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CONCLUSIONS AND RECOMMENDATIONS

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CONCLUSIONS AND RECOMMENDATIONS

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List of Abbreviations used

BU	Burnup
CFRMF	Coupled Fast Reactivity Measurement Facility, located at Aerojet Nuclear Company, Idaho Falls
CTR	controlled thermonuclear reactors
d	day(s)
D	discrepancy
E	energy
FBR	fast breeder reactor(s)
FP	fission product(s)
FPND	fission product nuclear data
$g\sigma_o$	effective thermal cross section (in a Maxwell spectrum) in Westcott formalism
h	hour(s)
HWR	heavy water reactor
HTGR	high temperature gas cooled reactor
I_{rel}	relative intensity
INDC	International Nuclear Data Committee
LWR	light water reactor
LMFBR	liquid metal fast breeder reactor
NDAT	Non destructive assay techniques (in safeguards)
P_n	delayed neutron emission probability
PWR	pressurized water reactor
RI	resonance integral
RP	review paper (presented at this meeting)
s,sec	second(s)
SPRT-method	a method used to determine optical model parameters ([75Del])

t_{cool}	cooling time
$T_{1/2}$	half life
WRENDA	World Request list for Nuclear Data
y	year(s)
Y_{cum}	cummulative yield
$\overline{\mu}$	average cosine of scattering angle in laboratory system
ν_d	total delayed neutron yield (per fission)
σ_{el}	elastic scattering cross section
σ_γ	capture cross section
σ_{th}	$= g\sigma_o$ (see there)

I. INTRODUCTION

The 15 review papers presented at the meeting covered the applications (review papers 2 to 6) and the status (review papers 1, 7 to 15) of fission product nuclear data of the following categories:

- fission yields;
- decay data;
- delayed neutron data;
- neutron cross section data.

The presentation of the review papers and of several related contributed papers was followed by plenary discussions about questions of general interest such as the justification of requests for improved accuracies, the priorities of the requests, and the comparison of different measurement and evaluation techniques. These discussions led to several general recommendations to the IAEA, which are reproduced in Chapter II.

After the plenary sessions, five working groups were formed (see Appendix C), four of which were each concerned with one of the data types mentioned above, and the fifth dealing with fission product bulk properties required for inventory assessments. On the basis of the review papers and the plenary discussions, the members of the working groups compared the requirements for FPND to the status of the data. The summary reports of the different working groups, which include statements about the present situation in each data field, and recommendations for future work, form the basis of the contents of Chapters III and IV.

On the last day of the meeting, the summaries of the working groups' conclusions and recommendations as well as the general recommendations to the IAEA were presented and discussed in plenary until agreement was reached.

II. GENERAL RECOMMENDATIONS TO THE IAEA

The discussions during the plenary sessions and within the working groups resulted in a number of general conclusions as well as recommendations to the IAEA. Some of them refer to the status of implementation of the general recommendations to the IAEA issued at the First FPND Panel held by the IAEA Nuclear Data Section (NDS) at Bologna in November 1973.

II.1. FPND Progress Report

The meeting participants unanimously agree on the usefulness of the Reports on "Progress in Fission Product Nuclear Data" issued by IAEA/NDS and recommend that they continue to be issued in annual intervals.

In the first issue of the Progress Report, a special circular addressed to FPND measurers had been included in accordance with a recommendation issued by the Bologna Panel. This circular specified the type of experimental and interpretation detail which measurers should include in the reports on their work, and which is needed by FPND evaluators for an adequate judgement and comparison of different experimental results.

It is strongly recommended by this meeting, that a similar circular to FPND measurers be included again in the next issue of the Bulletin. The reason for reiterating this recommendation from the Bologna Panel is that since then no significant improvement in the documentation of experimental work could be noted.

II.2. FPND requests

The participants emphasize the convenience of finding all requests for FPND in WRENDA (World Request List for Nuclear Data), which is published biennially by the IAEA. It is therefore recommended that all requests concerning FPND (e.g. also for β and γ-spectra or delayed neutron spectra from precursors) should be submitted for inclusion in WRENDA. While the conciseness, uniformity and handiness of WRENDA is acknowledged, it is pointed out that the justification of requests as presented in WRENDA is poor. However, if recommendations for new measurements are to be based on user requirements, a more detailed justification than can be given in WRENDA is needed. It is therefore recommended that new FPND requests are to be backed up by detailed studies and explanations which shall be included in the FPND Progress Report, together with a detailed justification.

II.3. List of FPND compilations

The list of FPND compilations and evaluations together with the explanatory text reported in the review paper 1 at this meeting was found to be a very useful, more informative update of the corresponding list prepared for the Bologna Panel. It is recommended that IAEA/NDS update and publish this list in periodic (initially annual) intervals.

II.4. Future coordinating activities

II.4.1. Compilation of decay data

The meeting strongly recommends that IAEA/NDS promote a comprehensive compilation of decay data for all unstable and metastable nuclides over the whole atomic mass range, including fission products and actinides.

II.4.2. Average resonance parameters and level scheme data

Since at higher incident neutron energies (keV-MeV range), only few experimental cross section data are available, evaluated cross-section curves are partially based on nuclear theory. Existing evaluations often show severe discrepancies between each other, which are mainly due to the different models and parameters used.

As the first step towards an improvement of the situation, the IAEA is asked to coordinate an international effort to find the most accurate methods of determining average parameters from resolved resonances. It is suggested that IAEA/NDS initiate an intercomparison of the best available methods. Also, strong support should be given to evaluations of level scheme data, which are needed for statistical theory calculations of inelastic scattering cross-sections.

II.4.3. Fission product yields

It is noted that at present there exist only two extensive evaluations of fission product yields which are continuously updated, namely those of E.A.C. Crouch and of M.E. Meek and B.F. Rider. These two evaluations differ significantly in many of their recommended values, but the most striking discrepancy lies in the assigned uncertainties, those recommended by Crouch being often by a factor 2 to 3 higher than those given by Meek and Rider. In order to resolve these discrepancies, the meeting strongly recommends both national and international support for fission yield evaluations. In a first attempt, the IAEA should try to establish close contacts between measurers and evaluators of fission yields, which should enable the evaluators to better judge the quality of their experimental input data.

II.5. Future meetings

Concerning future FPND meetings, it was agreed that another general meeting devoted to the whole field of FPND would only be needed if and when drastic changes in the requirements for a large variety of data would occur. However, it was recommended that smaller specialists' meetings devoted to only one type of data (like decay data, cross-sections etc) when discrepancies or gaps in the knowledge exists, be organised in the future.

II.5.1. Meetings on cross section-data

In view of the unsatisfactory situation concerning evaluated cross-sections (see section II.4.2.), the participants recommend that IAEA/NDS organise:

(i) a specialist meeting on the systematics of all parameters needed in nuclear model calculations of neutron cross sections; and

(ii) in a few years time, a specialists' meeting on the status of fission product capture cross-sections, where both experimenters and evaluators should re-examine the status of the cross section data.

II.5.2. Meeting 1978 on delayed neutron data

The working group on delayed neutrons endorsed the INDC recommendation to convene a specialists' meeting on delayed neutron data in 1978.

III. SUMMARY OF USER REQUIREMENTS

This chapter is supposed to give a summary of the FPND requirements agreed by the meeting, separated according to user areas. However, a number of requirements expressed in the review papers were not discussed at the meeting; these are assumed to be accepted, and were taken over directly from the review papers.

In order not to duplicate information, some of the data requirements, especially when many nuclides are involved, are not listed in detail in this chapter. A complete survey of all the FPND requirements reviewed by the meeting, and the status of the requested data, is found in Chapter IV.

All accuracies mentioned refer to the 1σ confidence level.

III.1. Environmental aspects

The meeting noted that in the assessment of individual or collective doses from releases of radioactive materials to the environment, the total uncertainty cannot be reduced much below a factor of 2. To this, uncertainties in FPND contribute only a negligible amount, by far the major contribution coming from the uncertainties in the environment transfer factors. It is therefore concluded that, at the present state of knowledge, no further information on FPND is required for environmental assessments.

III.2. Design of power reactors cores

III.2.1. Thermal reactors

The target accuracies required for the prediction of reactivity effects due to fission products, and for the variation of reactivity effects with reactor temperature are the same as at the Bologna meeting: 2% for the prediction of reactivity lifetime and 10% for the variation of the FP reactivity effect with temperature. This requires fission yield and capture cross section data of the most important absorbers:

Tc 99, Rh 103, Xe 131, Xe 135, Cs 133, Nd 143, Pm 147, Sm 149

Sm 151, Sm 152.

Most of the requirements have by now been fulfilled; those still unsatisfied are included in Tables 5 and 11 of Chapter IV.

Tables 5 and 11 include in addition the requests concerning reactivity effects found in WRENDA 76/77, whose number exceeds those expressed in Bologna. Furthermore, a study by Ottewitte, submitted as contribution to RP 3, pointed to the significance of the half lives of Xe135 and Sm149 precursors for the concentration of these absorbers. From this study, requests for half life data were deduced which are included in Table 6 of Chapter IV.

III.2.2. Fast reactors

(i) Effects of neutron capture on reactivity

The meeting agreed that the present target accuracy for the prediction of reactivity effects of fission products should be 10%. In future, however, for the expected developments of high burnup fast reactors with heterogeneous cores, a target accuracy of 7% would be appropriate. The 10% target implies that the bulk capture effect of FP is required to 10% accuracy.

The resulting accuracies for individual FP capture cross sections are, according to the Bologna Panel, 20 to 30% for the important isotopes. However, the participants from Japan, France and US did not agree with this figure. Whereas S. Iijima felt that reactor designers in Japan would accept capture cross section uncertainties of 20%, the participants from France and US emphasized an accuracy goal of 10% in the main FP capture cross sections. It was finally agreed that, in view of the fact that systematic errors in the capture cross sections of individual FP do not necessarily tend to cancel in the lumped FP, a 10% accuracy for the capture cross sections of main FP should be aimed at.

