussion the Panel agreed on the FPND requirements presented in the chapters 4,5 and 7, which imply that

- burnup can be determined to about 3% by methods presently employed for destructive analysis;
- requested FPND accuracies are just adequate for non-destructive analysis; the implied uncertainties do not constitute a major source of error.

The Panel noted that generally ^{148}Nd, determined by destructive methods, is the most suitable and widely used burnup monitor. Other burnup monitors are required for practical cases where ^{148}Nd is less suitable. Burnup determination by non-destructive methods is gaining importance, since it is less expensive.

The short-lived (compared to fuel irradiation time) FP ^{95}Zr-Nb, ^{103}Ru, ^{140}Ba-La and ^{141}Ce are used for the determination of burnup after short-term irradiation and of fission rates within fuel elements prior to discharge (rating measurements). Generally, such measurements are performed employing non-destructive analysis and, compared to long-lived stable FP, uncertainties are increased by the complexity of irradiation histories. The Panel agreed that for these determinations an accuracy of 5% should be achieved; this implies the FPND requirements presented in Appendices A1, A3 and A4.

a) FPND requirements for burnup monitors are well defined. For the determination of burnup primarily fission yields of burnup monitors are required. For non-destructive analysis, half-lives and absolute γ-ray intensities are needed in addition. In order to derive the burnup from the measured inventory of a monitor FP, corrections for build up and burn-out of this FP due to neutron capture may have to be calculated. Uncertainties due to these corrections should be $\lesssim 1\%$ of the burnup. The requirements for the cases discussed below are given in chapter 7 and Appendices A1 and A4.

- The isotope ^{142}Nd is not formed in fission. Therefore the amount of ^{142}Nd found in a mass-spectrogramme is used to correct for contamination by naturally occurring Nd in a destructive measurement of FP Nd. Prior to this correction the ^{142}Nd formed by neutron capture in ^{141}Pr has to be subtracted. Presently available thermal fission yields and the thermal capture cross-section of ^{141}Pr are adequate. No requirements have yet been specified for fast burnup.
- At high burnups from irradiations in high thermal neutron fluxes a non-negligible amount of ^{148}Nd is formed via neutron capture in ^{147}Nd. The Panel noted that the capture cross-section of ^{147}Nd was still unmeasured, while available data for fission yields and the half-life were found to be sufficiently accurate for corrections.
- Further corrections may have to be applied for buildup and burnout of burnup monitors. The accuracies requested for fission yields of burnup monitors are sufficient for these corrections and needs for neutron capture cross-sections are discussed in chapter 7.

b) The situation is different for isotope correlation studies where the method is based on a comparison of measured and calculated ratios of FP atoms or activities. The Panel noted that the only isotope ratio used routinely for burnup determination is that of the neutron capture product ^{134}Cs to ^{137}Cs. FPND requirements expressed by the Panel are based on RP 5 and 6, and results of a sensitivity study by Foggi and Ley (ref [46] quoted in RP 6).

(viii) Safeguards: FPND requirements for post-irradiation fuel analysis are mainly covered by burnup requirements, but FP isotope ratios (correlations) are used more extensively in safeguards in order to derive additional information such as cooling time, ^{239}Pu buildup etc. (see RP 6). However, the usefulness of these methods for routine investigations in safeguards remains to be proven. More work has to be done to assess quantitatively the accuracies that can be achieved with the procedures for analysis of spent fuel outlined in RP 6 and their impact on FPND requirements.

The FPND that have to be known and their present adequacy for safeguards are summarized below as observed by the Panel:

- Most of the FP used for ratios are also burnup monitors and the FPND accuracies requested for burnup are adequate for safeguards.
- ^{154}Eu, formed by neutron capture in ^{153}Eu, is potentially useful for the determination of burnup, fluence and ^{239}Pu fissions. FPND accuracies for mass chains 153 and 154 requested in RP 5 for burnup determination correspond to a tolerable uncertainty of $\sim 3\%$ in the ^{154}Eu inventory, and hence also in the ^{153}Eu inventory. This implies that the amount of ^{153}Sm removed by neutron capture has to be known to 3% accuracy. Since the half life of ^{153}Sm is known to $< 1\%$, the term $\sigma\phi$ should be known to $\pm$ 3% of $(\lambda + \sigma\phi)$. Requirements for the unknown capture cross-section of ^{153}Sm are discussed in chapter 7, other requirements taken from RP 5 are given in Appendices A1, A3 and A4.

  However, the Panel noted that also mass chains 149, 151 and 152 contribute significantly to the ^{154}Eu inventory at high burnup levels through multiple neutron capture, as shown by Eder and Lammer (reference [3] quoted in RP 6). Capture cross sections and fission yields are required in addition for these mass chains, but the accuracies needed are not yet known.
- Isotope correlations using ratios of Kr, Xe and Nd fission products have so far been studied purely empirically (see RP 5 and 6). Much more work is required, including calculations and sensitivity

studies, in order to understand the processes involved, develop the method to practical applicability and specify FPND requirements (see RP 6).

For fresh fuel assay a complete library of FPND including FP with half-lives down to 1 sec are of greatest importance.

3.2.2 Recommendations:

(i) The Panel recommends that investigations be performed in all user areas, where this has not yet been done, aiming at a detailed specification of needs for individual FPND and their accuracies. Such investigations should yield the following information:

- identification of FP important in the area concerned; criteria for significance of FP with respect to yet unknown properties;
- accuracy requirements for bulk properties of FP or for FP inventory data;
- needs for individual FPND backed up by sensitivity studies; presently available accuracies of FPND should be used, as observed by the Panel, or taken from more recent evaluations.

These types of investigations should not only be performed to back up a WRENDA-request (see Chapter 2) but form the basis for review papers and discussions of the proposed follow-up meeting on FPND. The Panel recommends, that studies be initiated as soon as possible.

(ii) When assessing the needs for individual FPND, users should also take into account:

- whether higher accuracies for some FPND are requested in other application fields with high priority, and
- which sub-division of FPND needs might be least expensive to be satisfied.

The appendices on comparison of FPND status and requirements may help in these decisions.

3.3. FP decay heat

3.3.1. Observations and conclusions

(i) Total energy released after reactor shutdown ("afterheat"): In three different fields of application a knowledge of the decay heat generated within a fuel after reactor shutdown is required:

- residual power as a function of time after emergency shutdown of a reactor (in case of an accident), starting from zero up to a few days cooling time (RP 4);
- fuel handling and intermediate storage at the reactor site, starting from 8 hours up to a few months cooling time (RP 4);
- fuel transport, reprocessing and waste disposal, starting from about 1 month cooling time (RP 7).

The latter is discussed in the previous section. For the other fields which are covered by RP 4, C. Devillers gives a survey of different user needs. The Panel affirms the urgent need to improve the accuracy of the afterheat function in order to save unnecessary deratings of reactors. The accuracy requirements for the total heat released as a function of time has been assessed by the Panel in all 3 areas and is presented in Table A5-Ia of Appendix A5.

(ii) FP contribution to total afterheat: The Panel endorses the conclusions of C. Devillers (RP 4):
FP energy release has to be known primarily from thermal fission of ^{233}U, ^{235}U and ^{239}Pu and from fast fission of ^{235}U and ^{239}Pu (see Table A5-Ib in Appendix A5). Of secondary interest are contributions from ^{241}Pu thermal fission (recycled Pu) and fast fission (10-20% contribution to total fissions) and ^{238}U fast fission (about 1/3 of the accuracy required for primary fissile nuclides).
However, it has been observed (RP 4) that the calculated afterheat changes by $\lesssim 1\%$ only if one replaces ^{239}Pu thermal fission yields by fast fission yields. Therefore the knowledge of fast fission yields appears to be not of primary importance.

The contribution of FP to the total decay heat is $\lesssim 40\%$ up to 1 sec cooling time, $\lesssim 50\%$ at 10 sec and $\sim 90\%$ from 100 sec onwards. This explains the accuracy requirements for the total energy released by FP as summarized in Appendix A5 (Table A5-Ib).

(iii) Calculations and measurements of FP decay heat: M. Lott has reviewed (RP 15) existing calculations and measurements of energy released by FP. The conclusions of Lott, Devillers (RP 4) and the Panel are summarized below.

Comparison of calculations:

Essentially two methods are used to calculate the total FP energy release. In one approach the total decay heat is represented by an analytical formula which could be derived only from highly discrepant measurements (K. Shure, see RP 15 for details). In the second and most

widely applied approach the decay heat is calculated from inventories of individual FP and their energy release per decay. Only this latter method needs FPND and is referred to as "calculations" in the following discussion.

At short cooling times ($\lesssim$ 10 sec) the calculations compared in RP 4 and 15 tend to under-estimate the heat release, particularly after short irradiations. It can be concluded that this is due to very short-lived ($\lesssim$ 1 sec) FP with unknown ND which are, however, less significant at the end of irradiations in reactor operations. Measurements would be required in order to fill this gap, but rather large uncertainties of individual FPND could be tolerated in order to reach the required accuracies of 25% at 1 sec and 20% at 10 sec cooling time (see Table A5-Ib, Appendix A5) for the total FP heating, as due to the very large number of contributing FP a partial cancelling of the uncertainties can be expected. On the other hand, the number of "unknown" FP increases with decreasing cooling time. The use of an improved analytical expression, derived from new consistent measurements of FP decay heat, might be more suitable below $\sim$1 sec cooling time. Further investigations are therefore necessary to show whether and which new measurements of FPND are required and/or whether the unknown FP could be replaced by a lumped short-lived FP for certain cooling times.

At cooling times of $\sim 10^2 - 10^3$ sec individual FP are more significant and the calculations partly disagree. Available FPND are not sufficient and improvements are required.

FPND required for cooling times above 10^3 sec are generally well known from measurements. Calculations agree well between 10^3 and 10^7 sec . Above 10^7 sec, where only few FP are important, discrepancies among calculations could be resolved by a comparison and critical re-evaluation of the input data used.

Apart from some general statements about accuracy requirements for FP decay heat the Panel noted only deficiencies in particular FPND as included in the data libraries compared in RP 15, but no studies on their significance were available. Therefore the Panel recommended an immediate action on the French group (Devillers, Lott) who surveyed the subject for the meeting, to prepare a list of important FP dominant at each cooling time of interest for inclusion in the Panel proceedings (see (iv) below).

Comparison with measurements:

Discrepancies exceeding individual experimental errors between the re-

sults of different FP decay heat measurements are observed, which exceed by far those between calculations. The Panel noted that these discrepancies cannot be resolved as the different experimental conditions do not allow a direct comparison. Nor can the reliability of the calculations be checked in a meaningful way against discrepant measurements.

Benchmarks:

Existing discrepancies among experimental results and possible systematic errors can only be resolved if new measurements, employing all available methods, are performed under identical irradiation conditions; independent results could be obtained if such benchmark experiments would be performed at different laboratories. After collection and proper evaluation, these results could serve to derive an improved analytical expression for the heating function.

In order to allow a comparison between different calculations and between calculation and experiment, benchmark calculations should be simultaneously performed at pertinent laboratories for the irradiation conditions of the experiments and for a wide range of cooling times. Uncertainties of FPND should be incorporated in the FPND libraries used in these calculations and the uncertainty of the total FP decay heat calculated in each individual case.

The analysis of the results of experiments and calculations should yield the following information:

- It should be possible to check the reliability of the calculations and derive an overall uncertainty of the afterheat function.
- The analysis of agreements and disagreements between measurements and calculations for different cooling- and irradiation times should help to check uncertainties and to identify significant deficiencies of input data used in the calculations.
- The comparison between all decay heat results at very short cooling times should help to determine whether or not ND of new short-lived FP, and which ones, have to be measured and included in FPND libraries.
- Finally, these benchmarks should enable to establish a detailed list of FPND requirements for "afterheat" for all cooling times.

(iv) Upon the recommendation of the Panel, C. Devillers has provided a list of FP contributing $\leq 1\%$ to the total FP energy release at cooling times of 10^0, 10^1, 10^2 ... 10^9 sec for 5 different practical cases (including ^{233}U, ^{235}U, ^{239}Pu thermal and ^{239}Pu fast fission). The results are presented in detail as appendix to RP 4, and all 5 cases are combined in

a graphical representation shown in Appendix A5, Table A5-II. The calculations confirm the Panel's conclusions in several points:

- Up to ~100 sec there is a large fraction of FP contributing less than 1% to the total FP decay heat.
- No FP contributes more than 4% to the total FP decay heat up to ~100 sec.
- Only few FP are significant above about 10^6 - 10^7 sec.

(v) The results of Devillers' and Vossebrecker's* investigations can be combined with the Panel's findings to the following conclusions:

- The present knowledge of FP chain yield data appears to be adequate for decay heat calculations. It should be sufficient to check the influence of the difference between thermal and fast fission yields for ^{235}U and ^{241}Pu.
- Fractional cumulative yields can probably be derived adequately from empirical charge distributions, as discussed in chapter 4. However, this point should be further investigated by sensitivity calculations.
- Requirements for decay data can be given qualitatively at least for the dominant FP identified by Devillers.
- The present knowledge of neutron capture cross-sections is sufficient for decay heat calculations (see RP 4).
- Rather large statistical uncertainties of individual FPND can be tolerated below ~100 sec cooling time.
- Detailed specifications of FPND requirements have to await the completion of benchmark experiments and calculations. Therefore no detailed comparison of FPND status and user requirements for after-heat has been performed by the Panel.

3.3.2. Recommendations

(i) Although the FP decay heat values obtained from different calculations agree well for cooling time between 10^3 and 10^7 seconds, it is not possible to draw any definite conclusions on the uncertainty of the after-heat function from this agreement, as the sources of data are often the same. Therefore the Panel recommends that error bars should be included in libraries of FPND. Errors should also be estimated for theo-

* Stimulated by this Panel, H. Vossebrecker (INTERATOM GMBH, Bensberg, Köln, FRG) has recently calculated uncertainties of the FP decay heat at various cooling times from FPND uncertainties. The results were communicated to the Scientific Secretaries of the Panel and are summarized here since they are of interest in the context of the Panel's findings:

- The calculations confirm that considerable FPND uncertainties can be tolerated at short cooling times.
- Uncertainties of fission yields do not contribute significantly to the overall uncertainty of the decay heat.

retically derived ND values and new calculations of afterheat functions and their uncertainties be performed.

(ii) Internationally coordinated benchmark experiments on FP energy release should be performed at different laboratories. These measurements should be performed at given cooling times following irradiations at constant sample power. The irradiation conditions should be as identical as possible. The methods involved are:

- calorimetry should be used wherever possible to serve as reference method;
- other methods should be applied where calorimetry cannot be used, i.e. above 60-100 seconds;
- above 100 seconds all methods should be used at given reference points to allow an intercomparison.

The precision of these measurements should be as high as possible.

Parallel to these benchmark experiments and for the same measurement conditions, coordinated afterheat calculations, including estimates of uncertainties, should be performed at different laboratories. This would allow a better and direct comparison between different calculations and experimental results and would give a first global test of the reliability of FPND libraries.

The results of all benchmark experiments and calculations should be collected, analyzed, evaluated and published together with conclusions in a final report.

The Panel considers it important to have results of the benchmark experiments available as soon as possible. Therefore the Panel recommends to start with first priority measurements on ^{235}U thermal fission, which is simpler to perform, and only on a restricted range of cooling times. ^{235}U could then serve as a standard for further measurements. Benchmark experiments on ^{239}Pu thermal fission are proposed with second priority.

The Panel recommends that IAEA/NDS acts as the point of contacts and organizes the benchmark experiments. Lott will work out the guidelines with respect to experimental conditions and methods to be used and send them to IAEA/NDS for distribution. He will also supply IAEA/NDS with a list of laboratories and/or scientists that could participate in benchmark experiments. IAEA/NDS will work out a time schedule together with Lott and takes the responsibility for contacting other laboratories and coordinating the experiments. Lott will collect the results of the benchmark experiments and organize the evaluation and conclusion of the intercomparison. IAEA/NDS will assist him in the publication and distribution of the final report.

(iii) No means has yet been established to communicate information on finished or on-going studies related to afterheat. In order to fill this gap, and particularly for the benefit of the reviewer of this subject for the following meeting, the Panel recommends that all such information be communicated to IAEA/NDS for collection and transmission.

(iv) Although a detailed formulation of user requirements will have to await the completion of the benchmark experiments, some actions should follow Devillers' study of FP important for afterheat:

- The tolerable overall uncertainty of the remaining FP can be derived with the aid of the presently available status of the listed FP.
- More detailed FPND requirements can be worked out for cooling times exceeding a few hours ($\sim 10^4$ sec)
- Evaluators could concentrate on updating the status of nuclear data of important FP and communicate poorly known FPND to measurers via the newsletter proposed in Chapter 2.

4. FP YIELD DATA

4.1. Chain yields

This section deals with fission products whose cumulative yields are essentially identical to the total chain yields.

4.1.1. Observations and conclusions: user requirements

(i) The Panel agreed that burnup measurers would be satisfied at present with an accuracy of 2% in the yields from the major fissile isotopes with a long-term goal of 1%. The yield accuracies required for short lived FP used in non-destructive fuel analysis were considered to be not as stringent in view of the lower accuracy of the methods concerned.

The Panel noted that at present ^{148}Nd is the most suitable burnup monitor that is commonly used for different fast reactor fuel types. However, it has been noted in RP 5 that the variation of its fission yield with the median energy of fast reactor spectra (expressed as spectral index in RP 5) may exceed the requested accuracy, particularly the long term aim of 1%. Therefore the variation of the ^{148}Nd fission yield with incident neutron energy has to be known

to the accuracies specified in Appendix A1 in order to achieve the required burnup accuracies. As any determination of ^{148}Nd either for burnup or in a fission yield measurement involves a determination of all FP Nd, the Panel recommends to extend measurements of the energy dependence of yields to all Nd isotopes. This should enable users to select the most suitable burnup monitors.

(ii) Thermal yield requirements for fuel design are met by the available data (see Appendix A1).

In the case of fast reactors the requirements are separated into those for the calculation of the gas pressure within a fuel element, and those for the investigation of chemical interactions of FP with the fuel and cladding material. The former requires yields of stable rare gas FP only.

For investigations of the chemical state of fast reactor fuel, the knowledge of complete mass yield curves is required. This is primarily of importance for fuel design and development. However, such investigations are also of interest for burnup, as information on diffusion, migration and volatility of FP influence the selection of burnup monitors for different types of fast reactor fuel. Requirements for fuel design contributed by R.H. Flowers are presented in section 3.2 (item (v)). Independently, this topic was discussed by the subgroup on chain yields. Requirements expressed by Flowers and the subgroup are presented separately in Appendix A1.

(iii) All further requirements for FP yields as presented in review papers and agreed by the Panel are summarized in Appendix A1. They are, however, subject to the limitations discussed in chapter 3 (inventory data). In particular, the Panel noted that certain yields can be estimated within an uncertainty margin of 10-30% by interpolation or calculational methods, which would satisfy some user requirements. Since accuracy objectives for bulk properties (e.g. total FP captures (RP 3) and FP decay heat (RP 7)) can be achieved by different ways of allocating requirements for individual FPND, the study of other solutions is recommended on the basis of available yield uncertainties and the capability of estimating unmeasured yields.

(iv) Stable and long lived FP contribute to the production of photoneutrons via capture- and decay γ-rays. Although this topic was not discussed in detail by the Panel, it should be noted that the knowledge of FP chain yields is required, and detailed needs should be investigated.

4.1.2 Observations and conclusions: status of FP chain yields

(i) Thermal fission yields

From the information presented in RP 11a and the data given in Appendix A1 it appears that the majority of the requirements for thermal fission yields has been met with the exception of a few cases where discrepancies among experimental data and larger uncertainties still exist, as shown in more detail in Appendix A1. However, the Panel did not consider it economically feasible to initiate additional extensive measurement programmes for the determination of thermal yields. Evaluators should rather try to resolve discrepancies by careful examination and selection of existing experimental data and recommend some limited less expensive measurements if deemed necessary.

(ii) Fast fission yields

The Panel noted that "fast" yields of certain FP important for users depend on incident neutron energy in the range of interest for fast reactor applications (see RP 5 and 11b). Therefore, user requirements have to be understood, at least in principle, as being expressed for yield data as a function of fast reactor spectrum. However, the Panel concluded that a term "fast yields" should be maintained and associated with a set of yield data for the present survey (Appendix A1) as well as for future considerations for several reasons:

- In the past, reactor neutron spectra used in fission yield measurements were generally not defined. Consequently, fast yields obtained in current evaluations, from which the data status is drawn, are not well defined either. Therefore the status of fast yields reviewed by the Panel has to be used in this sense and is explained in detail in Appendix A1.
- For most fast reactor applications the change of yields with neutron energy is well within the requested accuracy limits. Even for the most stringent requirements, the variation of yields in the mass peaks is expected to be tolerable.
- Future large fast reactor power stations will have rather similar neutron spectra.
- Therefore it is desirable that also in the future "fast yields" be evaluated, although for defined neutron spectra, which may be associated with some kind of information on the energy dependence of yields. In the transition period, fast yields have to be used as they are defined by evaluators.

Yield measurements will continue to be performed in fast reactor spectra and will most likely be considered as one separate group of data by evaluators. The classification "fast yields" will be used for this type of measurements, but information on the neutron spectrum in which yields were measured should be included in publications. The way in which fast yields will be presented by evaluators depends on their individual approach to the problem, but it would be desirable to relate the definition of "fast yield" with neutron spectra of commercial fast breeder reactors.

A number of requirements for fast yield data have not been attained; however, extensive measurement programmes are in progress in various Member States. These programmes, the expected accuracies to be attained and the projected completion dates are outlined below:

Euratom (Koch)

Absolute yields of Cs, Ba, Ce, Nd, Sm and Eu isotopes, and relative yields of Kr and Xe isotopes are being measured in fission of ^{232}Th, ^{233}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am and ^{243}Am irradiated in the French reactor Rapsodie. The work on ^{235}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu and ^{241}Pu will be completed in 1974, the remainder before 1977.

France (Bouchard)

Measurements are being made of the yields of all Nd isotopes from the fission of ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu irradiated in the fast reactor Rapsodie and Phenix. The measurements in Rapsodie are almost finished, while those in Phenix should be completed in 1975. Nd yields in fission of ^{238}Pu, ^{242}Pu and ^{241}Am are also being measured in Phenix.