All capture cross section requirements are included in Table 12 of Chapter IV.

(ii) Effect of neutron scattering on reactivity

The effect of neutron inelastic scattering of the lumped FP is about 10 to 15% of the capture effect on reactivity. This means that an accuracy of 30% would be required for the scattering effect of lumped FP. This requirement is apparently met, as the various recent calculations of the scattering effect do not differ by more than 15%.

If the uncertainty in the scattering effect could be decreased, e.g. to 20%, the requirements for capture cross sections could be relaxed. It is, however, not sure if such an increase in accuracy can be reached with the present evaluation methods.

The transport cross section ($\sigma_{el}(1-\bar{\mu})$) was considered by S. Iijima to be of importance for the determination of the leakage of neutrons from the reactor. According to Iijima the reactivity is affected by the transport cross section to the same degree as by the inelastic scattering, but in the opposite direction.

(iii) Time dependence of reactivity

At short times after reactor start-up the time behaviour of the lumped FP depends partly on the cross sections of some radioactive isotopes (T1/2 $\gtrsim$ 1d) such as: Ru103, Rh105, Pm149, Mo99. These cross sections are not well known and it would be valuable to investigate the effect of their uncertainties on the total uncertainty of the time dependence of reactivity.

(iv) Sodium void reactivity

The meeting endorsed the conclusion of J. Rowlands that the effect of FP on sodium void reactivity should be predicted to within 30% accuracy. There was some discussion about the way in which this requirement could be met. J. Rowlands suggested to determine the FP effect on sodium void reactivity as the difference between the FP reactivities in a normal and in a voided core. This difference amounts to about 15% of the total FP reactivity, which leads to the requirement that the total FP reactivities (both in normal and in voided core) should be determined to ± 3.5%. According to J.Y. Barré, however, it would be sufficient to analyze integral measurements performed in different fast reactor spectra. The meeting concluded that this question needs further investigation.

(v) Doppler reactivity

It was agreed that the contribution of FP to the uncertainty of the Doppler reactivity should be less than 7%. Since according to calculations by Butland [76But], the net contribution of FP to the Doppler reactivity does not exceed 15% (see also RP 3), this leads to the requirement for an accuracy of 50% in the FP effect. For the resulting requirements on the bulk FP cross sections, it has to be taken into account that the effects of capture and inelastic scattering are of opposite sign and that therefore the requirements for these separate components may be more stringent than 50%.

(vi) Determination of reactivity by delayed neutrons

The requirement to be able to measure reactivites from the kinetic response of the reactors leads to a need for delayed neutron data to enable the reactor period-reactivity relationship to be determined to 3 to 5%. This requires:

- total delayed neutron yields per fission from Th232, U233, U235, U238 and Pu239 to ± 3% (Pu240 and 241 to lower accuracy);

- an accurate knowledge of the time dependence of delayed neutrons in the range of 1 to 100 seconds, in order to be able to determine the relationship between reactor period and reactivity to 3-5%.

- the delayed neutron spectra, so that the reactivity worth of delayed neutrons relative to prompt neutrons can be determined to ± 2%.

Further sensitivity studies are needed to formulate the accuracy requirements for the time dependence and the energy spectra. Calculations made using different sets of data which are available could help to define these requirements.

III.3. Reactor operation

III.3.1. Contamination of reactor components by fission products

The requirements for FPND for the prediction and control of FP release and contamination of reactor components have remained the same as at the Bologna Panel, the tolerable uncertainty in the inventory of important isotopes being 40%. Table 1 lists those dominating FP isotopes for which the 40% accuracy requirement was not met at the time of the Bologna Panel and the present status of the required data. The table shows that the requirements are essentially met, with the exception of Cs 136.

Table 1: Important FP isotopes for the control of contamination of reactor components (= Table I of RP 4)

FP	data determining precision of inventory	important for reactor type	present accuracy
Ag 110m	σ_γ Ag109	LMFBR	<30%
Sb 125	cum. yield	"	<20%
Te 129m	" "	PWR	<15%
		HTGR	30%
		LMFBR	<30%
Cs 134	σ_γ Cs133	LMFBR	30%
Cs 136	" Cs135	"	30% to factor 2

III.3.2. Failed fuel detection

As already stated at the Bologna Panel, the required precision in the inventory of gaseous FP used for the detection of fuel failure is 40%. The current status of those short lived FP that had not fulfilled the requirements at the time of the Bologna Panel is given in Table 2.

Table 2: Achieved accuracy in the inventory of FP used for failed fuel detection

(= Table II of RP 4)

FP	PWR	HTGR	LMFBR
Kr 90	6	6	20
Kr 91	7	7	30
Xe 138	3	4	9
Xe 139	5	6	13
Xe 140	5	5	12
Xe 141	6	6	29

The table shows that all data of importance to failed fuel detection are known to the required accuracy.

III.3.3. Decay heat

(i) Required bulk accuracies

According to RP 4, the knowledge of the residual heat after reactor shutdown is important in three different respects:

- For the removal of residual heat after normal operation or emergency shutdown, with cooling times ranging from 0 to 10^6 sec.

- For the handling of irradiated fuel and its temporary storage, where cooling times range from a few hours to several months or even years (10^5 to 10^8 sec.)

- For fuel transport, reprocessing and waste packaging.

The highest precision in the prediction of afterheat is demanded for the heat removal after shutdown. The meeting agreed that, for PWR's and BWR's, accuracies as given in Table 3 should be aimed at. As compared to the Bologna Panel, Table 3 includes also requirements for the thorium-cycle, and the target accuracies are higher than those requested at Bologna (which are equal to those listed in RP 4). The needs for higher accuracies w ere particularly emphasized by the US delegates, on the basis of the requirements by the US Nuclear Regulatory Commission as well as by reactor vendors.

(ii) Status of decay heat accuracies

Sensitivity studies performed in France and USA for U235 and Pu239 decay heat from thermal fission are supported by agreement between different summation calculations and the latest experiments. The decay heat accuracies for these 2 cases, as calculated assuming infinite irradiation and neglecting neutron capture, is included in Table 3.

The present status for fast fission in U235 and Pu239 has not yet been evaluated, but is probably represented by the larger uncertainty values of Table 3.

From Table 3 it can be seen that the priority I requests are met for U235, but possibly not for Pu239. The much tighter priority II requirements are not yet met. The status of U233 data is probably similar to that for U235, but experimental support is sparse. Probably the priority I requirements for Pu241 and U238 can be met, but more study is needed.

(iii) Individual FPND requirements

From the above requirements for precisions of decay heat predictions and from the sensitivity studies performed by C. Devillers together with an analysis of the available data (RP 4), a number of requirements for individual FPND has been derived:

- Half life data are required to 5% accuracy for:

  Sr 91; Y 98; Zr 95, 98; Nb 97, 100; I 131, 132, 135;

  Xe 135; Cs 134; and La 140.

  The measurements for these half-lives reveal discrepancies, which may be resolved by evaluation.

- Uncertainties in average decay energies contribute the major part to the overall decay heat uncertainty. A 10% accuracy is required for the decay energies of the following important nuclides whose β-spectra are unknown, namely:

Table 3: Fission product decay heat:

accuracy requirements and their priorities (in brackets) - status 1)

Cooling time

Fissioning system	1 - 20 s req. %	status %	20 - 10^4 s req. %	status %	10^4 - 10^6 s req. %	status %	10^6 - 10^7 s req. %	status %	10^7 - 10^8 s req. %	status %
thermal										
U 235	10(I) 5(II)	4–8	5(I) 2(II)	2–4	10(I) 5(II)	1.5–3	10(I) 5(II)	3–5	≤5(I)	3–5
Pu 239	10(I) 5(II)	8–15	5(I) 2(II)	2–6	10(I) 5(II)	2–6	10(I) 5(II)	3–5	≤5(I)	3–5
U 233	10(II) 5(III)		5(II) 2(III)		10(II) 5(III)		10(II) 5(III)		≤5(II)	
Pu 241	30(I) 15(II)		15(I) 6(II)		30(I) 15(II)		30(I) 15(II)		≤15(I)	

	10^2 - 10^7 s required %	10^7 - 10^8 s required %	integrated over time 0 - 10^5 s required %
fast			
U 235, Pu 239	10(I) 5(II)	≤ 5(I)	10(I)
U 238 Pu 241	30(I) 15(II)	≤15(I)	30(I)
Th 232	30(II) 15(III)	≤15(II)	30(II)

1) A range of uncertainties is given for each cooling time, reflecting the uncertainty in the estimated standard deviation, and its variation with decay time.

Br 88, 89; Sr 95, 96; Y 96, 96m; Zr 100; Nb 102; Mo 103, 104, 105; Tc 105, 107; Te 135; I 137, 138; Cs 141, 142; Ba 143, 144; La 144, 145, 146.

For some other FP an accuracy of 5% in the decay energy is desirable:

Sr 89; Y 90, 91; Rh 106; Cs 137; Ba 140; La 140; Ce 141; Pr 143,144.

- Independent yields: at short cooling times (10 sec), the influence of yield errors on the decay heat uncertainty is mainly due to the uncertainties in direct yields. In order to achieve an overall accuracy of 5% for this short cooling time, it is required that the uncertainties in direct yields are not larger than those given in the evaluation of Meek and Rider [77Mee], the values of which have mostly been obtained by calculations.

As is pointed out in RP 4 (Table VIII), the effect of neutron capture should increase the decay heat in a power reactor at decay times longer than 10^4 s; in a typical thermal power reactor the increase may amount to more than 8% after 10^7 s (3 months), but the exact figure depends on the fluence.

The prediction of this effect requires the knowledge of the capture resonance integral for Cs 133 and Pm 148m.

III.4. Out of pile fuel cycle

It was indicated at the Bologna Panel that FPND requirements for fuel cycle purposes are not very severe and existing data are mostly adequate. The present meeting found that for most of the problems of the out of pile cycle, this statement is still valid. Some requirements were however expressed, mainly concerning the calculations of decay heat released during interim storage and of the mass balance at the reprocessing stage.

III.4.1. Interim storage and transport

In connection with interim storage and transport of burnt fuel before reprocessing, knowledge of the released fission product decay heat is required to an accuracy of 15% for cooling times $10^5 s \leq t(cool) \leq 10^8 s$. For cooling times > 10^7 sec, after which only a few long lived FP contribute significantly to the decay heat, this requirement is equivalent to the requirement for 5% accuracy in the decay power of each of the dominating FP.

For some of these FP, the 5% accuracy target is not reached different decay power calculations being discrepant by more than 5%; the discrepancies are caused by differences in the input data. The resulting requirement is:

- 5% accuracy in average $(E_\beta + E_\gamma)$ - energy of:
  Sr 89, Cs 137, Ce 141 and Pr 144.

Another problem of concern to irradiated fuel transport, and involving FPND, is the shielding of high energy gamma rays. According to a contribution by Austin et al to RP 5, for a particular flask design uncertainties of 30% in the γ-source strength have been noted, the dominant isotopes being: Ru/Rh106, La140, Cs134, Ce/Pr144.

III.4.2. Reprocessing

It is now generally agreed that cooling times before reprodessing will be $\gtrsim 10^7$ sec, and never as low as 3×10^6 sec as auggested at Bologna for FBR fuel. A range of relatively short-lived FP included at Bologna can therefore be omitted from consideration so far as reprocessing is concerned.

At the reprocessing stage, the decay heat due to FP insolubles, mainly Ru103 and Ru/Rh106, plays an important role, especially for FBR fuels. A 10% accuracy in the total decay heat of the insolubles, for cooling times $\gtrsim 10^7$ sec, is required.

For environmental and reprocessing purposes, a comparison of the material contained in the dissolved spent fuel with the amount of different isotopes in the original fresh fuel is of great interest. In order that such a "mass balance" becomes adequately accurate, extensive calculations, implying fission cross sections, FP yield, decay and capture cross section data, have to be carried out for each fuel type.

The most important FP in this context are the volatile isotopes of impact on the environment, H3 and I129, and the insolubles which remain in the fuel after the first solvent extraction, i.e. Zr/Nb95, Ru103 and Ru/Rh106. For a mass balance, the inventory of H3 should be known to 5%, whereas for the other FP an uncertainty of 10% in the inventory is tolerable.

Assuming that the main quantity affecting the inventory of these isotopes is the fission yield, the following data requirements can be expressed for the purpose of mass balance calculations:

- thermal and fast fission yields from the major and some minor (Pu240, 241) actinides for H3 to ± 5%;

- thermal and fast fission yields from the same actinides for Zr/Nb95, Ru103, Ru106 and I129 to ± 10%.

III.4.3. Shutdown flux

In a contribution to RP 5, Austin mentioned that in some reactors, shutdown flux levels are influenced by photoneutron reactions in light elements. A good example is the Winfrith HWR, for which the dominant neutron source for some hours after shutdown is provided by high energy (γ-n) reactions in deuterium.

A knowledge of this source strength to ~ ± 50% is desirable, both to aid instrumentation design and to assist in interpretation of shurdown reactivity determinations. Br86 would appear to be an important FP contributing energetic γ-rays.

III.4.4. Nuclear incineration of minor actinides

According to the recent Euratom state-of-the-art review (EUR-5801e),FPND requirements for nuclear incineration of minor actinides are already met, as far as establishing technical feasibility is concerned. In the event of a decision to develop the process with a view to its large scale operation, accurate FPND will be needed to evaluate the reactivity effects and to calculate the quantities of FP formed. It was endorsed by the present meeting, that these requirements are unlikely to arise within the next 2 to 3 years.

III.4.5. Alternative fuel cycles

Possible future FPND requirements for alternative fuel cycles as described in RP 5 will have to be assessed as soon as the needs arise. In particular, additional data will probably be required for high burnup and the thorium fuel cycle; these may include further FP cross section data, and further fission yield-data for minor actinides and for fast fission of Th232.

III.5 Investigations on irradiated fuel

Three topics were covered under this title: burnup studies, reactor neutron dosimetry measurements, and non-destructive analysis in safeguards. These studies are related by the method of investigation used, which is to deduce some 'original' quantity (like the number of fissions, the number of fissionable isotopes, the neutron spectrum etc) from the measurement of the amount of a certain FP contained in an irradiated sample.

III.5.1. Burnup

The "burnup" (BU) of an irradiated fuel denotes the relative number of heavy metal isotopes that have been lost through fission:

$$BU = \frac{\text{number of fissions x 100}}{\text{initial total number of heavy element atoms}} \quad [\text{atom \% fission}]$$

The basic burnup quantity as defined above can be directly related to a number of other quantities like the average or terminal fission rate, the individual sources of fission etc which are required for different applications (a list of such applications if found in RP 6).

According to RP 6, many applications require that the burnup be determined to an accuracy as high as 1.5-2%. This requirement applies particularly to the determination of the number of fissions (absolute or relative), and to the calculation of the residual fissionable nuclide content and the reactivity worth of fuel.

The most accurate and widely applicable method of measuring the burnup is the FP monitor-residual heavy atom technique. In this method, the fuel specimen is dissolved and the numbers of atoms of a selected FP monitor and of the heavy metal atoms are determined.

This is a destructive method, which is not always desirable and applicable. Non-destructive BU measurements are most often performed by γ-spectrometry of FP. Such measurements provide less accurate BU values ($\gtrsim$ 5%), but have the advantage of giving rapid information on relative BU.

(i) Destructive techniques: choice of FP-monitor

The most accurate technique for destructive BU measurements is isotope dilution mass spectrometry. For this technique, the chemically most suitable elements which may be used as FP monitors are Nd and Ce.

Thermal reactors. For a long time, Nd148 has been considered a nearly ideal BU monitor for thermal LWRs, because its thermal fission yield seemed to be practically identical for U235 and Pu239 (1.68%). Recently however, it was found that Nd147 had a high thermal capture cross section (σ_γ= 440 ± 150 barn [74Hec]), which means that the published and generally accepted yield of Nd148 was probably too high. This assumption is also supported by recent measurements of Nd148 yields by W.J. Maeck [76Mae], which suggest that the thermal U235 fission yield of Nd148 is ~ 1.65%. Therefore, the Nd148 yield for U235 and Pu239 should be carefully remeasured and evaluated, so that Nd148 may be used as monitor for highly accurate BU determinations in mixed U235-Pu239 fuel.

In highly enriched fuel, with only one major source of fission, U235 or Pu239, it is recommended that the sum of Nd145 + Nd146 be used as BU monitor. The sum of these isotopes seems to be nearly independent of the integrated neutron flux [76Mae], and it is therefore probably not affected by capture effects.

For thermal reactor fuels in which U233 and U235 are the principal fission sources, Ce140 should be a better monitor, as its thermal fission yield for these two actinides is nearly the same ($\approx$ 6.35%).

If the purpose of the BU measurement is to determine the individual fission sources, such FP should be chosen as monitors, whose fission yields for the various fissioning nuclides are significantly different. In this case, the most suitable FP monitors for thermal reactors are the Kr-isotopes Kr83,84,86 and the Ru-isotopes Ru101,102,104.

Fast reactors. Nd isotopes may also be used as BU monitors for most of the fast reactor fuels. *E.g.*, Nd143 would be suited for U233-U235 and Pu239-Pu241 fuel, Nd146 (or the sum of all stable Nd-isotopes minus Nd144) for U233-Pu239, Nd148 for U235-Pu239.

The accurate determination of BU in fast reactors requires also a knowledge of the variation of the monitor's fission yield with the neutron spectrum. At present, the neutron energy dependence of Nd-fission yields (and also of some other important FP) is being investigated at different laboratories, by evaluation of existing data as well as in new experiments.

To distinguish fission sources in fast reactor fuels, the stable isotopes of Nd(143,148,150) and Sm(147,149,152,154) are the best monitors.

(ii) Non-destructive technique: γ-ray scanning

Gamma ray activities, or their ratios, of specific FP can be used to derive information on different parameters of the fuel history. In particular, for the applications related to BU studies, the following quantities may be deduced from γ-spectrometric measurements:

- the number of fissions from the activity of Cs137, or after short irradiations, from Ce144;
- the fluence, from which the relative BU can be deduced, from the activity ratios Cs134/Cs137 or Eu154/Cs137;
- the ratio of Pu239 to U235 fissions from Ru106/Ce144 or Ru106/Cs137;
- the fission rate at shutdown ("terminal" fission rate) from Ba/La140 or Zr/Nb95;
- the ratio of the Pu239 to U235 fission rates at shutdown (less important) from Ru103/Ce141 or Ru103/Zr95.

(iii) Required accuracies for individual FPND

The accuracy target of 1.5-2% for burnup determination, means that the fission yields of the stable FP monitors used in destructive techniques are required to 1-1.5%, and the fission yield of the radioactive FP used for γ-scanning to an accuracy of 1.5%. Measurements with γ-spectroscopy require in addition the absolute γ-ray intensities of the major γ-lines to 1%. Furthermore, in order to take the neutron capture into appropriate account, thermal, resonance and fast capture cross sections of those FP whose neutron capture would effect the number of BU monitor isotopes, have to be known; an accuracy of 5-10% is in general sufficient. In summary, the following data are required for BU studies:

- to an accuracy of 1.5%: the thermal and fast fission yields of Nd145,146,148; the thermal yields of Kr83, 84,86, of Ru101,102,104 and of Ce140; the fast yields of Nd143,144,150 and of Sm147,149;

- to an accuracy of 2%: the thermal fission yields of Zr/Nb95, Ru103,106, Cs137, Ba/La140, Ce141,144;

- to an accuracy of 1%: the absolute intensities of the major γ-rays of Zr/Nb95, Ru103,106, Cs137, Ba/La140, Ce141, Ce/Pr144, Nd147, Eu154,155.