India (Ganguly)

Radiochemical measurements of fast yields of nuclides in the wings of the mass yield curves from the fission of ^{233}U, ^{235}U and ^{239}Pu are being made. Expected completion date 1976.

Switzerland (von Gunten)

Radiochemical measurements by γ-spectrometry of yields of nuclides from mass 87-105 and 129-151 are being made for fission of ^{235}U and ^{239}Pu in the Proteus reactor which has a neutron spectrum similar to a Helium cooled fast reactor. The experiments have been completed and the accuracy achieved is 2-5%. The final results have been submitted to Nucl.Sci.Eng.

U.K. (Sinclair, Crouch)

Mass spectrometric measurements of fission yields of all Nd isotopes and of some long lived isotopes from fission of ^{235}U, ^{239}Pu, ^{240}Pu and ^{241}Pu, irradiated in the DFR reactor, are being made by Sinclair.

The work should be completed by 1976.

Similar measurements are being made by Crouch for fission of ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu irradiated in the DFR reactor; the first three of these should be completed by 1975, the others will start in 1974. He is also carrying out a similar series of irradiations in PFR, starting in 1974.

U.S.A. (Maeck)

Mass spectrometric measurements of yields of the entire mass yield curve are being carried out on samples which have already been irradiated in EBR II. Measurements have been completed for ^{235}U and ^{238}U, but have still to be done for ^{233}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am and ^{237}Np. Samples of ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu were irradiated in two different EBR II spectra so as to examine the effect of neutron energy.

USSR

Measurements are in progress on the reactors BOR-60 and BR-5 in connection with an investigation programme for fast reactor physics and burn-up. Yield measurements using mono-energetic fast neutrons are also being carried out on a number of fissioning nuclides.

It is possible that these measurements will be sufficient to satisfy user requirements after they will have been reported and evaluated, but the Panel feels unable to express this possibility in a quantitative way.

(iii) Effect of neutron energy on fission yields

Systematic studies of the effect of neutron energy on yields should be performed at least in the mass ranges 103-125 and 140-155. For other chain yields it should be sufficient at present to check the extent of the energy dependence. The ultimate goal would be the derivation of an expression that associates yields with neutron energies. The important function of evaluators is to correlate measured yields with neutron energy, identify significant changes and find the most suit-

able way to describe fast reactor spectra in terms of an energy dependent parameter.

Several ways are used to characterize fast reactor spectra:

- The spectrum can be given point wise or in energy groups.
- An average or median energy can be given. The fast yield data included in ENDF/B-IV are defined for a reactor spectrum having an average energy of 0.5 MeV.
- The recent results of Maeck et al (see RP 5) are associated with a spectral index $\sigma_f(^{238}U) / \sigma_f(^{235}U)$.
- The Lawrence Livermore Laboratory (USA) defines a fission-spectrum source as one that gives ^{115g}Cd R-value of 2.80 for ^{235}U fission (i.e. ^{115g}Cd yield ratio from fission spectrum/thermal ^{235}U fission). This definition can be extended to characterize any neutron spectrum or discrete neutron energy.

Some of the measurements in the USA (Maeck) described above together with yield measurements on ^{239}Pu and ^{238}U with monoenergetic fast neutrons in the UK (Cuninghame) should throw light on the problem of the energy dependence of fission yields. It is to be hoped that some suitable parameters by which this effect can be characterized will emerge from these results.

The requirements summarized in Appendix A1 are the ones essential for the nuclear fuel cycle of thermal and fast reactors. The Panel wishes to stress that other fission yield work at neutron energies up to 14 MeV, including measurements in the ^{252}Cf fission spectrum, would not only help in the evaluation of the neutron energy dependence of the fission yields, but would also be essential to improve our understanding of the fission process itself.

(iv) Evaluation work

In view of the increasing volume of experimental data on energy-dependent fission yields it is desirable to rationalize the compilation of these data. It is recommended that evaluators exchange compilations of experimental data with the object of establishing a common computerized data base which can be used by all evaluators and others interested in FPND.

Discrepancies have been discussed in review paper 11a and during the meeting which urgently need clarification. In evaluations in which the normalization procedure (see RP 11a) is used, any changes in some adopted yields would entail a renormalization of the whole yield

curve. This, in turn, involves changes in all FP yields that could occasionally exceed previously assigned uncertainties.

Evalution work is important for the quantitative determination of the dependence of fission yields on incident neutron energy. Evaluators are asked to systematically compare and analyze experimental results from different well defined fast reactor spectra. In parallel, the analysis should be extended to yield data from thermal neutrons to 14 MeV. These investigations should aim at deriving the most suitable and simple description of fast reactor spectra, and presenting the energy dependence of fission yields. Appendix A1 indicates the work required to satisfy user needs.

4.1.3. Recommendations

(i) In the case of thermal fission yields the Panel recommends that evaluators be supported by the pertinent authorities and by the authors of published data in their task to carefully analyze existing experimental data and uncertainties in order to resolve existing discrepancies. In order to reach required accuracies gamma-spectrometric measurements, as recommended in RP 11a, would be sufficient.

(ii) In these cases where the accuracy achieved for fast fission yields (see Appendix A1) does not meet the requirements, further work should be done to reach this accuracy. It is possible, and in many cases probable, that the work in progress summarized above will satisfy the requirements after it has been reported and evaluated.

(iii) Measurers should include in publications specifications of neutron spectra from which they obtain fast fission yields. Work in progress should be completed and reported as soon as possible.

(iv) Investigations of the effect of neutron energy on fission yields should be done by both measurers and evaluators. The present requirements are given in Appendix A1. In order to help establishing the systematics of this effect, the Panel recommends that laboratories be encouraged to continue FP yield studies for incident neutron energies up to 14 MeV or neutron energy spectra other than those of fast reactors (e.g. ^{252}Cf fission neutrons).

(v) Evaluators should aim at establishing, and working from, a common computerized experimental data base.

4.2. Direct and cumulative yields

This section deals with FP yields that cannot be calculated with confidence from total chain yields.

4.2.1. Observations and conclusions

(i) Direct and cumulative yields are needed wherever an inventory of (short-lived) radioactive species is required. Presently needs were expressed for FP release, contamination of reactor components, fuel failure detection, (RP 4) as well as for fuel handling (RP 7). As discussed in section 3.2, the requirements for uncertainties of cumulative yields can be raised to about 30–40% in the case of FP release and contamination of reactor components. Again, the other needs are subject to the limitations expressed in section 3.2 on inventory data.

(ii) FP decay heat: Using mainly calculated (E.A.C. Crouch, AERE-R7680, 1974) and some experimental (Appendix A2, RP 11a) data. the following distribution of fractional cumulative yields of FP listed by C. Devillers for cooling times of 1 s - 100 s (see section 3.3. and Appendix A5) is obtained:

- about 60% of all listed FP, $\sim$70% at 100 s and $\sim$70% of those FP which contribute $>$ 2% to the total FP decay heat have $\geq$ 95% of the total chain yield.
- only about 20% of all listed FP at 1 s cooling time and 4% at 100 s have $\leq$ 60% of the total chain yield.
- none of the FP contributing $>$ 2% to the total FP decay heat have $<$ 80% of the chain yield.

This survey is for thermal fission yields of ^{235}U and ^{239}Pu. The situation is not much different for fast fission of these isotopes. The main uncertainties are in calculated fractional independent yields and tend to cancel for cumulative yields of FP with Z $>$ Zp, particularly for cumulative yields close to total chain yields. Therefore calculated cumulative yields of $\geq$95% should generally be correct within 5%, uncertainties of calculated cumulative yields $\geq$60–70% should still be within 10–50%, but may be a factor of 2 or more below about 60–70%.

Since a large fraction of the FP contributing to the total decay heat at cooling times up to 100 seconds have low yield uncertainties, and the Panel concluded that rather large uncertainties of individual FPND can be tolerated in this range of cooling times, calculated fractional yields may be sufficient for the time being, until more detailed investigations on needs are available.

(iii) Future needs: Detailed lists of independent and cumulative yields and their accuracies required for FP-decay heat calculations and environmental aspects should be available at the follow-up meeting.

(iv) RP 11a, appendix B, shows that only very few measurements of direct and cumulative yields from thermal neutron fission exist, the majority being for ^{235}U. As Appendix A2 shows, they are just sufficient to fulfil most of the requirements expressed at this Panel. However, the overall uncertainties of the available data should be evaluated, as some remarkable discrepancies are evident in table B1 of RP 11a, and experimental data are often not consistent with a Gaussian charge dispersion curve (cf. Appendix A2).

(v) There are practically no measurements of direct or cumulative yields in fast neutron fission. Much experimental work remains to be done to satisfy the user needs.

(vi) A number of cumulative yield requirements for fuel handling concern branching ratios to metastable and ground states of FP. Since these yields cannot be derived from charge dispersion curves, they have to be measured directly or to be determined with the aid of chain yields and branching ratios.

(vii) The Panel noted that calculational methods for fractional yields using semi-empirical charge dispersion models could help to fill gaps in experimental data. However, experimental data are too scarce to check the general applicability of these models. Furthermore, there is experimental evidence that the presently adopted charge dispersion model, using a unique Gaussian width parameter, is not adequate (see RP 16). Therefore it is at present impossible to estimate meaningful uncertainties in calculated independent yields. A possible exception is ^{235}U thermal fission, where sufficient experimental data are available for deriving Gaussian charge dispersion

parameters of individual mass chains. Further measurements of independent yields are required

- to check the reliability of existing models and help to develop improved models;
- to allow an estimation of the uncertainties of predicted yields;
- to allow a more reliable extension of these models to other heavy nuclides and other non-thermal neutron energies.

RP 16 shows that for the development of improved semi-empirical models further investigations in other areas, which are beyond the scope of this Panel, are also required, such as prompt neutron emission, primary fragment mass and charge, fission theory, etc.

(viii) It should be noted that extensive measurements of direct yields are being performed by Amiel (Israel), the results of which should throw light on charge dispersion models.

4.2.2. Recommendations

(i) Further measurements of independent yields, particularly in ^{235}U thermal fission should be encouraged to improve and check calculational models.

(ii) Measurements of independent FP yields for other heavy nuclides should be initiated to fill the gaps and enable to check predicted yields.

4.3. Calculational Methods

4.3.1. Observations and conclusions

The Panel noted that a number of fission product chain and independent yields required for applications are only available as calculated or estimated values, based on semi-empirical methods and interpolations. The Panel felt that calculated yield curves presented in RP 16 reproduce experimental data well enough to satisfy some user requirements for low accuracy yield data. However, at present uncertainties of calculated yields have only been estimated or obtained for overall fits to experimental mass yield curves. The Panel suggests that empirical uncertainties be derived systematically from a comparison of individual calculated and experimental yield data.

4.3.2. Recommendations

The Panel therefore recommends that

(i) promising work on the development of calculational methods for independent and cumulative FP yields, as reported in RP 16, be further persued;

(ii) semi-empirical models be improved whenever new data become available;

(iii) attempts be made to assign uncertainties to calculated FP yields.

5. DECAY DATA

5.1. Communication of new results

Decay data of short-lived fission products have recently gained increasing importance in applications. Concurrently much effort is being devoted to the measurement of these data and the Panel notes an urgent need that such data reach evaluators and users as fast as possible. Apart from the benefit of the newsletters proposed in chapter 2 the Panel wishes to emphasize that the Recent Reference sections of "Nuclear Data B" are invaluable.

5.2. Observations and conclusions

5.2.1 User requirements

(i) There was some discussion on precision data requirements for environmental research and routine work, but no agreement could be reached. Since no specific data requirements have yet been assessed in this area, the Panel concludes that requests for further measurements should await more detailed sensitivity studies. However, the more general request formulated in Appendix A3 seems to be justified at present.

(ii) The accuracy of half lives of ^{135}I and ^{135}Xe required for reactor kinetics (RP 3) is met.

(iii) Accuracy requirements for decay data put forward in RP 4 for burst fuel detection, FP release and contamination of reactor components are based on general considerations without taking into account available accuracies of FPND. As these requirements are not very stringent,

they are accepted by the Panel and are listed in Appendix A3. Apart from those decay data, for which accuracies have not been assessed, the needs in these areas are either fulfilled or easy and inexpensive to achieve. A revision might be necessary in cases where requirements for FPND other than decay data are not met, based on sensitivity studies.

In quoting accuracy requirements for branching ratios it is assumed that they are the same as those for γ-ray intensities.

(iv) Requirements for FP decay heat can only be given qualitatively at present (see section 3.3). The decay data required for the calculation of the energy released by FP and deposited within the reactor are FP half-lives and effective Q values (Q_{eff}, i.e. $Q-E_\nu$).

Apart from completely unknown FP, a number of FP with very uncertain half-lives and unknown Q-values contributes to the decay heat at short cooling times up to 100 sec. Although accuracy requirements cannot yet be given, an improvement of the present situation is definitely necessary.

Decay properties of FP important at cooling times $\gtrsim$1000 sec are known, but partly too unprecise to allow a reliable calculation of the partition of the energy released among β, γ and $\bar{\nu}$ (antineutrino).

(v) After some discussion the Panel agreed on burnup requirements as presented in Appendix A3. These include also requirements for non-destructive analysis of spent fuel in safeguards, which have, however, lower priority. The capability and practical applicability of the use of FP activity ratios is still under investigation and may justify needs for more accurate decay data.
The needs for fresh fuel assay in safeguards are agreed by the Panel, especially in view of their low priority.

(vi) Decay data requirements for fuel handling are generally acceptable at present. The Panel concluded that for problems concerning heat released by fission products in spent fuel the knowledge of average β energies in addition to γ-ray data (as proposed for FPND libraries: see annex 3 to chapter 2) are sufficient. However, for shielding (see (viii) below) high energy γ's and β's (bremsstrahlung) are important and the knowledge of their energies and intensities is required.

(vii) Applications in industry, agriculture and life sciences require mainly decay data. The Panel noted that in these fields not only pure FPND are required, but that also other uncertainties discussed in RP 8 and 9

constitute a problem. Nevertheless, FPND of higher accuracy are required for research work and included in Appendix A3.
The Panel supports the request for inclusion of Auger electron data in evaluations.

(viii) A.J. Fudge reported to the Panel that he had observed high energy gamma rays penetrating through thick shields around spent fuel during transport and reprocessing. Several of these gamma rays could not be identified with the aid of tabulations of known FP gamma ray data, or their abundance is very uncertain. The Panel endorses the conclusion of Fudge that the observed gamma rays are of very low abundance and not measured in decay property studies. In view of the hazard that high energy gamma rays penetrating through thick shields constitute, efforts should be made to identify and measure them as outlined in Appendix A3.

(ix) Fission yields can be measured rather accurately and inexpensively by gamma spectrometry. Decay data needs depend on the accuracy to which the yield is required. If yields are to be measured to 1-2% accuracy, then half lives and absolute γ-ray intensities are needed to $\pm$ 1% and better.

(x) Prompt γ-rays in fission as well as high energy gamma rays from fission products and bremsstrahlung are sources of photoneutrons. Short-lived FP with high Q values should be studied for high energy γ's and β's. This subject was, however, not discussed by the Panel in greater detail and further investigations on existing information and pertinent FP are still necessary.

5.2.2. Individual decay data

(i) Equilibrium activities: In the case of FP where the daughter reaches equilibrium with its parent rapidly, it is assumed that the equilibrium activity is important for users. The half life of the daughter and the branching ratio of the parent to the daughter are considered to be unimportant in those cases. Instead, radiation intensities of the daughter nuclei per decay of the parent nuclei and their accuracies are included in this survey.

(ii) Half life requirements are generally met at present with the few exceptions noted in Appendix A3. In some cases it would be sufficient to assess the uncertainties or to resolve discrepancies. In future half-lives may be requested for a number of shorter lived FP after needs for environmental aspects, fresh fuel assay in safeguards and afterheat are assessed. The uncertainties of these data, including those of FP listed in Appendix A5, should be evaluated for the next survey of the field of FPND.

(iii) For branching ratios it is assumed that in most fields the required accuracy is expressed as % uncertainty per decay, except if the uncertainty of the branching ratio itself is specifically requested. With these assumptions specifically expressed requirements (Appendix A3) are met.

(iv) A number of needs for absolute gamma ray intensities is not yet met and new measurements are needed. Particularly in gamma ray intensity measurements statistical counting uncertainty and systematic errors (calibration, impurities) should be separated. In addition to the more general recommendations included in chapter 1, the Panel strongly recommends that this be taken into account by evaluators and measurers, and that the latter include pertinent information in their publications. It should be mentioned that for the evaluation of absolute intensities of gamma rays auxiliary decay data like internal conversion electron intensities or conversion coefficients and ground state beta decay branching are required, the accuracy depending on their contribution to the overall error.

(v) Gamma ray energies are generally needed only for identification of FP. The accuracy required has to be compatible with the resolution of commonly used Ge(Li) detectors. Since detectors used in research measurements on gamma rays are usually of higher resolution than those used in application fields, gamma ray energies are sufficiently accurately known, with the exceptions noted in Appendix A3.
Needs for group and mean energies of gamma rays, which are required with much lower accuracy, are a forteriori satisfied.

(vi) β-ray and conversion electron data uncertainties have only been evaluated by Martin and Blichert-Toft (1970) and by Martin (1973) (references [1] and [8] in Appendix A3). However, these evaluations do not include all FP listed in the table of Appendix A3, and the status field had to be left blank for some FP. An inspection of this table

shows that for those FP, for which uncertainties are available, most requirements have been fulfilled. Further requirements for β-ray data not expressed for individual FP arise from evaluations of absolute γ-ray intensities and decay branching ratios, from decay heat calculations and environmental studies.

(vii) It has been noted in subsection 5.2.1 that data on the energy release of individual FP needed for FP decay heat calculations are lacking or inconsistent. In order to deduce effective decay energies from Q values, the energy carried away by antineutrinos ($\bar{E}_\nu$) has to be known, which requires measurements of β-spectra. G. Rudstam informed the Panel that several of the "unknown" FP (see subsection 5.2.1) have been identified at Studsvik, Sweden, and that his laboratory would be in a position to directly measure $\bar{E}_\beta$ and $\bar{E}_\gamma$ separately. Such measurements would be very valuable not only in reducing the number of FP with poorly known decay properties but also would they allow a comparison with data deduced from β-spectra. Upon the recommendation of the Panel these measurements have already been initiated.

(viii) Auger electron and X-ray data are only given by Martin and Blichert-Toft (1970) and Martin (1973) among the evaluations discussed in RP 12 (references [1] and [8] in Appendix A3). The accuracies of available data listed in these publications are presently sufficient to satisfy requirements for applications discussed in RP 8, but do not include all FP for which the data are needed.

5.3. Recommendations

(i) User requirements: further investigations of needs should be performed to yield more specific requirements for individual decay data. This applies to all user areas where needs for individual FP have not yet been assessed, and to those requirements which are based on more general considerations and are not satisfied by available data.

(ii) Evaluations: the survey of the status of decay data presented in Appendix A3 is essentially based on evaluated uncertainties of references [1,2,2a,8] (reference numbers are those of Appendix A3) and is therefore incomplete. The situation is better in the case of half life data (Appendices A3 and A5) where evaluated uncertainties are also available from RP 12 and Nuclear Data Sheets. Therefore the Panel wishes to impress especially on evaluators of decay data the need to give uncertainties, list experimental data and auxiliary assumptions

used in evaluations. Decay schemes and β-branching intensities based on γ-ray measurements and theoretical conversion coefficients should be checked carefully. Data on average β energies, Auger electrons and X rays and their uncertainties should be included in evaluations. An extensive literature search should be made for the next meeting of this kind and lists of further measurements required should be given where data are lacking or unresolved discrepancies exist.

(iii) FP decay heat: the Panel recommends that average β and γ energies be measured for FP where the decay energy is poorly known and supports the initiation of such measurements at Studsvik (Sweden). Furthermore, efforts should be concentrated on measuring β-spectra which have (so far) been studied far less than γ-spectra. A suitable method would be to measure the gross β-spectrum (from low energy to maximum) for individual FP.

(iv) In all cases, where specific needs for individual FP and groups of FP listed in Appendix A3 have clearly not yet been fulfilled (particularly γ-ray intensities), further measurements should be performed to satisfy them.

(v) More emphasis should be given to measurements of intensities of β-transitions to ground states and metastable states with half-lives of more than a few hours (e.g. ^{95m}Nb, ^{99m}Tc). More accurate data, also on conversion electrons, than presently available are required to enable evaluation of absolute γ-ray intensities in those cases where requirements have not yet been met (cf. Appendix A3). For some FP nuclides with very high intensities of ground state β transitions (e.g. ^{144}Ce-^{144}Pr) direct measurement of the gamma ray emission probability is preferable (cf. e.g. the method proposed by K. Debertin, contribution to RP 12, these Panel proceedings, Vol. 3).

6. DELAYED NEUTRONS

Observations and conclusions

6.1. Absolute total delayed neutron yields

The situation for thermal and fission spectrum total delayed neutron yields is considered to be satisfactory for all fissile nuclides in the context of reactor design and operation (review papers 3 and 4). For ^{238}U, where the difference between the older work of Keepin and the new Los Alamos work (table 1, paper 13) is about 15%, the fission spectrum total delayed neutron yield requires checking in order to meet the $\pm 5\%$ accuracy required for the special reactor kinetics purposes outlined in RP 3.

For ^{239}Pu it is observed that the accuracy of the fission spectrum average value of the total delayed neutron yield is only $\pm 8\%$ and does therefore not meet the required $\pm 5\%$.

The Panel believed that in general the requirements for burst fuel detection (review paper 4) are satisfied by the present data. However, it might be possible that the use of total delayed neutrons for burst fuel detection may be subject to errors due to changes in the fuel composition with time and to diffusion and absorption processes which differentiate between precursor chemical species.

In order to remove systematic errors in delayed neutron yield measurements, which may exceed $\pm 5\%$, due to differences in normalization, standard neutron sources should be prepared for the calibration of the efficiency of neutron counting equipment. An intercomparison of standard neutron sources used at different laboratories would be required.

6.2. Composite half-life groups

The use of 6 groups seems to satisfy practical requirements. If any need for higher accuracy arises, a splitting into more groups may be necessary alongside more accurate information on the decay curve.

It seems that the data for the group half lives and yields given for thermal and fast fission show only small differences which are probably not significant when considering various fast reactor spectra.

6.3. Delayed neutron precursors

For most practical purposes the chemical and isotopic identity of delayed neutron sources is unimportant except where chemical processes may be of interest: for example, in homogeneous reactor fuels such as in the molten salt fast reactor or in burst fuel detection.