- the capture cross sections:

  thermal and resonance to an accuracy of 3-5% for Cs133 and Eu153;

  thermal to 3-5%, resonance to 10% for: Cs134, Pr141, Nd 143,145, Sm153 and Eu154;

  thermal and resonance to an accuracy of 10% for Nd147;

  fast to an accuracy of 10%: for all Nd-isotopes.

III.5.2. Neutron dosimetry

Reactor neutron dosimetry provides information relative to neutron flux densities, fluences and neutron spectra. This information is needed in order to calculate accurately fission rates, burnup, damage rates etc.

At the 1975 ASTM-Euratom Symposium on Reactor Dosimetry, in Petten [75Pet], the accuracy requirements for fission rate determinations were stated to be in the range of 2-5% for FBRs, and somewhat lower for LWRs and CTRs.

At the present time, multiple foil activation is the only practical means for achieving the required accuracies. This technique involves the irradiation of selected materials, which have known neutron activation thresholds, followed by a γ-ray assay of the reaction products. Among others, it is common to use also fission reactions, like U235 (n,f), Pu239 (n,f), Np237 (n,f), Th232 (n,f) and U238 (n,f) and to detect selected FP. The usual detection method is γ-spectrometry, which restricts the suitable FP to those which are fairly longlived and have strong γ-rays, like:

Zr 95, 97; Ru 103; I 131; Te 132; Cs 137; Ba 140; Ce 143,144, or their respective equilibrium daughters.

If an accuracy of 2% in fission rates has to be achieved (FBR programmes), the nuclear data of the above mentioned FP should be known to the following accuracies:

- the fast fission yields and their neutron energy dependence to 2%;

- the absolute γ-ray intensities for the major γ-rays ($I_{rel} \geq 10\%$) to ± 1% (this requirement seems not to be fulfilled for Ru103, Te132, Ce144;

- the half lives to ≤ 1%.

III.5.3. Safeguards

Safeguards uses FPND mainly for its "non-destructive assay techniques" (NDAT). These techniques are at present only used to verify the information released by the reactor operators. NDAT consist in general in γ-ray scanning of burnt fuel and subsequent evaluation of FP γ-ray activity ratios.

The parameters to be checked include those which are determined in BU analysis, plus possibly some others like the irradiation time, cooling time, fuel composition etc. The values of the parameters, given by the reactor operator, may be checked by calculating - with these values - the expected activity ratios and comparing them to the actually measured ratios.

In addition to the quantities required for BU analysis (see section III.5.1.), information on the cooling time and the irradiation time may be of interest to safeguards, which can be deduced from the following activity ratios:

cooling time:	Ba140/Ce141	irradiation time:	Ba140/Cs137
	Ba140/Zr95		Zr95/Cs137
	Ce141/Zr95		Ce144/Cs137
	Zr95/Nb95		

It follows that the FP involved in NDAT are the same as in BU, which are listed in section III.5.1.

Under favourable experimental conditions, the γ-activities of the important FP can be determined to 3%; hence the calculations of activity ratios should reach at least the same accuracy. Sensitivity studies performed by M. Lammer (in a contribution to RP 6) define the accuracies of individual FPND required to meet the global accuracy target of 3%. Table 4 lists those FPND which do not yet fulfill the accuracy requirements.

Table 4: Unsatisfied FPND requirements for NDAT

accuracy requirements (%)

FP	Thermal fission yields U-233	U-235	Pu-239	Pu-241	Cross-section $g\sigma_o$	RI	$T_{1/2}$	γ-emission probability [1]
Ru-103	3	-	3	10	-	-	-	1-1.5 [2]
Ru-106	2	-	2	-	-	-	0,5 [3]	1 [2]
Cs-133	1	1	1	5	2	2	-	-
Cs-134	-	-	-	-	6	[4]	-	1-1.5
Cs-137	-	-	-	-	-	-	≤0,5 [3]	-
Ce-141	3	-	3	-	-	-	-	1-1.5
Ce-144	-	-	-	-	-	-	-	1-1.5 [2]
Sm-149 [5]	5	3-5	5	-	-	-	-	-
Sm-151 [5]	5	3-5	5	-	-	-	-	-
Sm-152 [5]	5	5	5	-	-	-	-	-
Sm-153	2	2	2	-	10^3 b	[4]	-	-
Eu-153	-	-	-	-	2	6	-	-
Eu-154	-	-	-	-	3-5	[4]	1	1-1.5

1) For major γ-rays

2) Accuracy achieved by individual measurements has to be confirmed

3) Accuracy achieved by individual measurements, but discrepancies exceed requirements

4) Significance of RI unknown; data should enable the calculation of the pile-cross-section to the accuracy shown for $g\sigma_o$

5) For Eu-154 activity

IV. CONCLUSIONS AND RECOMMENDATIONS

FOR THE DIFFERENT DATA TYPES

IV.1. Bulk properties of fission products

The contribution of all FP to quantities like absorption, reactivity worth, heat emission etc, is called a FP bulk property in general, and is referred to as (bulk) FP absorption etc in particular.

IV.1.1. Decay heat: technical recommendations

The bulk requirements for decay heat and the present accuracy status are summarized in Table 3 of Sect. III.3.3. The needs deduced for individual FPND accuracies are included in Tables 6 to 9 of Sect. IV.3.1.; the comparison of status and requirements in these Tables implies the recommendation to (re)measure or re-evaluate those data for which the requirements are not yet met. In addition, the following general activities and considerations concerning decay heat are recommended by the meeting:

(i) Decay heat measurements should be treated as benchmarks, and full experimental details made available (e.g. irradiation history, method of measuring the number of fissions; isotopic composition of sample).

(ii) Experiments in progress should be completed.

(iii) More measurements on fast fission decay heat should be made (the accuracy status of fast fission decay heat has not yet been evaluated, but it may be assumed to be approximately represented by the larger uncertainty values given in Table 3 for thermal decay heat).

(iv) A recommended decay heat curve should be produced for each fissile nuclide and be made available to IAEA/NDS for international dissemination.

Note that a curve for U235 thermal fission has already been reported by Schenter et al. (See RP 15, fig. 1 and 2, and Table VIII). This curve shows that the so-called "ANS 5.1," standard decay heat curve [61Shu] augmented by 20 %, which is still considered as guideline for safety requirements in US thermal reactors, is extremenly conservative, corresponding to a 10σ confidence level.

(v) To aid in reviewing and correlating the data needed for contruction of recommended decay heat curves, Schenter and Devillers (see list of participants) should act as collectors for summation calculations, and Yarnell and Dickens (see list of participants) for measurements.

(vi) Measurements at very short and very long decay times should be made if possible; although data for very long decay times ($t_{cool} > 10^7$ s) might better be obtained by measurements n individual fission products (the nuclides important for long decay times may be found from the Table A-5-II in Vol.II of the Bologna meeting proceedings and from the sensitivities in the Appendix of RP 4 of the present meeting; requirements are included in Tables 6 to 9 of Sect.IV.3.1.).

IV.1.2. Other bulk properties

In this paragraph, all those requirements for FP bulk properties are summarized, for which the needs of individual FPND have not been assessed explicitely. They are all related to the design of fast reactor cores.

(i) Requirements

The target accuracy for the bulk FP capture effect on reactivity of fast reactors is 7 to 10% (see Sect.III.2.2.i). To meet this target, individual FP capture cross sections seem to be required to an accuracy of ± 10%; in addition, experiments on samples of lumped FP are of great value. These requirements are treated in more detail in Section IV.5.1.

Concerning the FP scattering effect on reactivity, S. Iijima recommended that the influence of the transport cross section ($\sigma_{el}(1-\mu)$) on the neutron leakage be investigated. Iijima suggested that this effect may be as important as the inelastic scattering effect, but of opposite sign.

The effect of FP on the sodium void reactivity should be predictable to within 30%. The question how this target should be approached was not solved at the meeting. If, as suggested by J.L. Rowlands, the FP sodium void reactivity is determined as the difference of FP effects in a normal and in a voided core, the total FP effects in each core would have to be known to 3.5% accuracy. According to J.Y. Barré however, it would be possible to fulfill the 30% accuracy goal by an analysis of integral measurements in different fast reactor spectra.

The uncertainty contributed by FP to the total Doppler reactivity should not exceed 7%, which requires that the FP effect on Doppler reactivity should be known within 50% accuracy. The requirements on the bulk scattering and capture cross sections separately may however be more stringent, as the effects of these components are of opposite sign.

The relationship between reactivity and reactor period should be accurate to 3-5%. This requires the knowledge of certain bulk delayed neutron data:

- The total delayed neutron yields per fission from U233, U235, U238 and Pu239 to ± 3% (Pu240 and 241 lower accuracies);

- the time dependence of delayed neutrons in the range of 1 to 100 seconds - sensitivity studies are needed to determine the target accuracy;

- the delayed neutron spectrum, to determine the ratio of delayed neutron to prompt neutron reactivity worths to 2%.

(ii) Conclusions and Recommendations

- In deciding about the requirements on data for individual isotopes to meet the bulk FP requirements, possible systematic errors in the measurements and theoretical methods must be taken into account and can be dominating factors.

- It should be investigated whether the effect of FP on the fast reactor sodium void reactivity has to be measured or whether it can be derived from an analysis of existing integral measurements together with a study of the uncertainty in the differential cross section data.

- For the assessment of the accuracy requirements on the differential cross sections of FP, the influences of inelastic and elastic moderation, as well as capture, on the fast reactor Doppler effect have to be studied in more detail.

- The main parameters determining the time variation of the lumped FP cross sections in a fast reactor and the uncertainties in these parameters should be investigated (see also Sect. III.2.2.iii.).

- Further sensitivity studies are required to define the accuracy requirements for the time dependence of delayed neutron emission and for delayed neutron energy spectra, if possible before the IAEA's delayed neutron specialists' meeting planned for the Fall of 1978.

IV.2. Fission product yields

IV.2.1. Requirements

(i) Chain yields

Table 5 represents a summary of all unsatisfied chain yield requirements expressed at the meeting. Only the most stringent

Table 5: Unsatisfied chain yield requests

Nuclide	fissioning system th.. thermal f.. fast	Most stringent requirement accuracy 2) (%)	source of request 1)	priority	accuracy given by Meek+Rider 2)	Comment
^{3}H	$^{232}Th_{f}$					
	$^{233}U_{th,f}$					
	$^{235}U_{th,f}$					^{3}H analysis, required to 5-10% in fuel; for yield, 10% essential, 5% desirable
	$^{238}U_{f}$	5-10	MB	I		
	$^{239}Pu_{th,f}$					
	$^{240}Pu_{f}$					
	$^{241}Pu_{th,f}$					
^{95}Zr	$^{232}Th_{f}$	2	Dos,BU	I	8	Source of request: IAEA consultants meeting on dosimetry [76IAE]
	$^{237}Np_{f}$				2.8	
	$^{239}Pu_{f}$				2	
	$^{233}U_{th}$	2	BU	II	4	
^{97}Zr	$^{232}Th_{f}$				6	
	$^{237}Np_{f}$	2	Dos,BU	I	4	"
	$^{239}Pu_{f}$				2	
^{102}Ru	$^{239}Pu_{th}$	1.5	BU	II	2	
^{103}Ru	$^{232}Th_{f}$	2	Dos	I	6	Source of request: [76IAE]
	$^{237}Np_{f}$				2.8	
	$^{239}Pu_{f}$				1.4	
	$^{233}U_{th}$	2	BU	II	4	
^{104}Ru	$^{239}Pu_{th}$	1.5	BU	II	2	
^{105}Rh	$^{233}U_{th}$	5	P	II	16	
^{106}Ru	$^{233}U_{th}$	2	Sg	II	4	
	$^{239}Pu_{th}$	2	BU,Sg	II	2.8	
	$^{240}Pu_{f}$	10	MB	I	8	

Table 5 (continued)

Nuclide	fissioning system th.. thermal f.. fast	Most stringent requirement accuracy 2) (%)	source of request 1)	priority	accuracy given by Meek+Rider 2)	Comment
$^{107}Pd/Ag$	$^{239}Pu_{th}$	5	Dos	II	16	
^{109}Ag	$^{239}Pu_{th}$	5	ρ	II	8	
^{129}I	$^{232}U_{th}$ $^{235}U_f$ $^{238}U_f$ $^{239}Pu_{th}$ $^{239}Pu_f$ $^{240}Pu_f$ $^{241}Pu_f$	10	MB	I	16 8 11 16 8 16 16	
^{131}I	$^{232}Th_f$ $^{237}Np_f$ $^{238}U_f$	2	Dos	I	2.8 2 2	
^{127}Te	$^{233}U_{th}$	10	ρ	II	16	
^{132}Te	$^{232}Th_f$ $^{233}U_f$ $^{238}U_f$ $^{240}Pu_f$	2	Dos	I	2.8 8 2.8 6	
^{135m}Xe	$^{233}U_{th}$	3	ρ	II	4	
^{135g}Xe	$^{233}U_{th}$ $^{239}Pu_{th}$	1 1	ρ	II	2.8 1.4	
^{137}Cs	$^{232}Th_f$ $^{233}U_f$ $^{238}U_f$ $^{240}Pu_f$ $^{241}Pu_f$	2	BU	I	4 6 1 8 2	

Table 5 (continued)

Nuclide	fissioning system th.. thermal f.. fast	Most stringent requirement accuracy 2) (%)	source of request 1)	prio-rity	accuracy given by Meek+Rider 2)	Comment
^{140}La	$^{232}Th_f$	2	Dos	I	4	
	$^{233}U_f$				2	
	$^{240}Pu_f$				4	
	$^{241}Pu_f$				1.4	
^{143}Ce	$^{232}Th_f$	2	Dos	I	6	
	$^{233}U_f$				2	
	$^{240}Pu_f$				2.8	
	$^{241}Pu_f$				2	
^{143}Nd	$^{233}U_f$	1.5	BU	I	2	
	$^{237}Np_f$				4	
	$^{242}Pu_f$				4	
^{141}Ce	$^{233}U_{th}$	2	BU	II	2.8	
	$^{239}Pu_{th}$				2.8	
^{144}Ce	$^{232}Th_f$	2	BU	I	4	
	$^{233}U_f$				2.8	
	$^{239}Pu_f$				1	
	$^{240}Pu_f$				6	
^{144}Nd	$^{232}Th_f$	1.5	BU	I	4	
	$^{233}U_f$				2	
	$^{239}Pu_f$				6	
	$^{240}Pu_f$				4	
	$^{242}Pu_f$				4	
^{145}Nd	$^{233}U_f$	1.5	BU	I	2	
	$^{241}Pu_f$				1.4	
	$^{242}Pu_f$				4	
^{146}Nd	$^{233}U_f$	1.5	BU	I	2	
	$^{242}Pu_f$				4	

Table 5 (continued)

Nuclide	fissioning system th.. thermal f.. fast	Most stringent requirement accuracy 2) (%)	source of request 1)	priority	accuracy given by Meek+Rider 2)	Comment
^{147}Nd	$^{233}U_{th}$	3	ρ	II	4	
^{148}Nd	$^{233}U_f$ $^{240}Pu_f$ $^{242}Pu_f$	1.5	BU	I	2 4 6	
^{147}Sm	$^{232}Th_f$	1.5	BU	II	4	
^{149}Sm	$^{232}Th_f$	1.5	BU	II	16	
^{150}Nd	$^{232}Th_f$ $^{233}U_f$ $^{242}Pu_f$	1.5	BU	I	16 2 6	
^{151}Sm	$^{232}Th_f$ $^{233}U_{th}$	15 5	ρ	II II	23 2.8	
^{153}Sm	$^{233}U_{th}$ $^{235}U_{th}$ $^{239}Pu_{th}$	2	Sg	II	6 2.8 6	
^{155}Eu	$^{239}Pu_{th}$	5	ρ	II	11	

1) Source of request:

MB = fuel cycle mass balance (RP 5); see also Sect. III.4.2.

Dos = neutron dosimetry (RP 6); see also Sect. III.5.2.

BU = burnup (RP 6); see also Sect. III.5.1.

Sg = safeguards (RP 6); see also Sect. III.5.3.

ρ = reactivity changes: the requirements for fission yields which were stated at the Bologna meeting, have by now been met. The origin of the requirements listed here is WRENDA 76/77: some were found directly as requests for yield data, but most of them were taken over from the cross section requests (for core design) in WRENDA, assuming that the concentrations - and therefore the yields - of the absorbers must be known to an accuracy corresponding to that of the cross section.(RP 3). See also Para. III.2.

2) As the main evaluators are in strong disagreement on uncertainties assigned to chain yields, those of Crouch [77Cro] being in general considerably higher than those of Meek and Rider [77Mee], it is in many cases not clear whether requests have been met. The policy followed in producing this table was to be more conservative for the more important cases (priority I) by assuming that Meek and Rider have under-estimated the uncertainties by a factor of two. For the remainder (priority II), it was assumed that the uncertainties given by Meek and Rider are valid.

requirement for each FP is indicated, and the application area from which the request origins.

Additional requests may arise for alternative fuel cycles, as is pointed out in Sect. III.4.5.

(ii) Direct yields

There is only a general request relevant to direct yields: At short cooling times (≲10 sec), the decay heat uncertainty due to yield errors comes mainly from inaccuracies in direct yields. The decay heat uncertainty for this interval is to be less than 5%, which leads to the requirement that uncertainties in direct yields (with values exceeding 0.5%) should be comparable to those listed by Meek and Rider [77Mee]. Since these yields are based almost entirely on systematics, their validity cannot be assessed.

(iii) Fission yields versus neutron energy

The requirement for burnup and dosimetry to establish the number of fissions to 1.5-2.0% relative accuracy, requires that fission yields of fission monitors be known to 1.0-1.5% accuracy. This makes a knowledge of the dependence of yields on neutron energy necessary as this dependence is of similar size as the required accuracy. As, at the present time, methods for evaluating the energy dependence are not well established, the development of such methods is required.

IV.2.2. General recommendations and observations

(i) Compilations and evaluations

The tremendous amount of fission yield data available at present calls for both national and international support for evaluators. It is recommended that the support should be given in different forms:

a) The IAEA and other international agencies are asked for appropriate support, e.g. by establishing further contacts between measurers and evaluators.

b) National support should be given by provision of additional staff.

c) Measurers should supply evaluators with information needed. In order to provide revisions of old data, evaluators should send extracts of their files to the measurers concerned, asking for a revision of, or comments to, their entries, e.g. along the following lines:

- The indicated value or its error margins may have to be changed due to better knowledge of the method used or of constants used in the determination (half-lives, decay schemes, branching ratios, newly discovered isomeric states, neutron capture cross sections, yields of reference nuclides, etc);

- discrepancies to other measurements could be commented;

- duplicates should be removed from the compilation;

- values which have subsequently been shown to be wrong should be withdrawn.

(ii) ENDF/B-V Error Margins

It is understood that a new error evaluation of the yield data entering the ENDF/B-V file in progress and this is welcomed.

IV.2.3. Recommendations for measurements and evaluations

(i) Absolute Fission Yields

It is noted that the results of commonly used evaluation procedures (i.e., normalization of the total sum of mass yields to 200%) are severely influenced by discrepancies in measured element yields, which may comprise significant portions of the mass yield curves. In order to avoid such a bias of evaluated yields and enable the resolution of discrepancies, accurate absolute yield data are required. Experimenters are therefore requested to pay great attention to the absolute calibration of their data and apply two independent methods where possible. Accurate measurements of relative fission yields using gamma-ray spectroscopy can also help to resolve discrepancies, and the use of this technique is recommended for fission yields not having the requested accuracy.

(ii) Chain yields

The requested chain yields as listed in Table 5 should be measured and/or evaluated.