If chemical processes take place one would require better data on delayed neutron yields, delayed neutron emission probabilities (P_n) and fission yields to allow calculations for various situations of fuel composition and chemical fractionations. Fractionation can result in changes of composite half-lives and delayed neutron spectra which may be of interest in such situations.

There are conflicting data at present such that errors up to $\pm 50\%$ exist in these values.

Accurate P_n values and fission yields would allow calculation of total delayed neutron yields for different fuels; alternatively delayed neutron precursor yield measurements for each individual fissionable isotope would be necessary.

Looking further ahead, a consistent set of delayed neutron precursor data is necessary to describe all occurring situations of fuel composition, chemical fractionation and neutron spectrum.

The panel noted that precision measurements of P_n values are in progress in Israel (Amiel) and Sweden (Rudstam).

6.4. Energy spectra

The neutron energy spectrum for delayed neutrons as one group is available but no complete time dependent spectra.

Ifsynthesis of neutron spectra for various fuels or for situations of chemical fractionation is necessary it will be required to measure neutron spectra of individual precursors or at least of time dependent groups.

The Panel noted that G. Rudstam (Studsvik, Sweden) is measuring energy spectra of the following delayed neutron precursors:

(Zn or Ga)-79, Ga-80, Ga-81, Br-87, Br-88, Br-89, Br-90, Br-91, Rb-93, Rb-94, Rb-95, In-129, In-130, (Sn-Sb)-134, Sb-135, Te-136, I-137, I-138, I-139, I-140, (I+Cs)-141, (I+Cs)-142, Cs-143 and Cs-144. By the time of the publication of these Panel proceedings some of the results are already published, others are being prepared for publication.

Recommendations

(i) Further measurements are recommended in order to reach the accuracies required for the fission spectrum averaged total delayed neutron yields for ^{238}U and ^{239}Pu.

(ii) It is recommended that a standard neutron source with an energy spectrum similar to that of total delayed neutrons be prepared for intercomparison of individual laboratory standards used for calibration of neutron counting efficiency.

(iii) The Panel recommends further investigation of the significance of changes in effective delayed neutron data caused by chemical processes in the fuel. This would enable the identification of additional needs for individual delayed neutron precursor data including neutron spectra in the light of the present knowledge and of the measurements yet to be completed.

7. NEUTRON CROSS-SECTIONS

7.1. General recommendations for quoting accuracy requirements

(i) The Panel agreed that for reactor applications target accuracies for neutron reaction cross-sections of FP should be given in absolute values (i.e. b or mb). This is particularly important in cases where a cross-section is unknown in part of- or the whole energy range, since the significance of a particular FP depends upon its reaction rate which is proportional to the product of its reaction cross-section and its yield. The competition between neutron absorption and radioactive decay should also be considered

and the FP classified for accuracy requirements as proposed in RP 10.

(ii) As an exception target accuracies can be given in % if the amount of a product built up by neutron capture in a FP is of primary interest for specific applications such as flux monitoring. In this case the uncertainty in the rate of formation is directly proportional to the relative uncertainty of the capture cross-section irrespective of its value. The most important examples are ^{110m}Ag, $^{134,136}Cs$ and ^{154}Eu formed by neutron capture in ^{109}Ag, $^{133,135}Cs$ and ^{153}Eu, respectively (see Table A4-I).

(iii) The exception mentioned under (ii) above is, however, not applicable for neutron cross-sections as a function of neutron energy, unless restrictions with respect to the magnitude of the point cross-section and range of energy is given. It is recommended to request accuracies for integral quantities (e.g. resonance integral or fast reactor spectrum average cross-section), in % and convert the accuracy of this integral quantity to the absolute accuracy of $\sigma_c(E)$ by the prescripton $\sigma_c(E) \times \phi(E) = \text{const.}$

7.2. Observations and conclusions: user requirements

7.2.1. Physics design of power reactor cores (RP 3)

(i) In order to be able to predict the reactivity effect due to FP in thermal reactors within 2% accuracy, the required accuracies in the capture cross-sections can be expressed as in Table A4-I of Appendix A4. In order to evaluate changes in FP absorption caused by changes in moderator temperature, the shapes of the cross-section curves in the thermal range have to be known to the same accuracies particularly for ^{135}Xe and ^{149}Sm.

(ii) The effect of FP capture in a typical fast breeder reactor can be evaluated to the accuracies adopted by the Panel (section 3.2) if the FP capture cross-sections, averaged over the reactor spectra, can be calculated from differential data (point- or group cross-sections) to the accuracies shown in Table A4-II of Appendix A4. These accuracies are sufficient to satisfy requirements for the Na-void effect, if the shape of $\sigma(E)$ between 0.1 and 100 KeV is known.

(iii) For the Doppler coefficient no special needs for cross-sections of fission products are expressed.

7.2.2. Burnup determination and safeguards (RP 5 and 6)

Neutron capture cross sections are requested to accuracies sufficient to allow corrections for buildup and burnout of important FP to $\lesssim 1\%$ of the burnup at maximum burnups of 40 000 - 70 000 MWd/T (or (2.3-4) x 10^{21} nv t).

(i) Sensitivity studies presented in RP 5 show that the unknown thermal neutron capture cross-section of ^{147}Nd has to be known to $\pm$ 10% if it is of the order of $\sim$200-500 b. In accordance with recommendation 7.1 the Panel agreed on a requirement of $\pm$ 30 b for σ_c of ^{147}Nd. This request has highest priority.

(ii) B.F. Rider has evaluated the accuracy of the thermal capture cross-section of ^{141}Pr required to make the error in the burnup determination via ^{148}Nd due to wrong contamination correction $\lesssim 1\%$ at a thermal reactor burnup of $\sim$40 000 MWd/T (or $\sim 2.3 \times 10^{21}$ n v t). With an average ^{148}Nd thermal fission yield of 1.7% the tolerable uncertainty in the "effective yield" of ^{142}Nd (or ^{142}Nd inventory per fission) is $\sim$0.08% per fission, assuming a ratio of ^{142}Nd: ^{148}Nd $\approx$ 5:1 in natural Nd. With a thermal fission yield of 5.8% (^{235}U) of ^{141}Pr the required uncertainty of σ_c (^{141}Pr) is $\pm$ 2.8 b at this burnup level. Appendix A4 shows that this requirement is fulfilled by available data.

(iii) Among burnup monitors only thermal capture cross-sections of stable Nd isotopes and of ^{143}Pr are significant. Since the half-life of ^{143}Pr is similar to that of ^{147}Nd, the same accuracy requirement for σ_c can be used. The accuracy required for the thermal σ_c of stable Nd isotopes is $\pm$ 2 b at a maximum fluence of about 4×10^{21} n vt. Assuming an epithermal index $r \lesssim 0.3$, the corresponding accuracy requirement for the resonance integral (RI) is $\pm$ 6 b.

According to Fig. 5 of RP 5, the fast reactor averaged neutron capture cross-sections of stable and long lived burnup monitors should be known to about $\pm$ 25-50 mb.

(iv) For the calculation of the ^{134}Cs inventory the Panel adopted the accuracy requirements for thermal neutron capture cross-section data presented in Appendix A4. The uncertainties due to neutron capture in ^{133}Xe and ^{133m}Xe should be $\leq 1\%$ of the ^{133}Cs inventory. Accordingly, the term $\sigma_c \phi$ should be known to $\leq 1\%$ of λ ($\lambda >> \sigma_c \phi$) in the case of ^{133}Xe and $\leq 36\%$ of λ in the case of ^{133m}Xe (branching $^{133}I \rightarrow ^{133m}Xe = 2.8\%$). The corresponding cross-section requirements are $\pm$ 150 b for ^{133}Xe and about $\pm 10^4$ b for ^{133m}Xe at a thermal neutron flux of 10^{14} $n \times sec^{-1} \times cm^{-2}$. The value for ^{133}Xe calculated this way agrees with a sensitivity study (table III of RP 6): $\pm$ 153 b uncertainty of σ_c (^{133}Xe) result in 1% error in the ^{134}Cs inventory.

(v) The accuracy requirement of the unknown σ_c of ^{153}Sm can be calculated in the same way: if $\lambda >> \sigma_c \phi$, then σ_c should be known to about $\pm 10^3$ b ($\leq 3\%$ of λ) at a thermal flux of 10^{14} $n \times cm^{-2} \times sec^{-1}$.

7.2.3. Engineering design and operation of reactors (RP 4)

Regarding cross-section needs in this area the Panel came to the following conclusions which are partly based on the views expressed by C. Devillers (RP 4):

(i) In order to determine the contamination, the capture cross-sections of stable ^{109}Ag, ^{133}Cs and ^{135}Cs and of the radioactive capture products ^{110m}Ag and ^{134}Cs should be known within $\pm$ 20% for the neutron spectrum involved.

(ii) For a thermal neutron flux of $\phi = 10^{14}$ n cm^{-2} sec^{-1} the term $\sigma\phi$ dominates over λ for ^{135}Xe ($\sigma\phi \approx 20 \times \lambda$). In accordance with the discussion on inventory data needed for FP release in section 3.2, item (iii), the thermal neutron capture cross-section of ^{135}Xe has to be known to $\pm$ 5%. Under these conditions the capture cross-sections of other unstable rare gases can be neglected against λ. For failed fuel detection an accuracy of $\pm$ 10% is requested for the thermal neutron capture cross-section of ^{135}Xe.

(iii) Control rod purposes: A 10% accuracy in the capture cross-sections between 10 keV and 1 MeV is required for ^{151}Eu and ^{153}Eu and, with a lower priority, for ^{152}Eu and ^{154}Eu.

(iv) For gas tagging purposes in fast reactors the capture cross-section of stable Xe and Kr isotopes which are, however, not fission products, has to be known to within 10%. These requirements are not included in Appendix A4.

(v) Other FP capture cross-sections are required if they are relevant compared to the decay constant as discussed in section 3.2. However, no specific FP have been identified by the Panel.

7.2.4. Fuel handling

For fuel handling only the capture cross-sections of FP listed in Appendix A4 are important. The knowledge of spectrum-averaged cross-sections would be sufficient for this application, if their variations with neutron spectrum are within the requested accuracies.

7.3. Neutron capture cross-sections in the thermal and resonance region

7.3.1 Observations and conclusions

(i) The Panel noted that a number of user requirements on FP capture cross-sections for thermal reactors are not satisfied by available data (see Appendix A4). Further measurements are required.

(ii) Generally user requirements are expressed for effective capture cross-sections, averaged over particular reactor spectra, or for Maxwellian averaged cross-sections and resonance integrals. The knowledge of such integral data may be sufficient for some applications, if their changes with different thermal reactor spectra are within the requested uncertainties. Otherwise the capture cross-section has to be known as a function of incident neutron energy, particularly in the resonance region, the accuracy depending on the shape of the cross-section curve and the neutron energy (see also Appendix A4).

(iii) The Panel considers it desirable to describe the low energy cross-sections of FP in terms of resolved resonances. The energy range to be considered should include about 10-20 resonances. A better knowledge of resonance parameters may also improve the accuracy of calculated neutron capture cross-sections in the KeV range

7.3.2 Recommendations

(i) User requirements should be given for capture cross-sections in the thermal and resonance region separately.

(ii) Further measurements are required in order to satisfy all requirements listed in Appendix A4 which have not yet been fulfilled.

(iii) In addition to cross-section measurements, FP neutron resonance experiments should be pursued with an emphasis on the most important radioactive FP. The purpose of these measurements is to enable a description of the low energy cross-sections in terms of resolved resonances and to provide resonance parameters for calculated cross-sections in the KeV range.

7.4. Status of FP capture cross-sections for neutron energies > 1 KeV

7.4.1 Observations and conclusions

(i) The needed accuracy in σ_c for neutron energies above 1 KeV is not fulfilled by the existing microscopic data, except for some mono-isotopic nuclei.

(ii) Some experiments which may satisfy the needs for σ_c of ^{105}Pd, ^{151}Eu and ^{153}Eu (RPI), Zr and Mo isotopes (ORELA) and experiments at FEI Obninsk are in progress or have been recently completed.

7.4.2. Recommendations

(i) Recognizing that theoretical calculations cannot satisfy all the needs the Panel recommends that microscopic capture cross-section measurements on separated isotopes should be pursued for the most important fission product isotopes.

(ii) The Panel wishes to refer to the general recommendation in the introduction on the necessity for physicists to quote systematic and random errors and to emphasize that this has to be done even for the phenomenological parameters which enter into the nuclear

models used for cross-section calculations, in order to be able to give a good estimate of the error in σ_c . The knowledge of this error is needed for the application of the adjustment method to improve σ_c with the help of integral measurements.

(iii) Noting the importance of average level densities to the theoretical prediction of neutron capture, inelastic and other cross-sections of FP nuclides the Panel recommends that this topic be reviewed within a meeting on the state of the art of theoretical prediction of nuclear data or at a separate specialists meeting within the next two years.

7.5. Status of FP (n,n'), (n,2n) and other cross-sections

7.5.1. Observations and conclusions

(i) There are data in the Italian FPND library for 18 FP isotopes and in the Australian FPND library for a large number of FP isotopes. The ENDF/B-III and IV libraries are using the Australian data file for $\sigma_{nn'}$.

(ii) The needs for FP inelastic scattering cross-sections are as follows:

a) For reactor design, inelastic scattering data need to be improved particularly for neutron energies below 1 MeV.

b) For the analysis of reactivity worth measurements in reactor physics experiments the required accuracy for $\sigma_{nn'}$ might be of the order of 30%. Further studies are needed in order to specify the accuracy for each isotope in a particular experiment.

(iii) The inelastic scattering cross-sections can be calculated to sufficient accuracy for reactor design purposes if the level scheme (energy, spin and parity) of the target nucleus is well known. $\sigma_{nn'}$ should be described for each level separately.

7.5.2. Recommendations

(i) The needs for $\sigma_{n,2n}$, $\sigma_{n,p}$ and other threshold reaction cross-sections for fission products should be investigated.

(ii) The Panel recommends that a compilation and evaluation of nuclear level scheme data needed for calculations of $\sigma_{nn'}$ and σ_c be undertaken. It was suggested that evaluators of nuclear structure data include in such an evaluation also the most probable spin and parity values and indicate the possibility of missed levels.

7.6. Integral measurements of FPND

7.6.1. General conclusions and recommendations

Integral measurements have proven to be useful and should continue to be used for checking and/or adjusting FP capture cross-sections, provided that the neutron spectrum is well specified. Results on lumped fission products are not always applicable to all kinds of systems.

7.6.2. Thermal systems

(i) Observation and conclusion: There exists only one good measurement on lumped fission products in thermal systems. This experiment gives only values for thermal capture but no data for resonance capture. The accuracy of this experiment hardly satisfies the accuracy requirements set forth in review paper 3, i.e. 2% on reactivity life time or 5% on neutron capture. However, only if significant improvements in accuracies or values for resonance capture can be obtained should new experiments be considered.

7.6.3. Fast systems

Observations and conclusions

(i) From the STEK measurements on lumped fission product samples deviations of 15-25% between experimental and calculated reactivities are observed. Some conclusions should be drawn after the analysis of the ERMINE measurements will have been completed.

(ii) From integral measurements in FRO on separated isotopes some useful conclusions about the quality of evaluated cross-sections sets can be given. More detailed conclusions can be drawn after the completion of the analysis of the measurements in CFRMF, ERMINE, and STEK mentioned in RP 14.

(iii) For integral measurements a good accuracy (i.e. better than 10%) is needed in σ_c over the neutron energy range important for fast reactors for at least one fission product isotope (e.g. ^{127}I or ^{151}Eu) to be used as reference for relating measured reactivity changes to average capture cross-sections in given neutron spectra.

Recommendations

(i) In view of the different energy ranges which are effective in the various assemblies it is strongly recommended to combine the results of FRO, CFRMF, ERMINE and STEK in a comprehensive analysis of the data.

(ii) In view of the fact that many experimental results on the integral measurements of FP are not available at this time, a specialist meeting on integral measurements of neutron cross-sections and their impact on microscopic cross-section data should be organized as soon as possible. In such a meeting special attention should be given to FP.

8. SUMMARY OF IMPORTANT RECOMMENDATIONS*

8.1. General

(i) Users of FPND should perform detailed investigations of their requirements, specifically by sensitivity studies, to achieve a specification of needs for individual FPND and their accuracies. These investigations should take into account available FPND and their accuracies (sections 1.3, 3.2 and 5.3).

* References to chapters and sections of the original recommendations are given in brackets.

(ii) Measurers are requested to publish all details on experimental conditions, corrections applied and error analysis required for an adequate evaluation (section 1.3).

(iii) Evaluation work should continue to be performed at different places and should in future receive stronger support by pertinent authorities. Evaluators should
- publish all pertinent details of their work;
- assess random and systematic errors separately;
- attempt to resolve discrepancies;
- assign uncertainties to their recommended data;
- warn users in cases of unresolved discrepancies;
- recommend further measurements required where data are lacking or discrepancies exist.

(sections 1.3, 4.1, 5.3, 7.4)

(iv) Unsatisfied user requirements: Further measurements should be performed in all cases where user requirements have not yet been satisfied. Specific recommendations are included in chapters, 4,5,6 and 7, based on a comparison of user requirements with the status of FPND in Appendices A1-A5.

(v) A follow-up meeting should be convened in about three years to review the progress in FPND work stimulated by the present meeting with the aim of setting up a more complete request list (chapter 1).

8.2. International cooperation in the exchange and dissemination of FPND information

(all recommendations: chapter 2)

(i) The list of FPND compilations and evaluations, as provided by Valente from NEA/CCDN (RP 1b) to this meeting should be kept up-to-date and published at annual intervals. To determine the distribution of the list the assistance of Panel participants should be solicited as well as of the Members and Liaison Officers of INDC, EANDC and other regional and national nuclear data committees.

(ii) Two international newsletters, one on activities in the field of compilation and evaluation of FPND and one on measurement activities related to FPND, should be developed as soon as possible. These newsletters should contain information on available manpower, names and addresses,

work finished, underway and planned, recent publications and other pertinent information in brief form. Observed discrepancies should be stated and brought to the attention of the INDC Subcommittee on Discrepancies. After approval by INDC this recommendation should be brought to the attention of EANDC and other regional and national data centres, who should also be asked to assist in determining a suitable distribution. Members and Liaison officers of INDC are asked to make sure that the contribution of their countries to the newsletters are provided regularly and on time to the (still to be determined) publishing centres.

(iii) An international request list for FPND should be developed. The requests should be justified by appropriate sensitivity studies.

(iv) Formats: In order to avoid a proliferation of computer formats the Panel recommends that those developed for the ENDF/B library be adopted as standard formats.

(v) Circular to measurers: The Panel recommends to initiate a circular to measurers stating all information on experimental details required by evaluators which should be included in publications of experimental results. In order to determine the contents of this circular, a questionnaire will be sent to evaluators of FPND. The circular will be distributed to measurers and, in addition, be included in every issue of one of the two newsletters proposed above.

8.3. FP decay heat

(all recommendations: section 3.3)

(i) Error bars should be included in FPND libraries and calculations of the uncertainty of the total FP decay heat should be performed.

(ii) Benchmarks: In order to resolve discrepancies between existing measurements the Panel recommends that benchmark experiments on FP decay heat should be performed at different laboratories under similar irradiation conditions employing all suitable measurement methods. Simultaneously, calculations should be performed at pertinent laboratories for the irradiation conditions of the benchmark experiments and a wide range of cooling times. This should enable a check of the input data of FPND libraries and, together with the measurements, serve as a basis for assessing FPND requirements for FP decay heat. Benchmark experiments and calculations should be restricted to studies of ^{235}U thermal fission.

(iii) Information on finished or on-going studies related to afterheat should be communicated to IAEA/NDS for collection and transmission to the then reviewers of this subject for the follow-up meeting.

8.4. FP yield data

(i) Investigations on the effect of neutron energy on fission yields should be performed by measurers and evaluators. These investigations should help in finding suitable parameters by which this effect can be described and in establishing the systematics of the energy dependence of yields (section 4.1).

(ii) Further measurements of independent and cumulative fission yields should be encouraged to improve and check the prediction of yields by calculational methods (section 4.2).

(iii) The development and improvement of calculational methods for the prediction of fission yields should be further pursued. Attempts should be made to assign uncertainties to calculated FP yields (section 4.3).

8.5. FP decay data

(chapter 5)

(i) Beta decay data should be studied more extensively than in the past. Average β energies, β-spectra and β ray intensities, particularly for transitions to ground and metastable states, should be measured.

(ii) The Panel suggests that data on Auger-electrons be included in compilations and evaluations of decay data.

8.6. Delayed neutron data

(i) In order to avoid systematic differences in delayed neutron measurements due to counter-calibration the Panel recommends to prepare a standard neutron source with an energy spectrum similar to that of total delayed neutrons for inter-comparison with individual laboratory standards (chapter 6).

8.7. Neutron cross-section data

(i) Noting the importance of average level densities to the theoretical prediction of neutron capture, inelastic and other cross-sections of FP nuclides the Panel recommends that this topic be reviewed within a meeting on the state of the art of theoretical prediction of nuclear data or at a separate specialists meeting within the next two years (section 7.4).

(ii) The Panel recommends that a compilation and evaluation of nuclear level scheme data needed for calculations of $\sigma_{nn'}$ and $\sigma_{n\gamma}$ be undertaken. It was suggested that evaluators of nuclear structure data include in such an evaluation also the most probable spin and parity values and indicate the possibility of missed levels (section 7.5).

(iii) In view of the different energy ranges which are effective in the various assemblies used for measurements of integral FP cross-sections it is strongly recommended to combine the results of FRO, CFRMF, ERMINE and STEK experiments in a comprehensive analysis of the data.

(iv) In view of the fact that many experimental results on the integral measurements of FP are not available at this time, a specialists meeting on integral measurements of neutron cross-sections and their impact on microscopic cross-section data should be organized as soon as possible. In such a meeting special attention should be given to FP (section 7.6).

Appendix A1: FP CHAIN YIELDS

Comparison: status - user requirements

A1.1 Chain yields from thermal neutron fission

(i) The uncertainties of FP yields from thermal fission are those recommended by Walker (RP 11a). Since the uncertainties of chain yields in the peak regions of the mass yield curve do not differ much, and since most of the requirements are fulfilled, presently available accuracies are presented for all requested mass chains as a group, together with the user needs in Table A1-I.