(iii) Direct yields

In order to satisfy the request for decay heat (IV.2.ii.), it is recommended that work on direct yields should continue. Further measurements of fast fission direct yields should be performed, which would also improve the possibilities to predict yields, including a check of the hypothesis of a constant charge dispersion width.

For the purpose of improving systematics, more independent yields of single isomeric states should be measured, with emphasis on the thermal fission of ^{235}U. Measurements of independent yields, especially for fission reactions showing strong pairing effects (e.g. Th232), would also be needed for the further development of the odd-even systematics.

(iv) Interpretation of fission yields for various neutron energies

It is recommended that the energy dependence of fast fission yields be investigated, especially for those FP which are used in burnup and dosimetry studies (Zr95,97; Ru103; I131; Te132; Cs137; Ba140; Ce143,144; all stable Nd isotopes).

Because the change in many yields with neutron energy is small (<5%), a comparison of absolute literature yields, which often carry uncertainties of 2 to 5%, in general does not allow conclusions to be drawn about the energy dependence. It is therefore recommended, as a first step, that the changes in the relative fission product abundances be evaluated. These are in most cases determined to a much higher accuracy.

(v) Spectral Index

It is strongly recommended that in a measurement of fast-neutron-induced fission, the neutron spectrum should be defined by measurement. As a minimum, the spectral index defined as the ratio of the number of fissions induced in ^{238}U to that in ^{235}U should be indicated.

IV.3. Fission product decay data

IV.3.1. Requirements

Tables 6 to 9 summarize all the accuracy requirements which were expressed at the meeting, the assigned priorities, the sources of the most stringent request, and the accuracy status.

IV.3.2. Observations and recommendations

(i) The detailed requests listed in Tables 6 to 9 which are not yet met should be fulfilled. In addition, comparisons between the data (half-lives, branching ratios, and average energies) in different libraries should continue, and any serious unresolvable discrepancy thus discovered should lead to further request.

(ii) The detailed Request List in the Bologna Panel Proceedings (Vol.II, Table A3-I) should be updated with the help of the information given here and in the Appendix of RP 4. The IAEA should review both the requirements and the status of the

Table 6: Requests for half-life data

Nuclide	required accuracy (%)	priority	source of request 1)	accuracy status (%)	Ref 2)	Comments
Br 87	3-5; met	II		0.2	/1/	for delayed neutron calculation
Sr 91	5	I	DH	11	/2a/	(/3/: accuracy=2%)
Y 98	5	I	DH	8	/2d/	
Zr 95	<1; met	I	Dos	0.1	/2b/	
Zr 97	<1	I	Dos	1	/2c/	(/3/: accuracy=0.3%)
Zr 98	5	I	DH	10	/2e/	
Nb 97	5	I	DH	1	/2c/	discrepancies
Nb 100	5	I	DH	20	/2f/	
Ru 103	<1; met	I	Dos	0.13	/2g/	
Pd 115	5			11	/5/	
Te 132	<1	I	Dos	1	/3/	(new measurement: accuracy=0.4 /4/)
I 131	5 } met	I	DH	0.12	/2h/	
I 133	5 } met	I	DH	0.5	/4/	
I 135	5 } met	I	DH, ρ	0.15	/2i/=/3/	
Cs 134	5 } met	I	DH	0.24	/3/	
Cs 137	<1 } met	I	Dos	0.7	/3/	
Xe 135	5; met	I	DH, ρ	0.11	/3/	
Xe 135m	30; met	I	ρ	0.2	/3/	
Ba 140	<1; met	I	Dos	0.1	/2k/;/4/	
La 140	5; met	I	DH	0.5	/2k/	(new measurement: accuracy=0.02/4/)
La 147	5			25	/2L/	
Ce 143	<1; met	I	Dos	0.6	/3/	(new measurement: accuracy=0.1/5/)
Ce 144	<1; met	I	Dos	0.3	/6/	
Nd 149	30; met	I	ρ	0.6	/3/	
Pm 149	5; met	I	ρ	0.1	/3/	
Eu 154	{ 1	II	Sg	{ D=100 3)		
	{ 5	I				to resolve discrepancy between T1/2=8.5a and T1/2=16a

Table 6 (continued)

1) Sources of requests:

DH ... decay heat calculations (RP 4)

Dos ... neutron dosimetry (RP 6)

ρ ... reactivity changes (RP 3)

Sg ... safeguards (RP 6)

2) References:

The main source for the accuracy status was Table VI of RP 12 /2/. Only in case of default (or serious disagreement with other works), other sources are indicated.

/1/ G. Rudstam, RP 13 of this meeting, Table 1

/2/ J. Blachot, RP 12 of this meeting, Table VI. The following references are quoted in this Table:

/2a/ 69Kni = Knight J.D. et al, Nucl. Phys. A130(1969)753

/2b/ 71Deb = Debertin K., Y. Naturforsch. 26A(1971)596

/2c/ 73Med = Medsker L.R., Nucl. Data Sheets 10 (1973)1

/2d/ 77Sis = Sistemich K. et al, Z. Physik A281(1977)169

/2e/ 76Her = Herzog W. et al, Z. Physik 276(1976)393

/2f/ 74Koc = Kocher D.C., Nucl. Data Sheets 11(1974)279

/2g/ 75Per = Pérolat J.P., LMRI, private communication, 1975

/2h/ 72Eme = Emery J.E., Nucl. Sci. and Engg. 48(1972)319

/2i/ = /3/

/2k/ 74Pek = Peker L.K. et al, Nucl. Data Sheets 12(1974)343

/2L/ 75Loh = LOHENGRIN Collaboration, ILL Grenoble 1975

/3/ D.C. Kocher (editor) "Nuclear Decay Data for Radio-Nuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities", ORNL/NUREG/TM-102 (1977)

/4/ K. Debertin, contribution to RP 12. INDC(NDS)-87 (1978)

/5/ G. Skarnemark, Thesis Chalmers University, Goeteborg, Sweden, 1977

/6/ J. Legrand et al, "Table des Radionucléides" (published by CEA, Lab. de Métrologie des Rayonnements Ionisants) (1974)

3) D ... discrepancy

Table 7: Requests for average decay energies $(\bar{E}_\beta + \bar{E}_\gamma)$ to calculate decay heat

Nuclide	required accuracy (%)	priority	source of request 1) (RP)	accuracy status 2) (%)	Comments
Br 88,89	10		RP 4	35	
Sr 89	5		RP 4,5	8	discrepancy?
Sr 95	10		RP 4	25	
Sr 96	10			40	
Y 90,91	5		RP 4,5	8	
Y 96,96m				35	
Zr 100				35	
Nb 102				35	
Mo 103,104 105	10		RP 4	35	
Tc 105				25	
Tc 107				35	
Rh 106	5	I		6	
Te 135	10			35	
I 137,138	10			35	
Cs 137	5		RP 5	11	
Cs 141, 142	10			23	
Ba 140	5			7	
Ba 143, 144	10		RP 4	40	
La 140	5; met			2	
La 144	10			25	
La 145,146	10			35	
Ce 141	5		RP 4,5	11	discrepancy ?
Pr 143	5		RP 4	10	
Pr 144	5		RP4,5	7	

1) Source of request:

RP 4 .... removal of decay heat after shutdown

RP 5 .... interim storage and transport

2) The accuracy status was obtained from the Annex to RP4, through the sensitivities and the error in the afterheat due to $(\bar{E}_\beta + \bar{E}_\gamma)$

Table 8: Requests for γ-intensities (γs/disintegr.) of the major γ-rays (i.e. $I_\gamma \geq 10\%$)

Nuclide	required accuracy (%)	priority	source of request 1)	accuracy status (%)	Ref 2)	Comments
Br 86	50 ; met	II	RP 5	<25	/9/	high energy γ's requested
Zr 95	1		BU	1	/2/	
Zr 97	1		Dos	10	/2/	
Nb 94 m	5		σ_{act}	20	/2/	
Nb 95	1 ; met		BU	0.02	/3/	
Mo/Tc 99	5		σ_{act}	< 3	/2/,/4/	
Tc 100	5		σ_{act}	<10	/4/	
Ru 103	1		BU	3 (1)	/2/(/1/)	in brackets: new measurement /1/
Ru/Rh 106	1 [3]		BU	< 5 (1)	/2/(/1/)	"
Rh 104				< 5	/4/	
Pd 109	5	I	σ_{act}	11	/2/	
Ag 108				<20	/10/	
Ag 110				5	/2/	
Ag 110 m				2	/2/	for decay data libraries: γ-transitions see inconsistent and difficult to fit into a coherent scheme
In 116 m (T1/2=54')				< 5	/10/	
Te/I 132	1		Dos	< 4	/2/	
I 128	5		σ_{act}	10	/5/	
I 131	1		Dos	1.5	/2/	
Xe 133	5 ; met		σ_{act}	1	/2/	
Cs 134	1 [3]	II	Sg	< 1.5	/1/,/2/	
Cs/Ba 137	1 ; met			0.4	/2/,/4/	
Ba 140	1		BU	16(<1.5)	/2/(/1/)	in brackets: new measurement /1/
La 140	1 [3]; met			<3(<1)	/2/(/1/)	
Ce 141	1	I		4	/2/,/4/	
Ce 143	5		σ_{act}, Dos	<10	/2/,/4/	
Ce 144	1 [3]		BU	4(1.5)	/6/(/1/)	in brackets: new measurement /1/

Table 8 (continued)

Nuclide	required accuracy (%)	priority	source of request 1)	accuracy status (%)	Ref 2)	Comments
Pr 142	5	I	σ_{act}	14	/10/	
Pr 144	1 3)	I	BU	7 (<1.5)/4/(/1/)		in brackets: new measurement /1/
Nd 147	1	I	BU	<6	/2/	
Pm 148	5	I	σ_{act}	<5	/2/,/4/	
Eu154	1	I	BU, Sg	3	/2/	
Eu 155	1	I	BU	3	/7/	
Eu 156	1	II	Sg	5	/8/	

1) Sources of request:

- RP 5 ... for prediction of high energy (γ,n) reactions in Deuterium (see Sect.III.4.3.)
- BU ... burnup, non destructive determination (RP 6, and Sect.III.5.1.)
- Dos ... reactor neutron dosimetry (RP 6, and Sect.IV.5.2.)
- σ_{act} ... for cross section activation measurements in CFRMF
- Sg ... safeguards, non destructive methods (RP 6, and Sect.III.5.3.)