In some cases the uncertainties of presently available data, and/or discrepancies among experimental data, which cannot be resolved, exceed the accuracy required. These chain yields are indicated under "comments" in Table A1-I and surveyed in more detail in Table A1-II. Discrepancies are discussed in RP 11a, together with measurements required to resolve them and check existing data.

However, it is the feeling of the Panel that the status of thermal chain yields is so close to the required accuracies that an improvement of the data has no high priority (see chapter 4).

(ii) Safeguards: ^{154}Eu, formed from ^{153}Eu by neutron capture with contributions from lower mass chains by multiple capture is used in isotope correlation studies. An improvement of present data is needed, but the definite accuracy required is not yet known. This request has very low priority.

(iii) Fuel design: Requirements for gas pressure calculation are included in Table A1-I. Requirements for information on the chemical state in nuclear fuel are $\pm$ 15% for yields $\geq$ 1%. These requirements are met by presently available thermal chain yields (see RP 11a) with the exception of the few cases where yields have not been measured:

- ^{233}U: 128-130
- ^{235}U: 130
- ^{239}Pu: 107, 108, 129, 130
- ^{241}Pu: 89, 98, 100, 103, 105, 107-110, 130, 139

Table A1-I: Chain yields from thermal fission: status and user requirements.

application field	FP mass numbers [a]	fissioning nuclei	accuracy(%) needs	accuracy(%) status	comment
burnup RP 5	106,133,137,143 144,145,146,148 150	^{233}U ^{235}U ^{239}Pu ^{241}Pu	2-3 1-2 1-2 5	≤ 3 ≤ 2 ≤ 2 < 5	except A = 106,133 except A = 106,133 except A = 106,133,137 except A = 106
burnup RP 5	95,103,140,141	^{233}U ^{235}U ^{239}Pu ^{241}Pu	5 3 3 5	≤ 5 ≤ 2 2-5 < 5	except A = 103,141 except discrepancy also discrepancies except A = 103: no measurement
safeguards RP 6	149,151-153	^{235}U ^{239}Pu	- -	~ 6 3-10	) improvement needed) other requirements:) see burnup
fuel handling RP 7	89,90,91,95 103,106,125,129 131,133,137,140 141,143,144,147, 151,153	^{233}U ^{235}U ^{239}Pu	5-10	≤ 7 ≤ 7 ≤ 7	) except A = 125,129) discrepancies exist,) see Table A1-II A=153: status ~ 10%
Physics design of reactor cores RP 3	99,103,131,133 143,147,149, 151,152	^{233}U ^{235}U ^{239}Pu	6-11	≤ 6-7 ≤ 6-7 ≤ 6-7	) requirements met,) except discrepancies) at A = 103,131,) see Table A1-II
fuel design (gas pressure)	83,84,86,131, 132,134,136	^{233}U ^{235}U ^{239}Pu	10	<10	
FP release and contamination RP 4	90,95,103,106 109,125,131,133 135,137,140	^{233}U ^{235}U ^{239}Pu	20	< 20	requirements met; see also cumulative yields Appendix A2.

[a] Other mass numbers, for which only cumulative yields are required, are included in appendix A2 (e.g. 135Xe).

Table A1-II: Individual chain yields in thermal fission: unsatisfied requirements

FP mass no	fissile isotope	status (%)	accuracy required a) (%)	RP	P	Comments D = discrepancies among experimental data
95	^{239}Pu	1.6	3	5	2	D of 5% and more: see RP 11a
103	^{233}U	6	5	5	2	D even higher, see RP 11a } RP 3
	^{235}U	1.4	3	5	2	for D see discussion RP 11a } requires
	^{239}Pu	4.2	3	5	2	for D see discussion RP 11a } 6% accuracy
	^{241}Pu	?	5	5	2	no measurements
106	^{233}U	4	2-3	5	2	
	^{235}U	3	1-2	5	2	
	^{239}Pu	5	1-2	5	2	D even higher, see RP 11a
	^{241}Pu	6.6	5	5	2	
125	^{233}U	13	5-10	7	3	based on only one measurement
	^{235}U	7	5-10	7	3	D of 30% and more exist
	^{239}Pu	14	5-10	7	3	
129	^{233}U	?	5-10	7	2	no measurements
	^{235}U	23	5-10	7	2	
	^{239}Pu	?	5-10	7	2	no measurements
131	^{239}Pu	2.4	5-10	7	3	D and inconsistencies exceeding
			8	3	3	required accuracy: see RP 11a
133	^{233}U	3.5	2-3	5	2	D among experimental data, especially
	^{235}U	2.4	1-2	5	2	between Xe and Cs.
	^{239}Pu	2.7	1-2	5	2	^{239}Pu: see discussion RP 11a
137	^{233}U	2.3	2-3	5	2	D among experimental data exist, but
	^{239}Pu	2.7	1-2	5	2	average probably adequate.
141	^{233}U	7.6	5	5	3	
	^{239}Pu	4.7	3	5	3	

a) Only the review paper requesting highest accuracy is listed, except in cases of about equivalent accuracy or if the primary request has low priority.

P = Priority for improvement of present status: 1 = high
2 = medium
3 = low

Since other chain yields are known much more accurately than required, the overall accuracy should be sufficient (see chapter 4.), with the possible exception of ^{241}Pu.

Requirements for yields < 1% (± 50% for yields between 0.1% and 1% and within a factor 5 for yields < 0.1%) can be satisfied by interpolated and extrapolated yields supplementing experimental data.

A1.2 On the effect of incident neutron energy on yields

Fission yields in the region of the wings of peaks and in the valley of the mass distribution increase with increasing incident neutron energy. When going from thermal to fast reactor fission, the yields in the valley are enhanced by a factor of 3 for ^{235}U and a factor of 2 for ^{239}Pu.

This increase has to be compensated by a decrease in peak yields as the sum of all yields is 200%. However, the two-mode fission theory predicts that the change in peak yields is $\leq$ 3% from thermal to fast reactor fission. Therefore the variation of peak yields with different fast reactor spectra is expected to be even smaller

A1.3 Chain yields from fast neutron fission

(i) The main survey of data requirements and status presented in Table A1-III, is restricted to chain yields from fast fission of ^{235}U and ^{239}Pu, needed for current fast reactor programmes. The term "fast" used in this survey needs some further explanations (it is also discussed in section 4.2.).

Users require fission yields for fast reactor spectra. Available data have to be valid for the particular fast reactor spectrum involved within the requested accuracy limits.

In current evaluations "fast yields" are not well defined. Recommended yields are derived from experimental results obtained in different fast reactor spectra, fission neutron spectra (generally from ^{235}U, ^{238}U or ^{252}Cf), and sometimes even at discrete neutron energies ranging from 1.5 to 3 MeV. In order to allow a better comparison of this rather poorly defined status with user requirements, a range of values is given in Table A1-III (see explaination below). These values are derived from the survey given in RP 11b and information supplied by Panel participants.

In almost all cases, the lower limit is the status supplied by B.F. Rider. It corresponds to the data presently adopted for the ENDF/B file and published in [1]. It is important to note that weighted averages are dominated by the most accurate results and the uncertainty of the mean is even lower than experimental errors if the data are consistent. Contrary to other evaluators, Meek and Rider have also included estimated values in their evaluation procedure and have derived fast from thermal yields by drawing smooth curves through measured fast/thermal yield ratios in order to get completely evaluated mass yield curves. In very few cases the uncertainty of the most recent results of von Gunten (see section 4.2) are used.

Since the most accurate results were always obtained from measurements in fast reactor spectra, the lower limits represent the status achieved experimentally for particular fast reactor spectra. Uncertainties as low as 1-1.5% indicate that different measurements are fairly consistent and any effect of fast reactor neutron spectrum on yields falls within experimental error.

The upper limit is

- either derived from J.G. Cuninghame's judgement of the status, based on his survey of the subject for the Panel (RP 11b);
- or represents differences between yields recommended by Meek and Rider [1] and Crouch [2]; this partly supersedes the comparison in RP 11b between [2] and the earlier evaluation of Meek and Rider [3];
- or is the uncertainty given by Crouch [2] as the larger standard deviation of weighted or unweighted average.

Thus the upper limit reflects existing discrepancies and/or a possible effect of neutron energy on yields and/or the overall reliability of evaluated yields.

When comparing the status of yields with user requirements, the upper limit should be used (except for very large discrepancies), unless the evaluations or sources of experimental data are consulted directly. Yield data for other fissioning nuclei present in smaller amounts in fast reactor fuel are needed with much lower accuracy. It would be worth investigating if this required accuracy could be achieved using fission theory and systematics of mass yields (see 4.1 and RP 16).

Table A1-III: ^{235}U and ^{239}Pu fission yields from a fast reactor spectrum: status and user requirements

FP mass no.	relative accuracy (%) of fast chain yields								
	status[a]		user requirements[b]						
	^{235}U	^{239}Pu	review paper no.				fuel[c]	dosimetry	
			3	4	5	7	design	US[d]	others
83	2-7	2-8					10		
84	2-4	2-5					10		
85	2-5	2-5		20		5-10*	10*		
86	2-3	2-5					10		
87	2-5	3-6		≤20*					
88	2-4	3-7		≤20*					
89	3-6	3-6		<20*		5-10			
90	2-3	1.5-5		20		5-10			
91	2-10	1.5-6		<20*		5-10			
95	1.5-3	2-3	30	20	≤2	5-10		2	10
97	1.5-3	3-4	30						
98	1.5-3	2-6	35						
99	1.5-5	~3	20			10-20			
100	1.5-4	5-6	35						
101	2-7	2-7	20						
102	2-4	3-7	25						
103	2-6	3-5	20	20	≤2	5-10			
104	2-5	3-7	30						
105	4-26	≥6	20						
106	6-30	3-10	35	20	≤2	5-10			
107	≥16	≥16	25						
109	≥12	6-18	40	20		10-20			
111	2-40	12-25				10-20			
123	≥12	≥16				10-20			
125	≥8	≥8		20		5-10			
127	≥12	≥12		≤20*		10-20			
129	6-12	15		≤20*		5-10			
131	1.5-3	2-10	30	20		5-10	10		
132	1.5-6	3-5		≤20*		10-20	10		
133	1.5-3	2-5	20	20	2	5-10			

Table A1-III: (continued)

FP mass no.	relative accuracy (%) of fast chain yields								
	status[a]		user requirements[b]						
	^{235}U	^{239}Pu	review paper no.				fuel[c]	dosimetry	
			3	4	5	7	design	US[d]	others
134	2-7	4-5					10		
135	2-4	3-6	30	20					
136	1-5	3-5					10		
137	1-6	2-10	40	20	≤2	5-10		2	10
138	1.5-3	4-25		<20*					
139	1-5	6-10	40	<20*					
140	1.5-4	1.5-3		20	≤2	5-10		2	10
141	2-3	3-5	35	<20*	≤2	5-10			
143	1-5	1.5-7	30		≤2	5-10		2	10
144	1.5-6	2-3			≤2	5-10			
145	1-3	1.5-5	35		≤2			2	10
146	1-4	1.5-5			2			2	10
147	3-18	3-6	25			5-10			
148	1-3	1.5-6			≤2			2	10
149	3-5	2-5	30			10-20			
150	1.5-5	1.5-5			≤2			2	10
151	2-3	3-5	25			5-10			
152	2-3	3-6	55						
153	≥8	≥12	40			5-10			
155	12-50	≥16	55			5-10			
156	8-60	≥6				10-20			

a) For references and discussion of lower/upper limit of status see text.

b) In the user fields discussed in review papers 3, 4 and 7 and in fuel design, requirements for yields from ^{232}Th, $^{233,238}U$ and $^{240,241,242}Pu$ fast fission are not listed separately. They are about a factor of 2-5 less stringent than those for ^{235}U and ^{239}Pu.

* .. chain yield required for calculation of cumulative yield

c) Requirements listed are only for evaluation of gas pre sure within fuel.

d) The accuracy listed is only required by the LMFBR and FTR programme at Hanford (USA).

(ii) As burnup determination and fast reactor dosimetry require yields from fast fission of nuclei other than ^{235}U and ^{239}Pu to much higher accuracy than for other applications, their needs are listed separately in Table A1-IV together with the data status.

Only calculated fast yields together with their estimated uncertainties are available for ^{236}U, $^{240,241,242}Pu$ and $^{241,243}Am$. Peak yields for ^{241}Pu fast fission can be derived from thermal yields more reliably than for the other nuclides listed above; the estimated uncertainty limits are therefore lower.

The status for ^{233}U and ^{237}Np corresponds to information supplied by Rider and Cuninghame and the evaluation of Crouch [2].

The same sources as well as a contribution by Lammer [4] are used for ^{232}Th and ^{238}U. However, the low uncertainties of Rider (see [1]) are not used for most yield data, as unresolved discrepancies make the absolute yields obtained from a normalization uncertain (see detailed discussion in [4]).

(iii) The knowledge of the complete mass yield curve is required for investigations of the chemical state of fast reactor fuel. Of primary importance are all major fast chain yields, i.e. the mass ranges 80-110 and 125-155. As discussed in section 4.1, the requirements expressed by the subgroup on chain yields (SG) and by R.H. Flowers (F) are:

$\pm \leq$ 10%(SG) - 15%(F) for ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu
$\pm$ 15%(F) for ^{232}Th, ^{238}U and ^{240}Pu

These chain yields have to be known also for the calculation of afterheat.

Requirements for yields at the wings of the peaks and in the valley of mass distributions as expressed by Flowers (section 3.2) for the fissionable nuclei listed above are:

$\pm$ 50% for chain yields between 0.1 and 1%
within a factor 5 for chain yields < 0.1%.

(iv) For particular fast reactor spectra (corresponding to the lower limit in Table A1-III) many requirements for burnup and dosimetry applications have been fulfilled for yields from ^{235}U and ^{239}Pu fission. However, the data have to be analyzed in more detail for appli-

Table A1-IV: Chain yields from fast fission of other nuclei: status and requirements

mass no.	needed for[a]	status: relative uncertainty (%) of available data[b]									
		^{232}Th	^{233}U	^{236}U	^{238}U	^{237}Np	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am	^{243}Am
95	b,d	6-11	10	↑	3	6	↑	↑	↑	↑	↑
103	b	6-10	10-15		3-4	10					
106	b	10-25	6-15		10	10					
133	b	6-20	10		8-20	10					
137	b,d	6-25	5-10		6-20	5-10					
140	b,d	6-12	8-10		2	3-4					
141	b	6	8-15	15-20*	8	20	15-20*	6-15*	15-20*	15-20*	15-20*
143	b,d	8	10		8	10					
144	b	5-10	10		8	4					
145	b,d	8	10		8	15*					
146	b,d	10	10-15*		8	15*					
148	b,d	8	10-15*		8	9					
150	b,d	10	10-15*	↓	8	15*	↓	↓	↓	↓	↓
purpose		accuracy (%) required									
burnup		≤5	≤2	-	≤5	≤10	≤10	≤3	≤10	≤10	≤10
dosimetry[c]		2	-	2	2	2	-	-	-	-	-

a) b ... burnup, d ... dosimetry.

b) Status: for references and discussion of lower/upper limit see text.

c) These requirements are only for the LMFBR and FTR programme at Hanford, US. Other requirements are ± 10%.

* Only available as calculated yields (Sidebotham, see RP 11b and 16), estimated uncertainty.

cation and the effect of neutron energy on fast yields has to be considered (see below). The bulk of other burnup requirements is clearly not fulfilled.

Other user requirements for ^{235}U and ^{239}Pu fast yields are generally fulfilled, particularly if a different allocation of accuracy targets using available yield uncertainties is considered. Available fast yields from other nuclei except ^{232}Th and ^{238}U are not sufficient to satisfy needs for investigations of the chemical state of nuclear fuel.

An improvement of the situation is to be expected after the completion of current measurements listed in section 4.1.2. But additional evaluation work is required, as complete mass yield curves are not being investigated experimentally.

A1.4 Effect of neutron energy on yields

(i) Generally speaking, changes of FP chain yields as a function of fast reactor neutron spectrum should be known within the accuracy limits given in Table A1-III.

(ii) Burnup: At present the most widely used burnup monitor is ^{148}Nd, measured mass spectrometrically together with other Nd isotopes. It has been observed (RP 5) that relative Nd yields change systematically with fast reactor neutron spectrum. This change has to be known for ^{232}Th, ^{233}, ^{235}, ^{238}U and ^{239}, ^{241}Pu with the accuracies listed in Tables A1-III and A1-IV.

(iii) Apart from a recent study on ^{235}U fast yields presented to the Panel by W.J. Maeck (see also RP 5) no data are available on the variation of fission yields in the energy range of interest for fast reactors.

Measurements to $\pm$ 2% accuracy on the variation of Nd yields with neutron energy or fast reactor spectrum are required to enable the selection of most suitable burnup monitor nuclides. Such measurements should also include other nuclides in the mass range 140-160 to help in establishing the systematics of the energy effect. Further measurements with lower accuracy are needed for yields at wings and in the valley region to establish the energy effect for the chain yields requested in Table A1-III.

References:

[1] M.E. Meek and B.F. Rider, NEDO-12154-1 (Jan.1974)

[2] E.A.C. Crouch, AERE-R7394

[3] M.E. Meek and B.F. Rider, NEDO-12154 (Jan.1972)

[4] M. Lammer, contribution to RP 11b, these Panel proceedings, Vol. 3.

Appendix A2: INDEPENDENT AND CUMULATIVE FISSION YIELDS

Comparison: status - user requirements

A2.1 Present and future needs

The present survey includes only those needs which were expressed explicitly by the Panel. It should be noted, however, that this survey represents only a minority of requirements for independent and cumulative yield data. Many more FP will have to be included as soon as needs for afterheat and environmental aspects are assessed in detail.

A2.2 Cumulative yields in thermal neutron fission

(i) The status of cumulative yields from ^{233}U, ^{235}U and ^{239}Pu thermal fission is compared to user requirements in Table A2-I. An inspection of this table shows that most of the present requirements for cumulative yields in thermal neutron fission are met. This is mainly due to the fact that the majority of needs are expressed for the Kr and Xe isotopes which have been measured more extensively than other FP. Few data are available for ^{241}Pu (see below), and none have been requested. If they are required, accuracies will probably be a factor of 2-3 less stringent than those listed in Table A2-I.

(ii) Basic data: Fractional cumulative yields and their uncertainties have been evaluated by M. Lammer (as shown in the Annex to Appendix A2), based on the compilation of experimental data by W.H. Walker (RP 11a, Appendix B) and have been approved by Panel participants. Only those mass chains have been evaluated, for which at least one measurement of a fractional yield is available. However, Table A2-I contains the status of only those data which could be derived from measurements with sufficient confidence (see Annex to this appendix). The data status is marked with an asterisk (*) in Table A2-I if the corresponding fractional cumulative yield and its uncertainty was not obtained directly from measurements.

(iii) Uncertainties: Uncertainties of chain yields are those recommended by Walker, RP 11a. They are taken in quadrature with the uncertainties of fractional cumulative yields to calculate the uncertainties of cumulative yields, which are also shown in Table A2-I.

Table A2-I: Cumulative yields in thermal fission: status and requirements

FP	uncertainty (%)[a] for fission of ^{235}U	^{233}U	^{239}Pu	accuracy (%) required for[b] R P 4 rc	ff	others
T	~10	~10	~12	50		5-10 (RP7)
^{85m}Kr	2.5	3	~3	20	20	
^{85}Kr	2.3	2.3	2.7	20		5-10 (RP7),10(fd)
^{87}Kr	3.4*	?	~3.6*	20	20	
^{88}Kr	4.5*	?	<10*	20	20	
^{89}Kr	2.3	2	2.6	20	20	
^{90}Kr	3	2.1	2.4	20	20	
^{90}Rb	3	3.4*	~4*	20		
^{91}Kr	2.7	3.3	3.6		20	
^{129m}Te	?[c]	?[c]	?[c]	20		
^{133}I	≤2.6	5.3*	5*	20		
^{135}I	2.4	5.6	3.5	20		5(RP3)
^{135}Xe	2.4	2.6	3.5	20	20	5(RP3)
^{137}Xe	2.6	2.6	~3	20		
^{138}Xe	2.5	~3	6.6		20	
^{139}Xe	3.5	~4	5.6		20	
^{140}Xe	3.5	~5	3.6	20	20	
^{140}Cs	2.2	~6	?	20		
^{140}Ba	1	1.9	~10*	20		3-5(RP5)
^{141}Xe	10	~10	~6		20	

Table A2-I: continued

a) - Estimated uncertainties, marked with (*), are included here only if they are well below the requirements. Otherwise they are marked with (?) but included in the Annex to this appendix, except ^{129m}Te: see c).
- For ^{241}Pu see text.

b) rc ..... FP release and contamination of reactor components
ff ..... failed fuel detection
fd ..... fuel design

c) No measurements exist. To be used with ^{129}Sb or mass 129 yield and decay branching.

* estimated

Note: 1) Some of the fractional yields are based on single measurements with low uncertainties. However, not all of these uncertainties are reliable, as some discrepancies among data presented in Table B1 of RP 11a and in the Annex to this appendix show. Furthermore, part of the experimental data of fractional yields and their uncertainties have been derived from published chain yields, which do not correspond to those presented in RP 11a and adopted by the Panel.

2) In most measurements independent and cumulative yields are determined directly. Fractional yields are derived subsequently from known standard yields and chain yields. The uncertainties of these yields are therefore included in the uncertainties of the fractional yields as listed by Walker. Since the latter are again combined with uncertainties of chain yields, the resulting uncertainty of the cumulative yield is higher than that of the original measurement. It is, however, not the intent of this survey to go back to the original publications, and the combined uncertainties are probably more realistic in the light of the arguments under 1) above.

(iv) In ^{241}Pu thermal fission only the cumulative yields for ^{85}Kr and mass 135 are available. The uncertainties, taken from RP 11a (for ^{85}Kr see Annex), are:
^{85}Kr: 2.3%, ^{135}I and ^{135}Xe: 3.4%

A2.3 Cumulative yields in fast neutron fission

The only experimental data available are fractional independent yields of ^{133}I, ^{135}I and ^{135m}Xe in fast fission of ^{232}Th (see RP 11b). Therefore only user requirements are summarized in this survey and presented in Table A2-II . In view of the scarcity of data it is indicated in the table, for which FP, at least within the required accuracy, total chain yields can be used. Clearly, a lot of experimental work is still required to fulfill the needs.

From available experimental data the following comments can be made on the data status:

(i) The measurements of ^{133}I and ^{135}I fractional independent yields in Th-232 fast fission suggest that the limits for fractional cumulative yields given in Table A2-II hold for all fissile nuclides, assuming Gaussian charge dispersion. Using the uncertainties of fast chain yields given in Table A1-II the following uncertainties can be deduced for cumulative yields from ^{235}U and ^{239}Pu fast fission:

$\leq \pm$ 4% for ^{133}I

$< \pm$ 5% for ^{135}I and ^{135}Xe

(ii) The cumulative yield of ^{85}Kr can be deduced from the chain yield given in Table A1-II and the branching $^{85m}Kr \rightarrow {}^{85}Kr$ (see discussion in the Annex). The uncertainties are:

$\leq$ 5% for ^{235}U and ^{239}Pu fission in a typical fast reactor spectrum, and

$\leq$ 10% taking into account the energy dependence of the mass 85 yield.

Table A2-II: Cumulative yields in fast fission: user requirements

FP	required accuracy (%)[a]			
	RP 4		RP7	comments
	r.c.	f.f.		
T	50		5-10	no data available
^{85m}Kr	20	20		
^{85}Kr	20		5-10	± 10% for fuel design (see text, also for status)
^{87}Kr	20	20		} total chain yield can be used for ^{235}U and ^{239}Pu
^{88}Kr	20	20		
^{89}Kr	20	20		
^{90}Kr	20	20		
^{90}Rb	20			
^{91}Kr		20		
^{127m}Te			10-20	} can be deduced from chain yield and branching ratio
^{129m}Te	20		10-20	
^{132}Te				
^{133}I	20			$\gtrsim$ .99 of chain yield (see text)
^{135}I	20			$\gtrsim$ .98 of chain yield (see text)
^{135m}Xe	20	20		
^{135}Xe	20	20		≈ total chain yield
^{137}Xe	20	20		
^{138}Xe	20	20		
^{139}Xe	20	20		
^{140}Xe	20			
^{140}Cs	20			
^{141}Xe		20		

a) The accuracies listed are for fast yields of the main fissile isotopes ^{235}U and ^{239}Pu. Requirements for ^{232}Th, $^{233,236,238}U$, $^{240,241,242}Pu$ are a factor of 2-5 less stringent.

r.c. = FP release and contamination of reactor components

f.f. = fuel failure detection.

Annex to Appendix A2:

EVALUATION OF FRACTIONAL YIELDS

by M. Lammer

1. Abbreviations

The abbreviations given below are used throughout the text and the tables.

chy ..... chain yield(s)
cy ..... cumulative yield(s)
e,exp .... experiment(al)
fc ..... fractional cumulative yield(s)
fi ..... fractional independent yield(s)
G ..... (assuming) Gaussian charge dispersion
w,wa ..... weighted average
Zp ..... most probable charge
σ ..... Width of Gaussian charge dispersion

2. ^{85}Kr and ^{85m}Kr

In currently adopted decay schemes there is no direct branch from ^{85}Br to the ground state of ^{85}Kr. The adopted internal transition branch is:

$$^{85m}Kr \longrightarrow {}^{85g}Kr: \quad 0.212 \pm 0.009$$

Lisman et al (J. inorg. nucl. Chem. 33 (1971) 643) measured both ^{85g}Kr and ^{85}Rb by isotope dilution mass spectrometry and obtained fractional cumulative yields for ^{85g}Kr. These yields, together with the differences between them and the branching ratio from the decay of ^{85m}Kr (d) are listed below:

	^{233}U	^{235}U	^{239}Pu	^{241}Pu
fc	0.2296 ± 0.0028	0.2176 ± 0.0024	0.2260 ± 0.0018	0.2235 ± 0.0033
d	0.018	0.006	0.014	0.012

Only the values for ^{235}U and ^{241}Pu agree with the branching ratio within the error limits. For deriving the fractional cumulative yields of ^{85m}Kr shown in Tables A2III-A2V, these differences, rounded upwards, were taken as upper limits of the fractional independent yield of ^{85g}Kr.
Since the yield of ^{85g}Kr can be measured mass spectrometrically relative to stable FP Kr, the uncertainties assigned by Walker (RP 11a) to mass 84 and 86 chain yields are assigned in Table A2-II to the cumulative yield of ^{85g}Kr.

3. Summary of fractional yields

Tables A2-III to A2-V show in detail how the uncertainties listed in Table A2-I were obtained. Only those mass chains are included, for which at least one measurement on fractional yields is available. Wherever possible, fc were deduced directly from measurements. This includes cases where fc of a FP has not been measured directly, but deduced from fi of this FP on the next member in the chain assuming a Gaussian charge dispersion.

The Tables are generally self-explanatory, but some comments are given below. If several measurements of different fi and fc were available for a mass chain, they were plotted on probability paper and evaluated in detail. Experimental data are taken from RP 11a [1].

3.1. Table A2-III: fractional yields in ^{235}U thermal fission

Detailed evaluations of mass chains 87,88,91,139 and 140 are presented in Tables A2-VI to A2-X, and discussed further below. Fractional yields for mass 91 are presented in Table A2-VIII in order to illustrate their consistency with G in spite of their apparent disagreement with the calculated data of Crouch [2].

The selection of all other data in Table A2-III is self-evident.

Table A2-III: Details on status of cumulative yields from ^{235}U thermal fission

FP	fc	uncertainty (%) for			comments and data: underlined are data used to obtain fc e ... experimental, c ... calculated, w ... weighted average
		fc	chy	cy	
^{85m}Kr	≳.99	<1	2.3	2.5	for ^{85m}Kr and ^{85}Kr see text
^{87}Kr	≳.99	2	2.8	3.4	see Table A2-VI
^{88}Kr	.96	4	2	4.5	see Table A2-VII
^{89}Kr	.96	1	2.1	2.3	^{89}Rb fi: e .042 ± .007w, c .04, G / ^{89}Kr fc: c .96
^{90}Kr	.86	2.3	1.9	3	^{90}Rb fc: c .9976; fi: e .13 ± .01, c .15/^{90}Kr fc: e .86 ± .02, c .85;
^{90}Rb	.99	2.3	1.9	3	fi: e .63 ± .08, c .62
^{91}Kr	.59	2	1.8	2.7	see Table A2-VIII
^{133}I	1.00	≲1	2.4	≲2.6	^{133}I fi: e .024 ± .005w, G, used
^{135}I	.965	.4	2.4	2.4	as evaluated by Walker, RP 11a;
^{135}Xe	1.00	-	2.4	2.4	for ^{135m}Xe the decay branch from ^{135}I should be used.
^{137}Xe	.978	.3	2.6	2.6	^{137}Xe fc: e .978 ± .003
^{138}Xe	.952	.1	2.5	2.5	^{138}Cs fi: e .048 ± .001w, used with G
^{139}Xe	.80	3	1.8	3.5	see Table A2-X
^{140}Xe	.60	3.3	1	3.5	evaluated: Ba: fi = .07 ± .02, Cs: fi = .33 ± .02
^{140}Cs	.93	2	1	2.2	^{141}Xe fc: e .21 ± .02, fi: .20 ± .03
^{141}Xe	.21	10	1	10	^{141}Xe fc: e .21 ± .02, fi: .20 ± .03

Table A2-IV: Details on status of cumulative yields from ^{233}U thermal fission

FP	fc	uncertainty(%) for			comments and data: data used to obtain fc are underlined e ... experimental, c ... calculated, w ... weighted average
		fc	chy	cy	
^{85m}Kr	$\gtrsim$.98	~2	2.3	3	for ^{85m}Kr and ^{85}Kr see text
^{87}Kr	~.88*	~20*	2.3	20	^{87}Kr fc: c.98 / ^{87}Br fc: e.56±.04, c.68 ; fi: e.75±.20, c.56/ ^{87}Se fc: e.19±.04, c .12 / G (see text)
^{88}Kr	$\gtrsim$.80*	~25*	1.6	25	^{88}Kr fc: c.91/ ^{88}Br fc: e.47±.06, c.38; G, very uncertain (see text)
^{89}Kr	.86	1	1.6	2	^{89}Kr fc: e .86 ± .01, (c.88)
^{90}Kr	.67	1.5	1.5	2.1	^{90}Y fi: e .00008, c .0004/ ^{90}Rb fc: c .96 / ^{90}Kr fc: e .67±.01, c.32/
^{90}Rb	~.98*	~3*	1.5	3.4	^{90}Br fc: e .10±.03, c .053 / G, all e data used (see text)
^{91}Kr	.33	3	1.2	3.3	^{91}Kr fc: e .33±.01
^{133}I	$\gtrsim$.98*	$\lesssim$4 *	3.5	$\lesssim$5.3	^{133}I fc: c .999; fi: e .14±.01, .155±.010, c .17/G (see text)
^{135}I	.79	5	2.4	5.6	as evaluated by Walker, RP 11a;
^{135}Xe	$\gtrsim$.99	~1	2.4	2.6	for ^{135m}Xe the decay branch from ^{135}I should be used
^{137}Xe	.90	1.1	2.3	2.6	^{137}Xe fc: e .90±.01 w
^{138}Xe	.83	1.2	2.7	~3	^{138}Xe fc: e .83±.01
^{139}Xe	.48	2.1	3.1	~4	^{139}Xe fc: e .48±.01
^{140}Xe	.23	4.5	1.9	~5	^{140}La fi: e .0038±.0001[5] / ^{140}Ba deduced fc: .9962±.0001; fi: e .27±.04 /
^{140}Cs	.73	5.5	1.9	~6	^{140}Cs deduced fc: .73±.04 / ^{140}Xe fc: e .23±.01
^{140}Ba	.996	<0.1	1.9	1.9	
^{141}Xe	.051	6	7.6	10	^{141}Xe fi: e .051±.003; G: fi ≈ fc

3.2. Table A2-IV: fractional yields from ^{233}U thermal fission

Mass 87: fc for ^{87}Kr is obtained from a plot on probability paper through the experimental points. The uncertainty extrapolated from the error margins of experiments (worst case) ranges from + 7% to - 10%. Compared to a ^{89}Kr fc of $0.86 \pm .01$, the value of 0.88 obtained from the plot for fc of ^{87}Kr appears to be very unlikely. The experimental points as well as $\sigma = 0.93$ disagree with calculated data [2]. Therefore an uncertainty ranging from + 14% to - 20% should be a safe limit for fc of ^{87}Kr.

Mass 88: Only one measurement of $^{88}Br/fc$ is available. Using $\sigma = 0.64$ (mass 88 in ^{235}U thermal fission), the value of $Kr/fc = 0.94$ is obtained. With $\sigma = 0.93$ (mass 87 in ^{233}U thermal fission) Kr/fc becomes 0.83. We adopt $^{88}Kr/fc \geq 0.80 \pm 20\%$, where an uncertainty of - 20% is very unlikely compared to $^{89}Kr/fc$.

Mass 90: $^{90}Kr/fc$ is deduced from the experimental data shown; these are completely consistent with G ($\sigma = 0.60$, $Zp = 36.23$), but in disagreement with the calculation of Crouch [2] ($\sigma = 0.60$, $Zp = 36.47$). The uncertainty derived from experiments is < 1%. However, since Kr/fc was not measured and fluctuations of fc around G due to the odd-even effect are possible (Amiel [3]), we adopt an uncertainty of +2 to -3 %.

Mass 133: Only measurements of I/fi exist for this mass chain. Assuming an average σ of 0.5-0.7, $I/fi = 0.15$ ($\pm$ 0.01 wa) leads to $Xe/fi \leq 0.01$. Even with an abnormal σ of 0.9, $Xe/fi \approx 0.05$. Therefore Xe/fc and its uncertainty should be well within the limits given in Table A2-IV. The calculated values of Crouch [2] shown in this table were derived using an earlier result of $I/fi = 0.21$ quoted by Denschlag [4] which was revised later to 0.155 (see RP 11a).

3.3. Table A2-V: fractional yields from ^{239}Pu thermal fission

Mass 87: The Gaussian parameters $\sigma = 0.72$ and $Zp = 34.80$ are obtained from a plot of the two experimental data shown in the table, and Kr/fc is deduced to be 0.991. Other possibilities of plotting G within the error limits of the measurements yield a lower limit of 0.95.

Table A2-V: Details on status of cumulative yields from ^{239}Pu thermal fission

FP	fc	uncertainty(%) for fc	chy	cy	comments and data: underlined data used to obtain fc e ... experimental, c ... calculated, w ... weighted average
^{85m}Kr	$\gtrsim$.98	$\lesssim$2*	2.3	~3	for ^{85m}Kr and ^{85}Kr see text
^{87}Kr	$\gtrsim$.98*	~3*	2	3.6	^{87}Kr fc: c .992/^{87}Br fc: e <u>.83±.07, c .77</u> / ^{87}Se fc: e <u>.33±.06</u>, c .18 / G (see text)
^{88}Kr	~.95*	<10*	1.5	<10	^{88}Kr fc: c .95/^{88}Br fc: <u>e .61±.03</u>, c .49/G, pessimistic uncertainty (see text)
^{89}Kr	.86	1	2.3	2.6	^{89}Kr fc: <u>e .86±.01</u>
^{90}Kr	.64	2	1.4	2.4	^{90}Rb fc: c .993/^{90}Kr fc: <u>e .64±.01</u>, c .64/
^{90}Rb	.98*	4*	1.4	4	^{90}Br fc: <u>e .10±.04</u>, c .039/G (see text)
^{91}Kr	.31	3	2	3.6	^{91}Kr fc: e .31±.01
^{133}I	$\gtrsim$.98*	$\lesssim$4*	2.7	~3	^{133}I fc: c .999; fi: <u>e .15±.03</u>, c .17/G (see text)
^{135}I	.85	1	3.4	3.5	as evaluated by Walker, RP 11a;
^{135}Xe	>.99	<1	3.4	3.5	for ^{135m}Xe use decay branch from ^{135}I
^{137}Xe	.92	1	2.7	~3	^{137}Xe fc: e .92±.01
^{138}Xe	.85	1.2	6.5	6.6	^{138}Xe fc: e .85±.01
^{139}Xe	.55	2	5.2	5.6	^{139}Xe fc: e .55±.01
^{140}Xe	.30	2.7	1.6	3.6	^{140}Ba fc: c .997/^{140}Cs fc: c .87/
^{140}Cs	$\gtrsim$.70*	~30*	1.6	~30	^{140}Xe fc: <u>e .30±.01</u>, c .30/G, see text for expected fc of ^{140}Cs and ^{140}Ba
^{140}Ba	>.90*	$\gtrsim$10*	1.6	$\gtrsim$10	
^{141}Xe	.079	5	2.3	6	^{141}Xe fc: e .079±.004

Mass 88: As in the case of ^{233}U, only one measurement exists and the arguments for the uncertainty of Kr/fc shown in Table A2-V are similar. Values of 0.95-0.98 for Kr/fc are obtained from the plot.

Mass 90: The plot through the experimental data yields values for $\sigma = 0.65$, $Zp = 36.21$ and $Kr/fc = 0.98$. The uncertainty takes account of experimental errors and possible fluctuations due to the odd-even effect [3].

Mass 133: The same comments as for ^{233}U apply here.

Mass 140: The only measurement available for this mass chain is that for Kr/fc. Using $\sigma = 0.65$ from ^{235}U fission for $A = 140$, the following values are obtained:

$$Cs/fc = 0.77,\ Ba/fc = 0.976$$

In ^{233}U thermal fission $Cs/fc = 0.73$ and $Ba/fc = 0.996$ (Table A2-IV). The lower limits and uncertainties for Cs/fc and particularly for Ba/fc are rather pessimistic, but the actual data should be reliably within these limits.

4. Detailed evaluation of some fractional yields from ^{235}U thermal fission

Tables A2-VI to A2-X show experimental data, deduced values, weighted averages (wa), values obtained from the plot and adopted values for mass chains 87, 88, 91, 139 and 140. Deduced values were obtained using wa of exp. only. Values in the column "plot" were found by drawing a best straight line by eye through experimental and and deduced fc data (generally fitted to the wa) plotted on probability paper. Values of σ and Zp were determined from this line. Generally, the experimental wa are adopted, as Amiel and Feldstein [3] have observed systematic deviations of experimental fi from a Gaussian distribution, which they ascribe to an odd-even effect.

The data of Crouch [2] and Amiel and Feldstein [3] are shown for comparison. For calculating fi assuming a Gaussian charge dispersion, Crouch [2] used values of Zp and σ deduced from an eye fit to experimental fc data plotted on probability paper. Amiel and Feldstein [3] have calculated "normal" fi from ^{235}U thermal fission using Zp and σ of Wahl et al [5] and compared them to fi evaluated from experimental data.

Table A2-VI: Fractional yields of mass 87 chain in ^{235}U thermal fission

Element (Z)	data	exp [1]	deduced values and wa: method	deduced values and wa: value	deduced values and wa: wa	a) plot	adopted	Crouch [2]	Amiel [3] from: normal	Amiel [3] from: exp
Kr (36)	fc		Se/fc+Br/fi+Kr/fi	.91±.10		.996	$.99^{+.01}_{-.02}$ a)	.998	.999	1.00
			Br/fc+Kr/fi	≤ 1.00						
	fi	.14±.01	exp	.14±.01	.14±.01	.136	.14±.01	.084	.111	.152±.013
			1-Se/fc-Br/fi b)	.23±.10						
Br (35)	fc	(1.06)	Se/fc+Br/fi	.77±.10	$.85^{+.02}_{-.04}$	.86	.85±.04 c)	.914	.888	.85
			1-Kr/fi b)	$.86^{+.01}_{-.04}$						
	fi	.47±.12	wa of exp	.45±.08	.50±.05	.53	c)	.474	.604	.35±.06
		.43±.11	1-Kr/fi-Se/fc b)	$.54^{+.05}_{-.07}$						
Se (34)	fc	.46±.06	wa of exp	.32±.05	.35±.04	.33	c)	.440	.284	.50
		.41±.07	1-Kr/fi-Br/fi b)	$.41^{+.08}_{-.09}$						
		.26±.05								
		.25±.05								
	fi		Se/fc-As/fi	.30±.05	.33±.04	.31		.392	.275	.49±.07
			1-Kr/fi-Br/fi-As/fi b)	$.39^{+.01}_{-.09}$						
As (33)	fc	(.04±.02)	exp adopted	.018±.009	.018±.009	.023		.048	.009	.01
		.018±.009								
	Zp					34.82		34.60	34.82	
	σ					.64		.66	.56	

a) for other plot with discussion of uncertainty of Kr/fc see text;

b) upper limit, assuming Rb/fi = $0^{+.04}_{0}$;

c) note: ^{87}Br (to 2-3% per decay) and ^{88}Br (to 4-6% per decay, ie. 4-6% of ^{87}Br cumulative yield) are delayed neutron emitters (values: see S. Amiel, RP 13)

4.1. Table A2-VI mass 87 chain

Experimental data for Se/fc are discrepant and their weighted average is not reliable. Because of the large uncertainty of Br/fi, experimental data and deduced values just agree within the error limits. The values themselves are, however, not consistent with G, as shown by the deduced value of Kr/fc. The plot is obtained from a fit to wa. The adopted values are based on Kr/fi and G, from which Rb/fi $\leq$ 0.01 and Rb/fc = 1.00 are deduced.

In order to obtain a lower limit for Kr/fc, another line was drawn which is consistent with Kr/fi and the upper limit for Se/fc, but completely ignores As/fc. The following data were obtained:

Kr/fc	Kr/fi	Br/fc	Br/fi	Se/fc	Se/fi	As/fc	Zp	σ
.97	.145	.825	.34	.485	.33	.155	34.55	1.03

Although this curve with σ = 1.03 is very unlikely and disagrees with most experimental data, Kr/fc is still 0.97. Therefore the value of Kr/fc = $0.99^{+.01}_{-.02}$ should be reliable.

4.2. Table A2-VI: mass 88 chain

The situation here is very similar to that of mass 87. The plot is essentially based on Kr/fi (Kr/fc deduced) and Se/fc. The adopted values are deduced from experimental data for Kr/fi and Se/fc, and on Kr/fc obtained from the plot.

4.3. Table A2-VIII: mass 91 chain

Experimental data and deduced values are consistent and in excellent agreement with G (plot). On the other hand, there is severe disagreement with the calculated data of Crouch [2]. In his calculations, Crouch used a wrong experimental value for Sr/fi (0.30 ± 0.03 instead of 0.03 ± 0.03 [5]) and measurements of the ^{91}Sr absolute yield for Sr/fc. All experimental ^{91}Sr yield data are lower than the ^{91}Zr yield (91 chain yield) adopted by Crouch [6], but were measured relative to another chain yield and not as fractional yields. While the deviation of the measured ^{91}Sr cumulative yields from the total chain yield should be further investigated, these data are not used here.

Table A 2 - VII: Fractional yields of mass 88 chain in ^{235}U thermal fission

Element (Z)	data	exp [1]	deduced values and wa: method	deduced values and wa: value	deduced values and wa: wa	plot[a]	adopted	Crouch [2]	Amiel [3] from: normal	Amiel [3] from: exp
Rb	fc					1.00	1.00	.963	1.00	
(37)	fi					.038		.132	.013	.01
Kr	fc	1.04 ± .06	exp	$1.00^{+0}_{-.02}$	$1.00^{+0}_{-.02}$	.962	.96 ± .04	.83	.987	.99 ± .04
(36)			Se/fc + Br/fi + Kr/fi	$1.00^{+0}_{-.18}$						
	fi	.37 ± .03	exp	.37 ± .03	.37 ± .03	.35	.37 ± .04	.28	.315	.37 ± .03
			1 - Br/fi - sc/fc	.32 ± .23						
Br	fc		Sc/fc + Br/fi	.68 ± .23	.63 ± .05	.61	.59 ± .06	.55	.67	.62
(35)			1 - Kr/fi b)	$.63^{+.03}_{-.05}$			c)			
	fi	.56 ± .23	1 - Kr/fi - Se/fc b)	.51 ± .05	.51 ± .05	.49	.47 ± .07	.31	.58	.51 ± .03
			exp	.56 ± .23			c)			
Se	fc	.24 ± .06	wa of exp	.12 ± .02	.12 ± .02	.12	.12 ± .02	.24	.090	.11 ± .01
(34)		.11 ± .01	1-Kr/fi - Br/fi	.07 ± .23			c)			
	fi	.13 ± .02				.12		.18	.089	.11 ± .01
	Zp					35.30		35.35	35.25	35.32
	σ					.68		1.20	.56	.71

a) for other possibility and discussion see text

b) upper limit, assuming Rb/fi = $0^{+.04}_{0}$

c) note: ^{88}Br (to 5 - 6% per decay) and ^{89}Br (to 6 - 13% per decay, i.e. 4 - 8% of ^{88}Br cumulative yield) are delayed neutron emitters (values: see S. Amiel. RP 13).