2) References

(The main references for the stuatus of I_γ accuracies were /2/ and /4/; other sources were only consulted when the required information could not be found in /2/ or /4/.)

/1/ K. Debertin, contribution to RP 12

/2/ D.C. Kocher (editor) "Nuclear Decay Data for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities", ORNL/NUREG/TM-102 (1977)

/3/ Nuclear Data Sheets B8 (1972)29

/4/ J. Blachot et al, "Bibliothèque de Données Nucléaires Relatives aux Produits de Fission", CEA-N-1822(1975)

/5/ Nuclear Data Sheets 9 (1973)157

/6/ J. Legrand et al, "Table des Radionucléides" (published by CEA, Lab. de Métrologie des Rayonnements Ionisants) (1974)

/7/ Nuclear Data Sheets 15 (1975)409

Table 8 (continued)

/8/ Nuclear Data Sheets 18 (1976)553

/9/ " " " B5 (1971)151

/10/ M.J. Martin (editor) "Nuclear Decay Data for Selected Radionuclides", ORNL-5114 (1976)

3) Intensity of high energy γ-rays requested to 10% accuracy for shielding during fuel transport. (See Sect. III.4.1.)

Table 9: Request for branching ratio

Nuclide	required accuracy (%) in branching ratio	priority	status	Ref	Comment
I 135	5	I	6 3	/1/ /2/	to g and m; for reactor physics

References:

/1/ M.J. Martin, ORNL-5114 (1976)

/2/ H. Feuerstein, J. Oschinski, Inorg + Nucl. Chem. Letters 12 (1976)243

data; assistance in reviewing the status should be sought from the Data Centres and other evaluators. The results should be published in the Newsletter.

(iii) It is highly desirable (for their interchange and comparison) that all evaluated data be stored in a common format. The meeting recommends ENDF/B-IV format at present; and probably ENDF/B-V format when it has been approved and tested. For experimental data the use of the ENSDF format is recommended.

(iv) The meeting notes the incomplete status of uncertainties in beta and gamma transition probabilities in the several data files and recommends as first priority the completion of uncertainty analysis and inclusion of uncertainties in all data files. This is especially important for those nuclides that contribute most to decay heat at longer cooling times.

(v) The meeting recognizes that correlations likely exist among experimental results of decay data (see RP 11 and RP 13) and recommends that consideration be given to encouraging research in quantitative determinations of these correlations among experimental results. Results of these analyses should be included in uncertainties given in the several data files indicating, when possible, the source of the correlation.

(vi) Critical reviews should be made of the different theoretical or semi-empirical methods of predicting decay data when no measurements are available (e.g. half-lives, average energies).

(vii) The greatest source of uncertainty in average β or γ decay energies is frequently the uncertainty in the intensity of the beta-decay to the ground state of the daughter. More experimental effort is needed to measure this as accurately as possible for as many nuclides as possible.

(viii) The meeting recommends remeasuring complete beta-ray spectra of important long-lived fission-product nuclei (see RP 4 Appendix), especially for those nuclides which have not been remeasured since 1960. The measurements should provide beta-ray end point energies, $E_{\beta max}$, to ±10 keV, and the spectra should be measured at least for $E_\beta > 0.05 \times E_{\beta max}$. These measurements are needed to resolve uncertainties and differences in average beta-ray energies among the several data files, as noted in Table VIII (b) of review paper no. 12 (for decay heat calculations).

(ix) It is recognized that decay heat measurements and, even more, γ- and β-spectrum measurements on bulk fission products, can give valuable information on possible errors or discrepancies in the differential data.

(x) There is still a need for more and better data on internal conversion coefficients. Evaluators frequently need to make assumptions about transition types, and interpolate using tables of theoretical data such as that of Hager and Seltzer. Unfortunately there can be large discrepancies and uncertainties in multipolarities in making use of theoretical calculations.

(xi) Frequently it is not known which of two isomers is the ground state. Experiments should be made to remove such uncertainties: but in the meantime compilers of libraries should ensure that all their data (branching ratios, etc) are consistent with whatever choice they make.

IV.4. Delayed neutron data

IV.4.1. Requirements and status of total delayed neutron properties

Apart from the bulk requirements on delayed neutron properties which need further sensitivity studies, requirements on total delayed neutron yield accuracies were expressed for reactor physics purposes (Sect.IV.1.2.):

- to determine ν_d for U233, U235, Pu239 thermal and fast fission and U238 fast fission to ± 3%.

This requirement has not yet been met, especially for U238.

The meeting noted that, in order to approach the long term goal of assessing individual precursor spectra with sufficient accuracy, also the integral spectra, in equilibrium and time-dependent, require improvement.

At the Bologna Panel, it was recommended that a standard neutron source with an energy spectrum similar to that of total delayed neutrons be prepared for the calibration of the neutron counting facilities in individual laboratories. This has apparently not been done; however americium-lithium sources can be considered adequate and are available with absolute calibration.

IV.4.2. Requirements and status for individual precursor data

From the applications' side, no individual delayed neutron precursor data were requested. Perhaps the bulk requirements relative to reactivity studies (Sect.IV.1.2.) will lead to some needs for precursor data, but sensitivity studies are required first.

Nevertheless, some requirements are expressed below. In general, they refer to the goal of eventually obtaining systematics of delayed neutron precursors which are theoretically well understood and enable reliable predictions of delayed neutron yields, spectra etc.

(i) Half-lives

The status of the half-lives of the 67 precursors identified to date is given in Table 1 of RP 13. The overall accuracy is satisfactory. The only FP whose half-life should be reinvestigated is Cs141: its uncertainties would be required to be $\leq 5\%$, whereas there exists a discrepancy between measurements of $\approx 10\%$.

(ii) Branching ratios (P_n-values)

Table 2 of RP 13 reflects the present status of P_n values. There are 48 precursors having measured P_n-values, with uncertainties between 7 and 50%.

P_n values may be determined directly, by measuring the neutron activity of a separated precursor, or indirectly from the relation $P_n = \frac{\nu_d}{Y_{cum}}$ (Y_{cum} = cumulative yield of precursor under consideration)

The cumulative yields, as sum of independent yields, are very often obtained from systematics - which are not yet well established - and have in general high uncertainties. It is therefore desirable to perform more direct measurements, especially for those FP with unknown or indirect P_n values. An accuracy of 5 to 10% for such measurements is considered to be a realistic goal. This would significantly improve our knowledge of delayed neutron phenomena and would also have a positive impact on yield distribution models.

According to Table 2 of RP 13, direct P_n values have been measured for 43 FPs. The Table includes also the most recent measurements which were performed for As85-87, Br87-92, Rb94-98, Sb135-136, Te136, I132-141 and Cs143-147; but only about 40% of these have errors $<10\%$. They nevertheless suggest immediate reevaluation of the indirectly determined P_n values. The status of P_n values as found in Table 2 of RP 13 is reproduced in Table 10.

For the sake of developing systematics and the yield theory, P_n values of additional even Z isotopes should be measured; this requirement is of less importance to reactor physics.

Y98,99 and In128,129,130 have isomeric states requiring P_n measurements or establishment of the state(s) leading to delayed neutron emission.

Table 10: Status of P_n-values (taken from Table 2 of RP 13)

Precursor	accuracy 1) of P_n (%)	number of 2) direct determinations	number of 2) indirect determinations	Comments
As 84	46		1	
As 85	13	1	2	
As 86	21	1	1	Large discrepancy; direct determination preferred
As 87	32	1		
Se 87	15	1	2	
Se 88	60	1	1	Large discrepancy; direct determination preferred
Se 89	30		1	
Se 91	40	1		
Br 87	6	5		
Br 88	5	4		
Br 89	18	4		
Br 90	11	2		
Br 91	16	2		
Br 92	28	2		
Kr 92	10	1	1	
Kr 93	15	2	2	
Kr 94	64	2		
Rb 92	8	2	1	
Rb 93	8	6	3	
Rb 94	6	6	1	
Rb 95	6	6		
Rb 96	7	6		
Rb 97	10	4		
Rb 98	16	2		
Sr 99	70		1	
Y 97	19		1	
Y 99	67		1	

Table 10 continued

Precursor	accuracy 1) of P_n (%)	number of 2) direct determinations	number of 2) indirect determinations	Comments
Sn 134	42	1	1	
Sb 134	14	1	1	
Sb 135	17	1	1	
Sb 136	35	1	1	
Te 136	45	1	1	
Te 137	23	2		
Te 138	29	1	1	
I 137	8	5		
I 138	12	5		
I 139	9	2		
I 140	28	1		
I 141	34	1		
Xe 141	7	1	1	
Xe 142	8	1	1	
Cs 141	8	2	1	
Cs 142	D=100	3	1	direct exp. values between 0.086 and 0.285
Cs 143	7	4		
Cs 144	24	4		unweighted average, discrepancies between experiments = 100%
Cs 145	14	5		
Cs 146	6	2		
Cs 147	12	1		

1) accuracy given is the error of the weighted average of the P_n values taken into account;

D .... discrepancy

2) in columns 3 and 4 the number of those directly resp. indirectly determined P_n values are given that were taken into account in calculating the weighted average. In general, all values for direct P_n were used, but those for indirect P_n were taken only, when there were less than 2 direct values or when they agreed well with the direct values.

Estimates of unmeasured Pn values based on statistical models are less accurate than was anticipated. Therefore, if estimates are to be made, in the absence of expensive calculations incorporating nuclear structure effects, simple empirical model estimates are still preferred.