Table A2-VIII: Fractional yields of mass 91 chain in ^{235}U thermal fission

Element (Z)	data	exp [1]	deduced values and wa: method	value	wa	plot	adopted	Crouch [2]	Amiel [3] from: normal	exp
Sr (38)	fc		Rb/fc+Sr/fi	$.96^{+.04}_{-.06}$	$1.00^{+0}_{-.02}$	1.00	1.00	.985	1.00	1.00
			Kr/fc+Rb/fi+Sr/fi	$1.00^{+0}_{-.02}$						
			Br/fi+Kr/fi+Rb/fi+Sr/fi	$1.00^{+0}_{-.02}$						
	fi	.03±.03	exp	.03±.03		.02		.18	.032	.03±.03
Rb (37)	fc	.93±.05	exp	.93±.05	.98±.02	.980	.98±.02	.804	.968	.97±.03
			1-Sr/fi	.97±.03						
			Kr/fc+Rb/fi	$.99^{+.01}_{-.02}$						
	fi	.40±.02	wa of exp	.40±.02	.39±.02	.39	.39±.02	.48	.440	.38±.03
		.39±.03	Rb/fc-Kr/fc	.34±.05						
			1-Sr/fi-Kr/fc	.38±.03						
Kr (36)	fc	.59±.01	exp	.59±.01	.59±.01	.59	.59±.01	.323	.528	.59±.01
			Rb/fc-Rb/fi	.53±.06						
			1-Sr/fi-Rb/fi	.57±.04						
			Br/fi+Kr/fi	.62±.07						
	fi	.54±.02	exp	.54±.02	.54±.02	.536	.54±.02	.285	.485	.546±.015
			Kr/fc-Br/fi	.52±.07						
			1-Sr/fi-Rb/fi-Br/fi	.50±.08						
Br (35)	fc		Br/fi≈Br/fc	.075±.07	.05±.02	.054	.05±.02	.038	.043	.044±.018
			Kr/fc-Kr/fi	.05±.02						
			1-Sr/fi-Rb/fi-Kr/fi	$.03^{+.04}_{-.03}$						
	fi	.075±.07	exp	.075±.07		.054		.037	.043	.044±.018
	Zp					36.37		36.85	36.46	36.37
	σ					.55		.76	.56	.565

Table A 2 - IX: Fractional yields of mass 139 chain in ^{235}U thermal fission

Element (Z)	data	exp [1]	deduced values and wa			plot	adopted	Crouch [2]	Amiel [3] from	
			method	value	wa				normal	exp
Ba (56)	fc		Xe/fc + Cs/fi + Ba/fi:	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	fi	.011 ± .004	exp	.011 ± .004		.0065		.008	.010	.011 ± .04
Cs (55)	fc		1 - Ba/fi	.989 ± .004	.989 ± .004	.9945	.99 ± .01	.992	.990	.99
			Xe/fc + Cs/fi: 1.03±.03	1.00 $\pm^{0}_{.03}$						
	fi	.24 ± .02	wa of exp	.21 ± .02	.188 ± .014	.225	.19 ± .03	.237	.280	.206 ± .030
		.20 ± .03	1 - Ba/fi - Xe/fc	.17 ± .02						
		.18 ± .02	1 - Ba/fi - Xe/fi -I/fi	.11 ± .08						
Xe	fc	.82 ± .02	exp	.82 ± .02	.802 ± .014	.77	.80 ± .03	.755	.710	.78
			1 - Ba/fi - Cs/fi	.78 ± .02						
			I/fi + Xe/fi	.88 ± .08						
	fi	.79 ± .07	exp	.79 ± .07	.72 ± .03	.63	a)	.604	.601	.68 ± .10
			1 - Ba/fi - Cs/fi -I/fi	.69 ± .04						
			Xe/fc - I/fi	.73 ± .04						
I	fc		I/fi ≈ I/fc	.09 ± .03	.08 ± .03	.143	a)	.151	.109	.10
			Xe/fc - Xe/fi	.03 $\pm^{.07}_{.03}$						
	fi	.12 ± .05	wa of exp	.09 ± .03		.141		.148	.108	.09 ± .10
		.07 ± .04								
	Zp					54.09		54.10	54.19	54.12
	σ					.55		.58	.56	.54

a) note: not evaluated; ^{139}I (to 6 - 14% per decay) and ^{140}I (to 14 - 50% per decay, i.e. 3 - 10% of ^{139}I cumulative yield) are delayed neutron emitters (values: see S. Amiel, RP 13)

Table A2-X: Fractional yields of mass 140 chain in ^{235}U thermal fission

Element (Z)	data	exp [1]	deduced values and wa: method	value	wa	a) plot	adopted	Crouch [2]	Amiel [3] from: normal	exp
Ba (56)	fc		Cs/fc+Ba/fi	$.976^{+.014}_{-.043}$	.97±.03	.9995	$1.00^{+0}_{-.01}$	.9956	.9997	1.00
			Xe/fc+Cs/fi+Ba/fi	$.966^{+.034}_{-.038}$						
			I/fi+Xe/fi+Cs/fi+Ba/fi	(.86±.08)						
	fi	.046±.030	exp	.046±.030	.070±.015	.039	.07±.02	.076	.052	.046±.03
			1-Cs/fc b)	.07±.03						
			1-Xe/fc-Cs/fi b)	.08±.02						
Cs (55)	fc	.93±.03	exp	.93±.03	.93±.02	.961	.93±.02	.920	.948	.95
			1-Ba/fi b)	.954±.030						
			Xe/fc+Cs/fi	.92±.02						
	fi	.31±.02	wa of exp	.32±.02	.33±.02	.37	.33±.02	.347	.512	.33±.03
		.33±.03	1-Ba/fi-Xe/fc b)	.354±.032						
Xe (54)	fc	.60±.01	exp	.60±.01	.60±.01	.59	.60±.02	.573	.436	.62
			1-Ba/fi-Cs/fi b)	.654±.036						
			I/fi+Xe/fi c)	.494±.065						
	fi	.46±.06	exp	.46±.06	.56±.04	.49		.423	.410	.604±.040
			Xe/fc-I/fi	.566±.023						
			1-Ba/fi-Cs/fi-I/fi	.60±.04						
I (53)	fc		I/fi≈ I/fc c)	.034±.021	.046±.033	.095	d)	.15	.026	.02
			Xe/fc-Xe/fi	.14±.06						
	fi	.034±.021	exp	.034±.021	.034±.021	.093		.138	.026	.02
	Zp					54.35		54.35	54.59	54.06
	σ					.65		.82	.56	.82

a) for other possibilities and discussion see text;

b) assuming La/fi≈ 0 (even if Cs/fc=93 is adopted, deduced La/fi ≤ .01);

c) assuming Te/fc≈ 0 (assumption does not hold, if I/fc≈ .15);

d) note: not evaluated; ^{140}I decays to 14-50% by delayed neutron emission (S.Amiel, RP13)

4.4. Table A2-IX: mass 139 chain

With the assumption that La/fi < 0.001 and Te/fc < 0.01 (according to G), the experimental data and the deduced values are fairly consistent, but neither agree with the plot. The deviations are in qualitative agreement with those observed by Amiel and Feldstein [3] and could be due to an odd-even effect. The values deduced from experiments are therefore adopted.

4.5. Table A2-X: mass 140 chain

Except for the values of Cs/fc and Cs/fi, experimental results and deduced values do not agree. The plotted straight line takes account of all wa data but does not agree with them. Two other plots, which ignore some of the data, were attempted: plot A was obtained from Cs and Xe data only and ignores I/fc, plot B consists of a straight line drawn through Xe/fc, which, on probability paper, passes above I/fc and Cs/fc by about equal amounts.

The results are given below:

Plot	Ba/fc	Ba/fi	Cs/fc	Cs/fi	Xe/fc	Xe/fi	I/fc	Zp	σ
A	.997	.061	.936	.336	.60	.44	.16	54.29	.80
B	1.00	.022	.978	.39	.59	.53	.06	54.37	.56

None of the plots is consistent with experimental data; the adopted values are therefore based on the experimental value of Xe/fc and the consistent data for Cs, which also have highest weight in the averages. However, a value of Ba/fc > 0.99 results from all plots, in contrast to all deduced data of Table A2-X. Also La/fi = 0.03 (deduced from wa Ba/fc = 0.97) is not consistent with G and Ba/fi = 0.046 or 0.07. Therefore the value of Ba/fc = $1.00\ ^{+0}_{-0.01}$ is adopted.

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Appendix A3: DECAY DATA

Comparison: status - user requirements

A3.1. Abbreviations used in Appendix A3

Δ ..... accuracy, uncertainty
$T_{1/2}$.... half-life
Br..... decay branching ratio
I_γ..... gamma ray energy
E_β^{max}... end point energy of individual β's
$\bar{E}_\beta$ .... average β^- energy per decay
I_β .... β-ray intensity
Q ..... total energy released per decay
ce .... conversion electrons
I_{ce}.... absolute conversion electron intensities
α ..... total conversion coefficient
IT .... isomeric transition

A3.2. Decay data of individual FP

(i) Status and user requirements are compared in Table A3-I for individual FP decay data. Only those data are listed in this Table, for which needs have been expressed explicitly. The status of decay data is taken from individual evaluations which are indicated in the comments of Table A3-I. Unfortunately, most of the available evaluations (discussed in RP12) do not give uncertainties of recommended data. Therefore the status field had to be left blank in some cases, but references to Nuclear Data Sheets are given, where information on these data can be found.

For I_β and I_{ce} the uncertainties are given as % per decay and hence are absolute uncertainties, assuming that the uncertainty of the energy release per decay is important for users.

Absolute I_γ listed in Table A3-I is restricted to the most abundant γ-rays of a particular FP, defined as those γ-rays used for identification of a FP as well as those which are abundant enough to interfere with γ-rays of other FP in a mixed FP source. This is in

accordance with user requirements, except for life sciences: see (iv) below.

(ii) From Table A3-I the following unfulfilled requirements can be summarized. Almost all $T_{1/2}$ requirements are fulfilled, with the following exceptions:

- ^{154}Eu: not fulfilled
- ^{95}Zr, ^{125}Sb: discrepancies exceed required accuracy
- ^{89}Kr, ^{115m}In, ^{117m}Sn, ^{119m}Sn: uncertainties not evaluated

Also most of the accuracy requirements for branching ratios are met. Exceptions are (see Table A3-I for exact Br):

- ^{90}Kr and ^{91}Kr: uncertainties not evaluated
- ^{95m}Nb and ^{135m}Xe: not fulfilled

In the case of absolute I_γ many requirements are not yet met, especially those for burnup determination.

Since ce do not have large intensities per decay, all explicitly stated requirements are fulfilled, except for those cases where the presently available uncertainties are not evaluated.

For most of the β ray data no evaluated uncertainties are available. Also, $\bar{E}_\beta$ is generally not included in the references listed, while Mantel [24] does not give uncertainties.

(iii) The accuracy of gamma ray energies needed for FP identification is better than 1 keV, corresponding to a Ge(Li)-detector resolution of a few keV. This requirement is met for all FP listed in Table A3-I except for

- ^{91}Y ($\Delta E_\gamma \approx 10$ keV) and
- ^{123}Sn ($\Delta E_\gamma \approx 1$ keV)

and a few gamma rays of other FP with very low abundance. This covers all other areas requesting lower accuracy for E_γ (heat release, γ-transport).

(iv) For research work in life-sciences and agriculture information on the interaction of radiations with matter, including changes of β-spectra by absorbing material, is important. For these investigations all γ's, β's and ce's emitted by radionuclei have to be known, but high accuracy is required only for the most abundant branches. All information

on β emission, including β spectra, is needed. The types of β data included in Table A3-I should be sufficient to give information on the required and presently available accuracy.

(v) Safeguards requirements for non-destructive fuel analysis are covered by burnup requirements and are therefore not listed separately. In the case of correlations for estimating the cooling time existing FPND are more than adequate and therefore requirements are not included in Table A3-I.

(vi) I_γ of ^{140}Ba is based on the absolute value of the 537 keV γ-ray branching. The previously adopted value for I_γ(537 keV) was 24% [1]. Blachot has brought to the attention of the Panel that this value needs confirmation, as in the last evaluation of the Nuclear Data Group[25] 20% are recommended for this I_γ. The most recent (preliminary) result of Debertin [18] is 24.4 ± 0.3%, which confirms the value of [1].

(vii) In a contribution to RP 5, Tasaka and Sasamoto have compared systematically the results of different γ-emitting burnup monitors. From their study there is evidence that I_γ of the 622 keV γ ray of ^{106}Rh and the 695 keV γ-ray of ^{144}Pr could be in error by about 20%. The results of Debertin's measurements [23] should help to clarify.

A3.3 Requirements for groups of FP

(i) Review Paper 4 requests 20% accuracy on half lives of delayed neutrons groups or individual precursors (with $T_{1/2}$ > 1 sec) for failed fuel detection.
- group yields listed by S. Amiel, RP13 [4], meet these requirements.
- $T_{1/2}$ of precursors evaluated by G. Rudstam (RP12 [5], including first draft) also meet these requirements. ^{85}As, as well as the less important FP ^{84}As, $^{87,88}Se$, ^{97}Y and ^{135}Sb were not included in this evaluation.

(ii) γ-rays with E_γ of about 1-4 MeV penetrate through thick shileds, even if of low abundance. Some of the very low abundant γ-rays have still to be identified and should be included in decay studies of FP with high Q values. Most important are FP with $T_{1/2}$ of more than 100 days,
- e.g.: ^{106}Rh, ^{144}Pr (^{134}Cs, ^{154}Eu)

For Pu recycling shorter cooling times have to be considered also (see RP7). Important in this case could be e.g.:
- ^{140}La, ^{156}Eu

The accuracy required for I_γ is about 30%.

(iii) E_γ and I_γ of short lived FP are needed for high energy ($\gtrsim 2$ MeV) gammas for calculation of (γ,n) cross-sections. Accuracies required are not yet known.

(iv) For fresh fuel assay (safeguards, RP 6) the following (partially unmeasured) FP decay data are required:

$T^1/2$: 1 μs to 1 s: $T^1/2$ and I_γ within a factor 4

$T^1/2$: 1s to 1h: $T^1/2$ and I_γ to $\pm$ 10%

$$\Delta E_\gamma \approx 0.3 \text{ KeV}$$

These requirements are of low priority, since the methods concerned are not in practical use.

(v) For fission yield measurements I_γ should be known to 1% and better. Examples for FP yields measured γ-spectrometrically are: ^{85m}Kr, $^{92,93}Y$, $^{95,97}Zr$-Nb, ^{99}Mo, ^{103}Ru, ^{106}(Ru-)Rh, ^{131}I, ^{132}Te-I, ^{137}Cs, ^{140}Ba-La, ^{141}Ce, ^{143}Ce, ^{144}Ce-Pr.

(vi) For environmental considerations in cases of accidents or nuclear explosions decay data and γ-spectra are required, especially for gaseous FP, in cases where these data have not yet been measured or the FP not even been identified.

References:

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Table A3-I: FP decay data - status and user requirements

FP	accuracy (%) for[a]							RP	status and request for	comments[d], notes and references for status
	$T_{1/2}$	Br	E_β^{max}	$\bar{E}_\beta$	I_β[b]	I_γ[c]	I_{ce}[b]			
^{3}H	.1 D		1.1	1.2	0				status	$T_{1/2}$: D within 2%; $I_\beta = 100\%$
	10			10				4	contamination	status: all data [1]
	5-10			5-10	5-10			7	fuel handling	
			10	10				8	agriculture	
^{72}Ga	1.4			.07		2-9			status	status: I_γ [10]; other data (I_γ and β data without uncertainties)[11]: $\gamma_{\Delta Q}$ given instead of $\Delta\bar{E}_\beta$
	5-10		e	e	e	1	e	8	life sciences	
^{82}Br	.3 D		.2	.03	.3	.6-2			status	$T_{1/2}$: D within 2%
	5-10					1		8	industry	status: $T_{1/2}$, I_γ [2a]; other data [1]
	5-10		e	e	e	1		8	life sciences	
^{85m}Kr	.2	3.6				1.1-4			status	Br: to ^{85}Kr
	5	10				10		4	FP release	status: Br[2], other data [8]
	20							4	fuel failure	
^{85}Kr	.6 D	3.6	.9	.8	.01	2			status	$T_{1/2}$: D up to 4%, Br: $^{85m}Kr \rightarrow {}^{85}Kr$[f]
	5	10				10		4	contamination	status: Br[2], other data [1,8]
	5-10	5-10		5-10	5-10	5-10		7	fuel handling	
	5-10		10		10	1		8	industry	
	5-10		e	e	e	1		8	life sciences	
^{86}Rb	.2		.3-.7	.3	.1	.9			status	status: $T_{1/2}$ [2a], I_γ [1,2a], other data [1]
	5-10		10	10		1		8	agriculture	
^{87}Kr	.7	1				3.4-7			status	Br: $^{87}Br \rightarrow {}^{87}Kr$[g]
	5-10	10				10		4	FP release	status: Br[4], other data [8]
	20	20						4	fuel failure	
^{88}Kr	.7	2				5-7			status	Br: $^{88}Br \rightarrow {}^{88}Kr$[g]
	5-10	10				10		4	FP release	status: Br[4], other data [8]
	20	20						4	fuel failure	
^{89}Kr	.6	2							status	Br: $^{89}Br \rightarrow {}^{89}Kr$[g]
	5-10	10				10		4	FP release	status: Br[4]; other data [12] (I_γ given but not ΔI_γ)
	20	20						4	fuel failure	

^{89}Sr	.2 5–10 5–10 5–10		<.4 10 e	.5 5–10 10 e	.01 5–10 e			7 8 8	status fuel handling agric.,industry life sciences	status: T½ [2a], other data [1]
^{90}Kr	.6 10 10 10 10 20 20					10		4 4 4	status FP release contamination fuel failure	Br: $^{90}Br \rightarrow ^{90}Kr \approx 85\%$ [3] status: T½ [5] I_γ given in [7] without ΔI_γ
^{90}Sr	1.4 5 5–10 5–10 5–10		.4 e	.4 5–10 e	0 5–10 e			4 7 8 8	status contamination fuel handling agric.,industry life sciences	status: all data [1]; $I_\beta = 100\%$
^{90}Y	.2 5 5–10 5–10 5–10		.13 5–10 e	.2 5–10 5–10 e	.01 5–10 e			4 7 8 8	status contamination fuel handling agric.,industry life sciences	status: all data [1]
^{91}Kr	2.3 20	20						4	status fuel failure	Br: $^{91}Br \rightarrow ^{91}Kr \approx 93\%$ [3], $\sim \Delta Br < 20\%$ status: T½ [5]
^{91}Y	.2 5–10 5–10		.3 5	.3 5–10 5	.2 5–10	10 5–10		7 8	fuel handling industry	status: all data [1] I_γ very low, but $E_\gamma \approx 1.2$ MeV
^{95}Zr	.1 D 1–2 5 5–10 5–10 5–10		1 e	2 5–10 e	.9 5–10 e	1 1-2 10 5–10 1 1		5 4 7 8 8	status burnup contamination fuel handling agric.,industry life sciences	T½ : D: see h); i) status: T½ [2], I_γ [2a], I_β deduced from I_γ, other data [1]
^{95m}Nb	1.1 10	15–28 5–10				20 5–10	7 5–10	7	status fuel handling	Br: $^{95}Zr \rightarrow ^{95m}Nb$; 1); status: T½, I_{ce}, I_γ (from α) [1] Br: lower value [2a], higher value [1]

Table A3-I: continued

FP	accuracy (%) for[a] $T_{1/2}$	Br	E_β^{max}	$\bar{E}_\beta$	I_β[b]	I_γ[c]	I_{ce}[b]	RP	status and request for	comments[d], notes and references for status
^{95}Nb	.3	.2-.5	.3	.5	.04	.04			status	Br: ^{95}Zr → ^{95}Nb
	1-2					1-2		5	burnup	status: $T_{1/2}$ [2], other data[1], Br: see ^{95m}Nb
	5					10		4	contamination	
	5-10			5-10	5-10	5-10		7	fuel handling	
	5-10					1		8	agric.,industry	
	5-10		e	e	e	1		8	life sciences	
^{99}Mo	.2 D		.3-07	.25	1.2	6-5	~1		status	$T_{1/2}$: D within 2%; k);l)
+^{99m}Tc	10-20			10-20	10-20	10-20	10-20	7	fuel handling	status: $T_{1/2}$ [2a], I_γ[1,2], other data [1]
	10		e	e	e	1	e	8	life sciences	
^{103}Ru	.2			3	1.5	1.2-2	.4		status	i);k)
+^{103m}Rh	1-2					1-2		5	burnup	status: $T_{1/2}$ [2], other data[1]
	5					10		4	contamination	
	5-10			5-10	5-10	5-10	5-10	7	fuel handling	
	10					1			agriculture	
^{106}Ru	.6		.3-.8	.3	~2	3			status	γ's from ^{106}Rh[k]; i)
+^{106}Rh	1-2					1-2		5	burnup	status: $T_{1/2}$ [2], I_γ[2a], other data[1]
	5					10		4	contamination	
	5-10			5-10	5-10	5-10		7	fuel handling	
	5-10		10	10		1		8	agric.,industry	
	5-10		e	e	e	1		8	life sciences	
^{110m}Ag	.2 D			.07	2	1-2			status	$T_{1/2}$: D(max) 1.1%; k)
+^{110}Ag	5					10		4	contamination	status: Ag110m: $T_{1/2}$ [2]; I_γ[2]; ΔI_β from ΔI_γ
	10-20			10-20	10-20	10 20		7	fuel handling	ΔQ (instead of $\Delta\bar{E}_\beta$) from [13]
^{111}Ag	.2		.9-1.3	.9	~3	25			status	status: all data[1]
	10-20			10-20	10-20	10-20		7	fuel handling	
	10		e	e	e	1		8	life sciences	
^{123}Sn	.3			.4	~.1	10			status	status: I_γ[2a]; ΔI_β from ΔI_γ and β to gs = 99.4%
	10-20			10-20	10-20	10-20		7	fuel handling	[14]; $T_{1/2}$, Q ($\Delta Q \approx \Delta\bar{E}_\beta$)[14]

^{125}Sn	.3 10-20			.3 10-20	~10 10-20	~30 10-20		7	status *fuel handling*	status: T½ [2,14], I_γ[2a]; other data[15]: ΔQ_β given ($\approx \Delta \bar{E}_\beta$), ΔI_β *from* ΔI_β *to gs and* ΔI_γ
^{125}Sb	2 D 5 5-10			0.7 5-10	~2 5-10	1.7-5 10 5-10	2.2 5-10	 4 7	status contamination fuel handling	T½ : D up to 10% status: T½ [2a], other data[1]
^{125m}Te	1.7 10 5-10	3 10 5-10					< 1 5-10	 4 7	status contamination fuel handling	Br: $^{125}Sb \rightarrow ^{125m}Te$; 1) 99.7% ce[1] status: all data[1]
^{127}Sb	1.3 10-20	5/1.1 10-20		.3 10-20	≥ 2 10-20	1.7-10 10-20		 7	status fuel handling	status: Br: $^{127}Sb \rightarrow ^{127m}Te/^{127}Te$[2], other data from [16] (ΔI_γ, ΔI_β deduced from values shown; ΔQ *for* $\Delta \bar{E}_\beta$)
^{127m}Te	2 10-20	0.2 10-20		 10-20	.2 10-20	10-15 10-20	.2	 7	status fuel handling	Br: $^{127m}Te \rightarrow ^{127}Te$ k); status: T½, Br[2], I_γ[2a] I_{ce}, I_β deduced from Br;
^{127}Te	.8 10-20			~1 10-20	 10-20	~10 10-20		 7	status fuel handling	daughter of ^{127}Sb and ^{127m}Te, 1) status: I_γ[2a], other data[16] (incl. I_β, not ΔI_β)
^{129m}Te +^{129}Te	1 D 5 10-20	6.6 10 10-20		 10-20	 10-20	11-15 10 10-20	 10-20	 4 7	status contamination fuel handling	T½: D 3%; Br: $^{129}Sb \rightarrow ^{129m}Te$; ^{129}Te in equilibrium k) status: T½, Br, I_γ[2a], other data[17] (no uncertainties given, but ΔI_β, ΔI_{ce} ΔBr)
^{129}I	2.5 5-10		2.6 e	 5-10 e	0 5-10 e	10 5-10 5-10	1 5-10 e	 7 8	status fuel handling life sciences	status: T½ [6], other data[17], but no uncertainties given; E_β^{max} from Q_β; I_{ce}, I_γ estimated from α given in [17]; I_β = 100%
^{131}I	.1 D 5 5-10 5-10 5-10		.1-.3 e	.1 5-10 e	.7 5-10 e	.6-3 10 5-10 1 1	.5 5-10 e	 4 7 8 8	status FP release fuel handling agric., industry life sciences	T½ : D within 0.4%; includes ce from ^{131m}Xe status: T½ [2a]; other data[1]
^{132}Te	1.3/1 10-20 10-20 10-20		1-2.7 e	1.4 10-20 e	1 10-20 e	.1-6 10-20 1 1	8 10-20 e	 7 8 8	status fuel handling industry life sciences	T½ : $^{132}Te/^{132}I$, equilibrium after 1 day k) status: T½ [1,2], I_γ[2α], other data[1] I_β: $\beta^-(^{132}Te) = 100\%$, $I_\beta(^{132}Te) = 0$

Table A3-I: continued

FP	Accuracy (%) for [a] $T_{1/2}$	Br	E_β^{max}	$\bar{E}_\beta$	I_β [b]	I_γ [c]	I_{Ce} [b]	RP	status and request for	Comments [d], notes and references for status
^{133}I	.5								status	Status: all data [19], but no uncertainties given for requested data (except $T_{1/2}$);
	5					10		4	FP release	
	5-10		e	e	e	1	e	8	life sciences	
^{133}Xe	.2	.1	~1	.9	.2	1.1	~2		status	Br: $^{133}I \rightarrow {}^{133}Xe$ = 97.2%; ^{133m}Xe: 100% IT
	5	10				10		4	FP release	Status: $T_{1/2}$ [2,6], Br[2a], other data [1]
	20							4	fuel failure	
	10-20	10-20		10-20	10-20	10-20	10-20	7	fuel handling	
	10-20		e	e	e	1	e	8	life sciences	
^{134}Cs	.2				~1	.2-3			status	status: $T_{1/2}$, I_γ [2a]; ΔI_β deduced from ΔI_γ and level scheme
	1-2					1-2		5	correlation	
	5					10		4	contamination	
	5-10			5-10	5-10	5-10	5-10	7	fuel handling	
	5-10					1		8	agric., industry	
^{135}I	<.1								status	status: $T_{1/2}$ [2,9]
	5							3	kinetics	
	5							4	FP release	
^{135m}Xe	.2	13				.6			status	Br: $^{135}I \rightarrow {}^{135m}Xe \cong 9.5\%$; 1
	5	10				10		4	FP release	status: $T_{1/2}$ [9], Br [8,9], I_γ [8]
	20							4	fuel failure	
^{135}Xe	.1	1.3	1-1.7	1	2-7	.6/6	~8		status	Br: $^{135}I \rightarrow {}^{135}Xe$; ^{135m}Xe: 100% IT
	5							3	kinetics	status: $T_{1/2}$ [2,9], Br[8,9] other data [8]
	5					10		4	FP release	
	20							4	fuel failure	
	5-10		e	e	e	1	e	8	life sciences	
^{136}Cs	.2					5-10			status	ΔI_γ : except 818 keV (I_γ = 100%, ΔI_γ = 0)
	5					10		4	contamination	status: [2,2a]

^{137}Xe	.3 5 20					≥19 10			status FP release fuel failure	status: [8]
$^{137}Cs+$ ^{137m}Ba	.3D 1-2 5 5-10 5-10 5-10		≤.2 e	.2 5-10 e	.4/6 5-10 e	.5 1-2 10 5-10 1 1	<.1 5-10 e		status burnup contamination fuel handling agric.,industry life sciences	$T_{1/2}$: D > 3%; γ's from ^{137m}Ba; i status: $T_{1/2}$ [2a], other data [8]
^{138}Xe	.5 20								status fuel failure	status: [8]
^{139}Xe	1.2 20								status fuel failure	status: [5]
^{140}Xe	1.2 10 20								status contamination fuel failure	status: [5]
^{140}Cs	.6 20								status contamination	status [5]
^{140}Ba	<.1 1-2 5 5-10 5-10			~2 5-10	3.5 5-10	1.2D 1-2 10 5-10 1	3.3 5-10		status burnup contamination fuel handling agriculture	I_γ : D: see text; status: $T_{1/2}$ [2]; I_γ [18] (see text) other data [1]
^{140}La	~.1 2-3 5 5-10 5-10			.4 5-10	~3 5-10	.3-5 1-2 10 5-10 1	<.1 5-10		status burnup contamination fuel handling agric.,industry	i) status: I_γ [2a], other data [1]

Table A3-I: continued

FP	Accuracy (%) for [a] $T_{1/2}$	Br	E_β^{max}	$\bar{E}_\beta$	I_β [b]	I_γ [c]	I_{Ce} [b]	RP	status and request for	Comments [d], notes and references for status
^{141}Xe	.6								status	status: [5]
	20							4	fuel failure	
^{141}Ce	.3		.7		1.6	2	.5		status	i); status: $T_{1/2}$ [2a], other data [1] (uncertainty of $\bar{E}_\beta$ not evaluated $\rightarrow \Delta E_\beta^{max}$ given in table).
	1-2					1-2		5	correlation	
	5-10			5-10	5-10	5-10	5-10	7	fuel handling	
^{143}Pr	.2				.2				status	status: $T_{1/2}$ [2a], other data [20]
	5-10			5-10	5-10			7	fuel handling	
$^{144}Ce+$	.2		.1-.8	.5	~1	3-8	.3		status	k); i)
^{144}Pr	1-2					1-2		5	burnup	status: $T_{1/2}$ [2], I_γ [2a], other data [1]
	5-10			5-10	5-10	5-10	5-10	7	fuel handling	
	5-10		10	10		1		8	agric., industry	
	5-10		e	e	e	1	e	8	life sciences	
^{147}Nd	.3				≥10	8-10			status	status: $T_{1/2}$; I_γ [2a], other data [21] without uncertainties; ΔI_β estimated from ΔI_γ and level scheme of [21]
	5-10			10-20	10-20	10-20		7	fuel handling	
^{147}Pm	.1		.3	.3	0				status	status: [1]; I_β = 99.992 %
	5-10			5-10	5-10			7	fuel handling	
	5-10		5-10					8	industry	
^{149}Pm	.1					6			status	status: $T_{1/2}$, I_γ [2a]
	10-20			10-20	10-20	10-20		7	fuel handling	
^{151}Sm	5								status	status: $T_{1/2}$ [2a]
	5-10			10-20	10-20		5-10	7	fuel handling	

^{153}Sm	.4D 10–20 5–10		.5–1	10–20	5 10–20	2–5 10–20 1	5 10–20	 7 8	status fuel handling agriculture	T½ : D within 2% status: T½ [2a], I_γ [2a, 22], other data [22] (but no uncertainties); ΔI_β, ΔI_{ce} deduced from [22] and ΔI_γ
^{154}Eu	6D 1–2 5–10			5–10	5–10	~3 1–2 5–10		 5 7	status correlation fuel handling	T½ : D e.g. 8.5 (adopted) and 16 years status: T½ [2], I_γ [2a]
^{155}Sm	5–10		e	e	e	1	e	8	status life sciences	
^{155}Eu	.2 5–10 5–10 5–10		 e	 5–10 e	 5–10 e	3–4 5–10 1 1	 5–10 e	 7 8 8	status fuel handling industry life sciences	T½ : 1.8 years obviously wrong status: [2a]
^{156}Eu	.2 10–20			10–20	10–20	10–12 10–20		 7	status fuel handling	status: [2a]

a) Status: D ... some discrepancies among experimental data exist!
blank, if needs are given: not included in evaluations which give uncertainties (except Nuclear Data Sheets up to 1965).

b) Only most abundant β and ce considered in status; uncertainty given in % per decay, which is equivalent to absolute uncertainty.

c) Range of accuracy for most abundant γ's given.

d) D ... discrepancies
Δ ... uncertainty

e) For research work the accuracy should be as high as possible. All information on β decay is requested (see text).

f) Assuming 100% branching $^{85}Br \rightarrow {}^{85m}Kr$. If available, cumulative yields for ^{85}Kr should preferably be used.

g) The precursor is delayed neutron emitter. Its delayed neutron branch to ^{A-1}Kr has to be considered also.
The use of cumulative yields could be preferable, but ultimately β^- and delayed neutron branches will be used in inventory calculations together with independent yields.

Table A 3 – I: continued

h) A discrepancy of 2.3% exists between 2 measurements; see: K. Debertin et al. [23] (these Panel proceedings, Vol. 3)

i) Measurements of γ-ray emission probabilities (absolute intensities) to 1% accuracy at the Physikalisch-Technische Bundesanstalt, Braunschweig, FRG, are completed or in progress; see: K. Debertin et al. [23].

k) Daughter in equilibrium with parent at any time of interest; $T_{1/2}$ of daughter unimportant; radiation intensity per decay of parent is essential information and given in the table (Br is ignored).

l) Daughter reaches equilibrium with parent after about 10 $T_{1/2}$ of daughter in an initially pure source of the parent nuclide; at the end of long irradiations equilibrium is generally reached.

Appendix A4: NEUTRON REACTION CROSS-SECTIONS

Comparison: status - user requirements

A4.1 Abbreviations

A number of abbreviations are used, particularly in the tables, which are explained below:

σ .... neutron capture cross-section(s), specifically:
- σ_{th} ... in the thermal energy range
- σ_o ... at 2200 m/sec (0.0253 eV)
- $g\sigma_o$ ... averaged over a thermal maxwellian spectrum
- σ(E)... as function of incident neutron energy
- σ(fast) averaged over a fast reactor spectrum.

RI ... infinite dilution resonance integral for neutron capture

res .. resonance(s)

respars.. resonance parameters

E .... energy (of incident neutrons or resonances)

exp .. experimental

A4.2 Neutron capture cross-sections for thermal reactors

(i) The data of interest for thermal reactors are represented by σ_{th} and RI. User needs and data status are compared in Table A4-I. It can be seen that several requirements for σ_{th},RI are not fulfilled.

(ii) User requirements are expressed for integral σ-data such as σ_{th} and RI or pile -σ. However, a knowledge of σ(E) is required to an accuracy sufficient to allow the calculation of an average σ for any thermal reactor spectrum ranging from D_2O moderated reactors to HTGR. On the other hand, integral data may be sufficient, if they can be used for all thermal reactor spectra within the requested accuracy limits:

RP3: σ(E) is required in the thermal range (indicated in column 11 of Table A4-I), particularly for ^{135}Xe and ^{149}Sm.

RP5: σ_o or $g\sigma_o$ is sufficient for the thermal range. For the epithermal range σ(E) is required, if RI cannot be used within the requested accuracy for different reactor spectra (where $\phi(E)$ deviates from 1/E).

Table A4 – I: Neutron capture cross-sections for thermal reactors: status and user requirements

FP	type of σ	accuracy required for[a] RP3 (%)	RP4 (%)	RP5,6 (%)	RP5,6 (b)	RP7 (%)	data status[b] accuracy of σ_c (%)	σ_c (b)	E-range of resolved res	E-range for requirements[c]	Comments
^{99}Tc	σ_{th}	20					10	2		< 1 eV	
	RI	15					10		5.6-280eV	1-500 eV	79 res known
^{103}Rh	σ_{th}	6					4			< 10 eV	
	RI	50					5		1eV-4.1keV	1-200 eV	275 res known
^{109}Ag[d]	σ_{th}		} 20				15	0.6		< 1 eV	
	RI						13	7	5eV-2.5keV	1-300eV	81 res known
^{110m}Ag	σ_{th}		} 20				} 14	11			only one exp on pile -σ
	RI										
^{133}Xe	σ_{th}				} 150		} 50	90			only pile -σ available
	RI										
^{133m}Xe	σ_{th}				} 10^4						no data available
	RI										
^{133}Cs	σ_{th}	15	} 20	2		} 5-10	5	1.5		< 1eV	
	RI	10		2			7	30	5.9eV-3.5keV	1-500 eV	164 res known
^{134}Cs	σ_{th}		} 20	3		} 5-10	9	12			only pile -σ available
	RI			25			factor 20				
^{135}Xe	σ_{th}	8	5				3			< 4eV	no significant res except .084 eV
	RI	100					7		.084eV		

^{135}Cs	σ_{th} RI		} 20			6 20[e]	0.5 10[e]			RI: disagreements[e] no respars available
^{141}Pr	σ_{th} RI			} 2.8		2.6 1.4[e]	0.3 0.2[e]	85eV-10keV	< 20eV 20eV-2keV	RI: evaluations disagree[e] 120 res known
^{143}Pr	σ_{th} RI			} 30			10 25			
^{143}Nd	σ_{th} RI	6 30		2 6		3 20	10 30	55eV-5.5keV	< 10eV 10 - 500eV	negative res at- 6eV ~100 res known
^{144}Ce	σ_{th} RI			2 6		10 12	0.1 0.3			no respars available
^{144}Nd	σ_{th} RI			2 6			0.3 0.5	0.37-19 keV	< 0.5 eV 0.5eV-10keV	35 res known
^{145}Nd	σ_{th} RI			2 6			2[e] 35	4eV-4.6keV	< 0.5eV 0.5eV-1keV	evaluations disagree[e] 191 res known
^{146}Nd	σ_{th} RI			2 6			0.1 0.5	0.36-17 keV	< 0.5 eV 0.5eV-10keV	44 res known
^{147}Nd	σ_{th} RI			} 30						only preliminary data available
^{147}Pm	σ_{th} RI	15 8			} 5-10	7 7	13 150	5.4-317eV	< 1eV 1eV-200eV	negative res at -1.8eV 41 res known
^{148}Nd	σ_{th} RI			2 6			0.2 1	95eV-12keV	< 0.5eV 0.5eV-3keV	66 res known

Table A4-1: cont'd "Neutron capture cross-sections for thermal reactors: status and user requirements"

FP	type of σ	accuracy required for[a] RP3 (%)	RP4 (%)	RP5,6 (%)	RP5,6 (b)	RP7 (%)	data status[b] accuracy of σ_c (%)	accuracy of σ_c (b)	E-range of resolved res	E-range for requirements[c]	Comments
^{149}Sm	σ_{th} RI	20		f	f		3	1200	 0.1-249eV	$\lesssim$ 20eV	thermal extended to 20eV, RI unimportant
^{150}Nd	σ_{th} RI				2 6			0.2 2	 79eV-14keV	$<$ 0.5eV 0.5eV-3keV	78 res known
^{151}Sm	σ_{th} RI	8 40		f	f		15 20		 1.1-13eV	$<$ 0.5eV 0.5 - 30eV	negative res at -0.1eV, 10 res known
^{152}Sm	σ_{th} RI	20 10		f	f		3 5	3 15	 8eV-5keV	$<$ 1 eV 1-500eV	~ 100 res known
^{153}Sm	σ_{th} RI				~10^3						no data available estimates: ~factor 10
^{153}Eu	σ_{th} RI			3 10		5-10	~20 12	80 200	 0.4-100eV	$\lesssim$ 1 eV 0.4-100eV	σ_{th}: discrepant data ~ 90 res known
^{154}Eu	σ_{th} RI			3 10		5-10	~25	400			only one exp on pile -σ

a) Principally σ has to be known as function of incident neutron energy, but requirements are generally expressed for an integral σ derived from σ (E). However, $g\sigma_0$, RI or pile-σ may be sufficient, if the variation with reactor neutron spectrum (including HTGR) is within the requested uncertainty. With these limitations, the requirements are (see also text):

RP3: σ(E) required for thermal range shown in column 11 of the table, particularly for ^{135}Xe and ^{149}Sm.

RP4 and RP7: pile -σ may be sufficient.

RP5: $\sigma(E)$ and res pars desirable, except for low accuracy requirements.

b) σ_{th}: generally accuracy of σ_0 or for Maxwellian averaged σ ($g\sigma_0$); note that $\sigma(E)$ may be required;
RI: accuracy of RI (above 0.5 eV) calculated from res pars and compared to integral measurements;

c) σ_{th}: energy range, for which $\sigma(E)$, if requested, has to be known;
RI: energy range of resolved resonances required for description of RI or $\sigma(E)$ (except ^{135}Xe: range given for $\sigma(E)$)

d) Cross-section for formation of 252 d ^{110m}Ag;

e) Discrepancies among experiments and/or evaluations (shown in RP10, table III) exceed the uncertainty shown.

f) σ required, but definite accuracy not yet known (see section 3.2, item (viii)).

RP4 and RP7: $g\sigma_o$ (with the possible exception of ^{135}Xe) and RI may be sufficient for the FP listed in Table A4-I. For other FP not listed but discussed in sections 3.2 and 7.2 the knowledge of pile-σ should be sufficient.

If $\sigma(E)$ is required, the accuracy needed is inversely proportional to the neutron energy.

(iii) Column 11 of Table A4-I shows the energy range for $\sigma(E)$ required by users.

The thermal range is chosen to include the part of $\sigma(E)$ which contributes significantly to thermal captures (particularly important for reactor design).

Generally group cross-section data are used in large codes. However, the Panel recommends (section 7.3) to describe in evaluations the low energy part of a cross-section curve in the epithermal range in terms of resolved resonances. Therefore the energy range shown in column 11 of Table A4-I is chosen to include about 20 resonances or is extended to the highest resonance with supposedly significant contribution.

(iv) Data needs for safeguards are generally covered by burnup requirements. Additional requirements are:

- The ratio of capture cross-section uncertainties of ^{133}Cs to ^{134}Cs should be 1:3. In order to achieve the accuracy of burnup determination required by safeguards, the captures in ^{133}Cs (^{134}Cs) have to be calcuated to 1% (3) accuracy for any thermal reactor spectrum. This requires a knowledge of $\sigma(E)$ of ^{133}Cs and ^{134}Cs to the appropriate accuracy.

- Requirements for σ to be used in correlation studies depend upon the accuracy required for the result, which has not been determined at the time of the present Panel. Sensitivity studies aiming at 1% accuracy for a particular case quoted in RP 6, resulted in the following requirements for $\sigma\gamma$ of individual FP:

^{82}Kr	20	^{130}Xe	20%
^{83}Kr	3%	^{131}Xe	1.4%
^{129}I	20%	^{135}Xe	10%

(v) The data status is explained in Table A4-I. In the thermal range the the accuracy for $\sigma(E)$ is given, if another representation is not sufficient (e.g. ^{135}Xe, ^{149}Sm).

The status of the σ-data was supplied by P. Ribon, who considered also contributions by Walker, by Pope and Story, and by Sakata and Nagayama (see RP10). Additional values (e.g. res ranges) were taken from BNL-325, 3rd edition, Vol. I (June 1973).

A4.3 Neutron capture cross-sections for fast reactor applications

(i) User requirements and data status are compared in Table A4-II for fast reactors. The table shows that the majority of requirements is not fulfilled.

(ii) For the calculation of the Na-void effect in fast reactors (RP 3), $\sigma(E)$ is required in the energy range 0.1 - 100 keV for all FP contained in Table A4-II.

(iii) The data status is given for three different, partly overlapping, energy ranges, which are explained in Table A4-II. σ_c in the range of resolved resonances (up to several keV) may contribute significantly to the total σ_c(fast). A knowledge of average resonance parameters is important for the calculation of σ_c in the 10-100 keV range.

Presently available accuracies of data in the columns headed "res range" and "fast range" were supplied by P. Ribon together with comments on available experimental data and res-pars (section A4.4). The status of $\sigma(E)$ for $E \geq 0.1$ MeV obtained from the Bologna FP cross-section library was communicated by V. Benzi.

A4.4 Comments to data status in Table A4-II

^{95}Mo: $\bar{\Gamma}_\gamma$ is known to 7%, but dependence of S, $\bar{\Gamma}_\gamma$ and $\bar{D}$ on (J, π, E) is badly known;

only one measurement of $\bar{\sigma}$ in the 10 keV range with slowing down spectrometer (SDS).

^{97}Mo: same remarks as for ^{95}Mo.

Table A4-II: Neutron capture cross-sections for fast reactor applications

status and user requirements

FP	accuracy required [a]			accuracy achieved [b]				notes
	RP3	others		res range		fast range	≥0.1MeV σ(E)	
	(%)	RP	accuracy	(%)	E_{max} (keV)	(%)	(%)	
^{95}Mo	30				2.1	30	v.poor	c)
^{97}Mo	30				1.9	30	v.poor	c)
^{98}Mo	35			10	9	50	poor	c) d)
^{99}Tc	20			10	0.28	40	theo	d) e)
^{100}Mo	35			7	4.7	30	50	c) d)
^{101}Ru	20				0.67	40	theo	c)
^{102}Ru	25			30	1.3	30	v. poor	e)
^{103}Rh	20			5	4.1	10	30	
^{104}Ru	30			30	1.1	40	v.poor	d)e)
^{105}Pd	20				0.8	30	theo	e)
^{106}Ru	35	5	25-50 mb			fact.2	theo	
^{107}Pd	25			fact.5		fact.2	theo	e)
^{109}Ag		4	20%	13	2.5	25		
		7	10-20%					
^{131}Xe	30			5	4	40	theo	c)e)
^{133}Cs	20	4	20%	7	3.5	20	30	
		7	5-10%					f)
^{134}Cs		4	20%			fact.2		
^{135}Cs	30	4	20%	30		fact.2	theo	e)
^{137}Cs	40	5	25-50mb			fact.2		
^{139}La	40			5	10.4	<40		
^{141}Pr	35			15	10	20	30	d)
^{143}Nd	30	5	25-50 mb	20	5.5	30	theo	c)
^{144}Ce		5	25-50 mb			fact.2		

Table A4-II: (continued)

FP	accuracy required[a]			accuracy achieved[b]				notes
				res range		fast	≥0.1MeV	
	RP3	others			E_{max}	range	σ(E)	
	(%)	RP	accuracy	(%)	(keV)	(%)	(%)	
^{144}Nd		5	25-50 mb		19.4	35		
^{145}Nd	35	5	25-50 mb	15	4.6	30	theo	
^{146}Nd		5	25-50 mb	16	17	30		
^{147}Pm	25	7	5-10%	7	0.3	40	theo	c)d)
^{148}Nd		5	25-50 mb	5	12	~20		
^{149}Sm	30				0.25	30	theo	c)
^{151}Sm	25				<0.1	50	theo	e)
^{151}Eu		CR	10%			40	30	e)f)
^{152}Sm	55			5	5.1	<50		
^{152}Eu		CR	10%			fact.2		e)f)
^{153}Eu	40	7	5-10%		0.1	40	theo	d)f)
		CR	10%					
^{154}Eu		7	5-10%			fact.2	theo	e)f)
		CR	10%					
^{155}Eu	55					fact.2		e)

a) σ (E) required in the energy range 0.1 keV - 5 MeV; a fast reactor spectrum averaged σ is sufficient, if its variation is within the requested accuracy for different fast reactors.

CR ...requirement for control rod purposes in the energy range 10 keV - 1MeV

b) Detailed comments are given in the text

res range: range of resolved res; the accuracies are for RI above 0.1 keV, obtained from res pars;

E_{max}: energy of highest resolved res.

Table A4 - II (continued)

fast range: energy range above highest resolved resonance up to a few MeV as given by Ribon (see text).

$\geq$0.1 MeV: uncertainties given for Bologna library (see RP10)

poor ... estimated uncertainty of $\sigma(E) > 50\%$

v.poor ..very poor: theoretical estimate + few experimental data

theo ... theoretical estimate only.

c) The requested accuracy ($\gtrsim 30\%$) should be achieved (or improved to 20%) from a better knowledge of average resonance parameters in the 100 keV range and of level schemes of the target nuclei.

d) New evaluations based on available experimental data should allow a resolution of discrepancies.

e) A better knowledge of res-pars should improve the accuracy of calculated cross-sections.

f) An accuracy of $\sim 10\%$ can only be achieved (or improved, if required) from direct measurements.

g) σ for formation of 252 day ^{110m}Ag.

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^{98}Mo: same remarks as for ^{95}Mo (Γ_γ to 5%);
8 sets of exp data for $\bar{\sigma}$ above 1 keV.

^{99}Tc: $\bar{\Gamma}_\gamma$ known to 20%; only 4 res below 0.1 keV;
only 1 SDS measurement above 1 keV.

^{100}Mo: Probably a strong dependence of $\bar{\Gamma}_\gamma$ on parity;
7 sets of exp data above 1 keV.

^{101}Ru: $\bar{\Gamma}_\gamma$ known to 5%;
no exp data for σ_c.

^{102}Ru: no $\bar{\Gamma}_\gamma$ value;
3 sets of exp data above 1 keV.

^{103}Rh: well known res pars;
many σ_c measurements; improvement of accuracy of σ_c, if required, can only be obtained from direct measurements of σ_c.

^{104}Ru: 5 sets of exp data for σ_c.

^{105}Pd: $\bar{\Gamma}_\gamma$ known to 7%;
1 measurement of σ_c above 1 keV.

^{107}Pd: no experimental data.

^{133}Cs: res pars well known;
10 sets of exp data on σ_c above 1 keV.

^{134}Cs: no exp data on σ_c; radioactive nucleus: differential measurement impossible.

^{135}Cs: no exp data available.

^{141}Pr: more than 10 sets of exp data on σ_c above 1 keV.

^{143}Nd: $\bar{\Gamma}_\gamma$ known to 4% accuracy;
no exp data for σ_c

^{145}Nd: $\bar{\Gamma}_\gamma$ known to 6% accuracy;
no exp data for σ_c.

^{147}Pm: $\bar{\Gamma}_\gamma$ known to 8% accuracy, but highest res at 0.3 keV;
1 measurement of σ_c above 1 keV.

^{149}Sm: $\bar{\Gamma}_\gamma$ known to 4% accuracy:
1 measurement of σ_c above 1 keV.

^{151}Sm: no measurements of σ_c above 1 keV.

^{151}Eu: $\bar{\Gamma}_\gamma$ known to 6% accuracy;
6 sets of exp data above 1 keV.

^{152}Sm: $\bar{\Gamma}_\gamma$ known to 10% accuracy;
no exp data above 1 keV.

^{152}Eu: 1 measurement of σ_c above 1 keV; differential data can only be obtained from nuclear explosions.

^{153}Eu: 4 sets of exp data above 1 keV.

^{154}Eu: no measurements in fast range.

Appendix A5: FP DECAY HEAT

Since no sensitivity studies on the accuracy required for individual FPND have yet been performed, this appendix can serve as the basis for such studies. Presented are user requirements for total decay heat after reactor shutdown as well as the results of Devillers' study (appendix to RP 4) on FP that contribute significantly to the total decay heat, and the status of their half lives. Together with the status on cumulative yields and effective decay energies more detailed requirements should be worked out in future studies.

A5.1 User requirements on total decay heat

User requirements of the accuracy to which the total decay heat after reactor shutdown has to be known, is presented in Table A5-Ia as was observed by the Panel.

If we take an accuracy of $\pm$ 10% as the target for all times after shutdown up to several days, with $\pm$ 5% as a long term aim, and bear in mind that FP contribute only 40% of the total afterheat at 1 s cooling time, and 50% at about 10s, we arrive at the accuracy targets presented in Table A5-Ib for the FP contribution to the total afterheat. The values are given for the main fissile isotopes. For other fertile and fissile isotopes such as ^{238}U and ^{241}Pu the accuracies required are about a factor of 4-5 less (for individual FPND this means a difference only in fission yields).

A5.2 Contribution of individual FP to afterheat

The different cases computed by Devillers (RP 4, appendices) are summarized in graphical form in Table A5-II. Some of the FP listed in the table contribute significantly to the total heat released only in the case of ^{233}U thermal fission or ^{239}Pu fast fission (difference in mass yield distribution).

Table A.5-II together with the footnotes is essentially self-explanatory. It should give a good idea which FP have to be considered in more detailed studies.

In accordance with the Panel's conclusions the half lives of FP contributing only up to about 100 s to afterheat are required with lower accuracy than > 100 s which is indicated by (+) in Table A5-II (meaning: decay property is less important). The significance of other decay properties is indicated according to Devillers' calculations.

Precursors of important FP are indicated only in those cases where they have a significant influence on the time range the daughter contributes to the decay heat.

Current Nuclear Data Sheets were consulted in order to obtain the most recent status of half-lives. The references quoted for half-lives indicate also the latest update of other decay data by the Nuclear Data Group.

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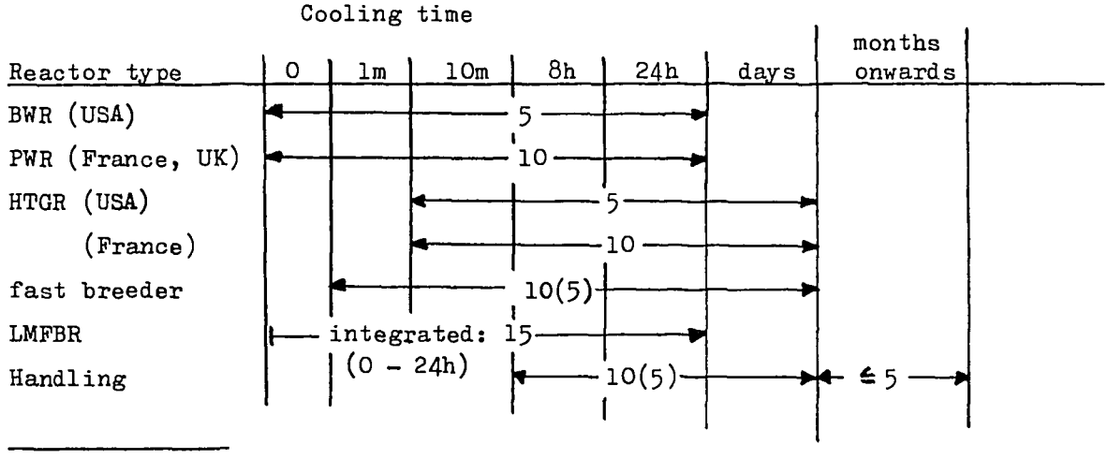
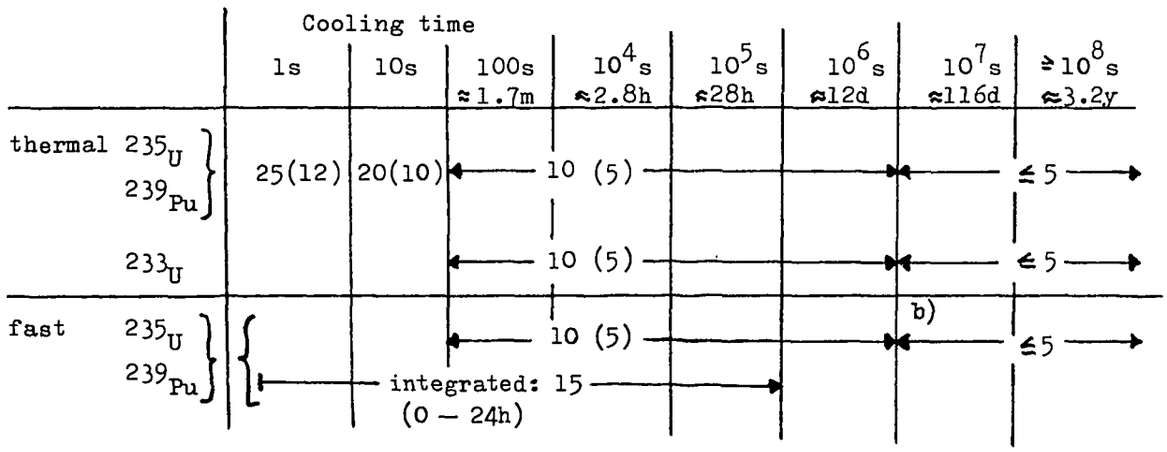
Uncertainty deduced by M. Lammer from data shown.

Table A5-I.a: Accuracy to which the total heat released after shutdown has to be known for different reactor types as a function of cooling time[a)]



a) Accuracy is given in %; higher accuracies given in brackets are a long term aim.

Table A5-I.b: Accuracy required for the energy released by fission products as a function of cooling time[a)]



a) Accuracy is given in %; higher accuracies given in brackets are a long term aim.

b) $\leq$ 5% accuracy required from 30 days onwards.

Table A.5 - II: FPND important for FP energy release after reactor shutdown.

FP[a]			decay property[b]					half-life				cooling time[c,f]									
									uncertainty			1 s	10 s	10^2 s	10^3 s	10^4 s	10^5 s	10^6 s	10^7 s	10^8 s	10^9 s
A	I	S	H	B	β	γ	E	value[c]	(%)[d]	e)	Ref			≈1.7 m	≈17 m	≈2.8 h	≈28 h	≈12 d	≈116 d	≈3.2 y	≈ 32 y
84	g	Br	+		+	+	+	31.7 m	0.3		7										
85	g	Kr	+		+	+		10.73 y	0.6		2,4										
86	g	Br	(+)		+	+	+	55.7 s	0.9		3										
87	g	Br	(+)	(+)	+	+	+	55.8 s	0.6		3										
	g	Kr	+		+	+		76.3 m	0.7		4										
88	g	Br	(+)	(+)	+	+	+	16.0 s	1.3		3										
	g	Kr	+		(+)	+		2.80 h	0.7		4										
	g	Rb	+		+	+		17.8 m	0.6		4										
89	g	Kr	+		+	+		3.18 m	0.6		6										
	g	Rb	+		+	+		15.2 m	0.7		6										
	g	Sr	+		+			50.52 d	0.1		2										
90	g	Kr	(+)	+	+	+	+	32.3 s	0.6		3										
	m	Rb	+	+	+	+	+	4.27 m	2		8										
	g	Rb	+		+	+		2.57 m	2.6		8										
	g	Sr	+		+			28.6 y	1.4		2										
	g	Y	(+)		+			64.06 h	0.2		5										
91	g	Rb	(+)		+	+	+	58.2 s	0.6		3										
	g	Sr	+	+	+	+		9.6 h	1.3	(D)	9										
	m	Y	+			+		49.71 m	0.1		9										
	g	Y	+		+			58.51 d	0.3		2,9										
92	g	Nb	(+)		+	+	+	4.50 s	0.7		3										
	g	Sr	+		(+)	+		2.71 h	0.4		10										
	g	Y	+		+	+		3.54 h	0.3		10										
93	g	Rb	(+)	(+)	+	+	+	5.81 s	0.7		3										
	g	Sr	+		+	+		7.36 m	2.0		3										
	g	Y	+		+	(+)		10.1 h	2.0	D	11										
94	g	Sr	(+)		+	+	+	75.6 s	1.2		3										
	g	Y	+		+	(+)		18.7 m	6.4	D	3										
95	g	Sr	(+)		+	+	+	28 s	11		3										
	g	Y	+		+	(+)		10.6 m	3		3										
	g	Zr	+	(+)	+	+		63.98 d	0.1	D,W	2										
	g	Nb	+		+	+		35.05 d	0.3		2										
96	g	Y	+		+	+		2.3 m	4.4		12										
97	g	Zr	+	+	+	+		17.0 h	1.2		13										
	m	Nb				+		60 s			13										
	g	Nb	+		+	+		72.1 m	1.0	h	13										
98	g	Y	(+)		+	+	+	2.3 s	?	D	1										
	g	Zr	+					30.7 s	~1	i)	14										
	g	Nb	(+)		+		+	2.8 s	7.2		14										
99	g	Mo	+		+	+		66.0 h	0.2	D	2										
100	g	Nb	(+)		+	(+)	+		?	k)											
101	g	Nb	(+)		+	(+)	+	7.0 s	4.3		16										
	g	Mo	+		+	+		14.62 m	0.4		16										
	g	Tc	+		+	+		14.2 m	0.7		16										
102	g	Mo	+					11 m	-		1										
	g	Tc			+	+		5.3 s			1										
103	g	Mo	(+)		+	+	+	60 s	-		1										
	g	Ru	+		+	+		39.35 d	0.2		2										
104	g	Tc	+		+	+		18 m	-		1										
105	g	Mo	(+)		+	+	+	42 s	7.2		17										
	g	Tc	+		+	+		7.8 m	2.6		17										
	g	Ru	+		+	+		4.44 h	1.2		17										
106	g	Tc	(+)		+	(+)	+	36 s	-		1										
	g	Ru	+					368.3 d	0.6		2										
	g	Rh			+	+		30.35 s			1										

Table A.5 - II: cont'd

FP[a]			decay property[b]					half-life				cooling time[c,f]									
									uncertainty			1 s	10 s	10^2 s	10^3 s	10^4 s	10^5 s	10^6 s	10^7 s	10^8 s	10^9 s
A	I	S	H	B	β	γ	E	value[c]	(%)[d]	e)	Ref			≈1.7 m	≈17 m	≈2.8 h	≈28 h	≈12 d	≈116 d	≈3.2 y	≈32 y
125	g	Sb	+		(+)	+		2.75 y	1.5		2										
129	g	Sb	+		(+)	+		4.32 h	0.7		18										
131	g	Sb	+	(+)	+	+		23.0 m	-		1										
	m	Te	(+)	(+)				30 h	6.7		2										
	g	Te	+		+	+		25 m	-		1										
	g	I	+		+	+		8.04 d	0.2	D	2										
132	g	Sb	+		+	+		3.08 m	2.2		3										
	g	Te	+		+	+		78 h	2.6		2										
	g	I	+		+	+		2.285 h	0.5	D,W	2										
133	g	Sb	+	+	(+)	+		2.7 m	13		3										
	m	Te	+		(+)	+		55.4 m	0.8		19										
	g	Te	+		+	+		12.45 m	2.3		19										
	g	I	+	(+)	+	+		20.9 h	1		2										
	g	Xe	+		+	+		5.29 d	0.2		2,4										
134	g	Te	+		+	+		43 m	-		1										
	g	I	+		+	+		53.2 m	-		1										
	g	Cs	+		+	+		2.062 y	0.3	W,D	2										
135	g	Te	(+)		+	+	+	19.2 s	1		3										
	g	I	+	(-)	+	+		6.585 h	0.1	W	2										
	g	Xe	+		+	+		9.172 h	0.1	W	2										
136	?	I	(+)		+	+	+	83 s	4	g)	1,3										
137	g	I	(+)		+	+	+	24.6 s	0.5												
	g	Xe	+		+			3.83 m	0.3		4										
	g	Cs	+	+	+			30.17	0.4	D	2										
	m	Ba				+		2.552 m			4										
138	g	I	(+)		+	+	+	6.6 s	3		3										
	g	Xe	+		+	+		14.17 m	0.5		4										
	g	Cs	+		+	+		32.2 m	0.3		4										
139	g	Xe	(+)		+	(+)	+	40.4 s	1.3		3										
	g	Cs	+		+	+		9.40 m	1.3		20										
	g	Ba	+		+			84.9 m	1.3		20										
140	g	Cs	(+)		+	+	+	64.0 s	0.7		3										
	g	Ba	+		+	+		12.789 d	0.1		2										
	g	La	+		+	+		40.27 h	0.2	(D)	5,2										
141	g	Cs	(+)		+	(+)	+	25.2 s	2		3										
	g	Ba	+		+	+		18.27 m	0.4		21										
	g	La	+		+			3.93 h	1.6		21										
	g	Ce	+		+	+		32.50 d	0.2	(D)	2										
142	g	Ba	+		+	+		10.7 m	1		22										
	g	La	+		+	+		92.7 m	0.8		22										
143	g	La	+		+			14.32 m	-		1										
	g	Ce	+		+	+		33.0 h	0.6	W,D	2										
	g	Pr	+		+			13.57 d	0.2		2										
144	g	La	(+)		+	+	+	40.3 s	0.8		3										
	g	Ce	+		+	+		284.5 d	0.2		2										
	g	Pr			+	+		17.28 m			5										
145	g	Pr	+		+			5.98 h	0.4		23										
146	g	Pr	+		+	+		24.2 m	0.9		24										
147	g	Nd	+		+	+		11.01 d	0.2	(D)	2										
	g	Pm	+		+			2.6234 y	0.1		2										
154	g	Eu	+		(+)	+		8.5 y	6	D	2										
156	g	Eu	+		+	+		15.16 d	0.2		2										
% of total FP decay heat not listed												<55	<50	<43	<26	<19	<12	<8	<6	<2.3	<1.3

Table A.5 - II: cont'd.

Explanations

a) A .... mass number
I .... isomeric state: g,m = ground, metastable state
S .... element symbol

b) H .... half life
B .... branching in decay to daughter product
β .... β-decay data
γ .... γ-decay data
E .... mainly effective total energy ($E_\beta + E_\gamma$) released required
+ .... knowledge of the decay property is required
(+)... decay property is less important

c) s .... seconds
m .... minutes
h .... hours
d .... days
y .... years

d) percent error rounded upwards, i.e.: 0.1 means: ≤ 0.1%
?..... value and uncertainty questionable
blank.... half-life unimportant
- ..... uncertainty not evaluated

e) quoted uncertainty to be used with caution

W .... warning: only one measurement
D .... discrepancies among experimental values exceed uncertainty quoted in table
(D) .. discrepancies, reflected in uncertainty quoted in table; e.g.:
- discrepancies exceed individual experimental errors;
- average of a large number of experiments including some discrepant values;
- some discrepant values, but majority within uncertainty
notes: explanations to values shown

f) The percent contribution to the total FP afterheat as a function of cooling time is indicated as follows:

——— 1-2%
▬▬ 2-5%
▬▬ 5-10%
▬▬ ≥ 10%
} maximum of 5 cases calculated by C. Devillers (appendix to RP 4)

------ precursor only

g) 3 isomeric states have been observed with half-lives 48 ± 3 s, 83 ± 3 s and 100 ± 3 s [3]. According to Devillers' calculation the 83 s isomer is indicated as ground state, whereas in [1] the 48 s isomer is given as ground state.

h) Half-life of ≲ 0.3 s reported in [14]. Therefore experimental uncertainty questionable.

i) No uncertainty given for this value; uncertainty deduced from other measurement quoted in [14].

k) [1] gives 2.5 m for ^{100}Nb. In [15] 1.5 ± 0.3 s ($\pm 20\%$) are reported for ^{100}Nb, following decay of ^{100}Zr. For half-life assignment see discussion in [15].

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