(iii) Spectra

Considerable progress on individual spectra has been made since the Bologna meeting. By now, spectra of about 30 precursors have been measured (the nuclides are listed in Table 4 of RP 13.)

Important nuclides still requiring measurement of spectra are

^{93}Kr, $^{97,99}Y$, $^{137,138}Te$.

The low energy (10 to 100 keV) part of the spectra has been measured for only about half of the precursors, and should be measured for the remaining ones, namely: (Zn,Ga)79; Ga80,81; Br88-91; In129,130; Sn134; I139,140. Of relatively high importance are the spectra of the shortlived halogens.

Further work on assessment of the properties of different spectrometer types, especially concerning response function and detector efficiency is urgently needed: experiments using He^3, time-of-flight, and proton recoil methods show considerable differences.

(iv) Average neutron energies

Average delayed neutron energies for individual precursors have been measured within $\approx$50 to 100 keV, including systematic errors which can now realistically be kept below 20 to 50 keV. (Note that the errors given by the SOLIS group [76Ree] to date do not include systematic errors.)

IV.4.3. Observations and conclusions

(i) Considerable progress concerning individual precursor data has been made since Bologna, which may be summarized as follows:

- There are 69 known precursors vs. 42 at the time of the Bologna Panel;
- Based entirely on energetics, $\sim$102 potential precursors (including isomeric states) have been identified that have yields of significance in fast or thermal fission.

- There are 48 precursors having measured Pn values (direct or indirect) vs. ~34 reported at Bologna.

- 15 more neutron spectra from individual precursors have been measured since the Bologna Panel. (by the time of the Panel ~12 had been measured)

(ii) The emphasis is shifting from group data towards data for individual precursors. These data constitute the basis for a reliable prediction of macroscopic properties like total number of delayed neutrons, delayed neutron energy spectra etc, and their dependence on all operational conditions (i.e. fuel composition, reactor power, operating history and cooling time).

As a guideline, it may be assumed that for any combination of microscopic quantitites that are worth ~1% of a macroscopic property, a 5-10% accuracy in the microscopic data should be reached.

(iii) The improvement of data for individual precursors presupposes a corresponding improvement in independent fission product yields.

IV.4.4. Recommendations

(i) In accordance with the requirements stated in the previous actions, the following measurements are recommended:

- measurement of fission spectrum averaged total delayed neutron yield (v_d) of U238;

- improvement of the knowledge of integral equilibrium and time dependent spectra;

- to improve the accuracies of Pn values of the FP listed in Table 10 to become 5 to 10%. At present, this rerequirement seems not to be met for ~70% of the 48 precursors with determined Pn values.

- to determine Pn values of additional even Z isotopes and of the isomeric states of Y98,99 and In128-130;

- to measure the delayed neutron spectra of Kr93; Y97,99; Te137,138. And the low energy part (10 to 100 keV) of (Zn,Ga)79; Ga80,81; Br88-91; In129,130; Sn134; I139,140.

(ii) Delayed neutron spectra from individual precursors measured by different techniques differ considerably. A resolution of these discrepancies is urgently required, in terms of analyzing response functions and efficiencies of the different detectors.

(iii) The goal of producing macroscopic delayed neutron properties from precursor data will require some additional accurate measurements of equilibrium and group data for comparison purposes.

IV.5. Fission product neutron cross sections

IV.5.1. Requirements and status:

(i) thermal capture cross sections and resonance integral data

A survey of all the requests for thermal neutron capture cross sections and resonance integrals, and the status of these data can be found in Table 11. Below, some comments concerning the requirements and status are given.

At the Bologna meeting, the variation of the Xe135 and Sm149 capture cross sections with neutron energy was required to an accuracy of ± 10% for the calculation of the temperature coefficient of reactivity. Whereas no recent data exist for Xe135, measurements for Sm149 were made at Brookhaven [74Bec], and at the Rensselaer Polytechnic Institute (R.P.I.) [75Hoc]. An evaluation of these data is recommended.

For the resonance integrals of Tc99 and Pd107, a discrepancy between the experimental values and the value obtained from resonance parameters exists.

The accuracy of 2% for the thermal capture cross section of Sm151 originates from recent measurements of Kirouac and Eiland [75Kir].

The requests found in WRENDA 76/77 and included in Table 11 may partly be superseded.

(ii) Fast capture cross sections

Fast capture cross sections are essentially needed for corrections in the burnup determination (Sect. III.5.1.) and for the prediction of the bulk FP reactivity effect (Sect. III. 2.2.).

The element most frequently used as BU-monitor is Nd. Therefore the fast capture cross sections of Nd143-150 are required with high priority: if they are larger than 100mb, they should be known to an accuracy of 10%, preferably as differential data. A more general request for BU monitors, which has much lower priority, is to know the fast capture

Table 11: Requirements and Status for Thermal Capture Cross-Section and Resonance Integral Data

FP	Quantity	required accuracy %	source of request	priority	status g) (%)	E-range of resolved resonances (eV)	Comments
^{83}Kr	σ_{th},RI	10	W	2	15/1/		
^{95}Zr	σ_{th}	20b	W	2	D=5b/4/		radioactive; D between 2 evaluations (/5/,/7/)
	RI	20b			D=3b/4/		
^{95}Nb	σ_{th}	100b	W	2	D=3b/4/		radioactive; "
^{99}Mo	σ_{th}	100b	W	2	D=5b/4/		" "
	RI	1000b			RI=26b/4/		RI= evaluated data (/5/,/7/)
^{99}Tc	σ_{th}	20	DH	1	$10^{b)}$/2/		
	RI	15				5.6– 280 eV	
^{101}Ru	σ_{th}	10	W	1	30/1/		
	RI	10			15/1/		
^{103}Ru	σ_{th}	35b		2	D=60b/3/		radioactive; D between 2 evaluations(/5/,/7/)
	RI	1000b			D=500b/3/		
^{103}Rh	σ_{th}	5	ϱ	1	4/2/	1– 4100 eV	met
	RI	10	W		5/2/		
^{105}Rh	σ_{th}	5	W	1	10/1/		radioactive
	RI	20			10/1/		
^{107}Pd	σ_{th}	10b	W	2	D=100b/3/		
	RI	10			6/3/		D between calc. and exp.RI>100%

Table 11 (continued)

FP	Quantity	required accuracy %	source of request	priority	status g) (%)	E-range of resolved resonances (eV)	Comments
^{107}Ag	σ_{th}	10	W	2	3 /1/		met
	RI	10			10 /1/		
^{109}Ag	σ_{th},RI	10	W	2	3 /1/	5eV–2.5 keV	"
^{127m}Te	σ_{th}	900b	W	2			105d isomer; estimate /5/ for σ_{th}=9.4b
	RI	20					
^{132}Te	σ_{th}	250b	W	2			radioactive; estimate /5/ for σ_{th}=2.4mb, RI=7mb
	RI	500b					
^{131}Xe	σ_{th}	15	S	1	11 /1/		met
	RI	10			5 /1/		
^{133}Xe	σ_{th}	3	W	2	50 /1/		radioactive
	RI	3					
^{135}Xe	σ_{th}	8	S	1	3 /2/		" ; met
	RI	100			7 /2/	0.084 eV	
	E-depend.	10	S				
^{133}Cs	σ_{th}	3(-5) c)	BU		3		met (according /1/ accuracy is 5%)
	RI	3(-5)			10	7.14– 3520 eV	139 resonances (according /1/ accuracy is 4%)
^{134}Cs	σ_{th}	3(-5) c)	BU		10		
	RI	10 d)			no data		
^{135}Cs	σ_{th}	10	W	1	8 /1/		
	RI	10			D=20 /3/		D between calcul. and exp. RI

Table 11 (continued)

FP	Quantity	required accuracy %	source of request	priority	status g) (%)	E-range of resolved resonances (eV)	Comments
^{141}Pr	σ_{th},RI	3-5 c)	BU		3 /1/	85 eV - 10 keV	σ_{th} and RI lower than 20b, therefore no requirement
^{143}Nd	σ_{th}	3-5 c)	BU	1	3 /2/		met
	RI	10 d)			>factor 2	6 eV - 5.5 keV	112 resonances
^{145}Nd	σ_{th}	3-5 c)	BU	1	5 /1/		met
	RI	10 d)			12 /1/	6 eV - 4.6 keV	192 resonances; nearly met
^{147}Nd	σ_{th}	10	BU b,f)	1	30 /6/		1 measurement with 30% accuracy
	RI	10					
^{147}Pm	σ_{th}	20	BU e)	1	4 /1/		met
	RI	20			30 /1/	1.6-160 eV	42 resonances
^{148g}Pm	σ_{th}	10	W	1	50 /1/		radioactive, $T_{1/2}$ = 5.37d
	RI	10			D=50 /4/		D between evaluations (/5/,/7/)
^{148m}Pm	σ_{th}	30	DH	1	12 /1/		met } $T_{1/2}$ = 41d
	RI	30			70 /1/	0.169eV	1 resonance }
^{149}Pm	σ_{th}	20	W	1	20 /1/		met } radioactive
	RI	20					
^{151}Pm	σ_{th},RI	10	W	2			radioactive
^{149}Sm	σ_{th}	20	?		3 /1/		met
	E-depend.	10				0.1-249eV	
^{150}Sm	σ_{th},RI	3	W	1	5 /1/		

Table 11 (continued)

FP	Quantity	required accuracy %	source of request	priority	status g) (%)	E-range of resolved resonances (eV)	Comments
^{151}Sm	σ_{th}	8	ρ		2 /6/		met
	RI	40			5	0.45-295.7 eV	121 resonances
^{152}Sm	σ_{th}	20	ρ	2	3 /1/		met
	RI	10			5	8-5000 eV	
^{153}Sm	σ_{th}	1000b	BU		no data		radioactive
	RI	20	W				
^{153}Eu	σ_{th}	3	Sg		15 b)		
	RI	10 d)	BU		12 /1/	0.457-97.6 eV	76 resonances
^{154}Eu	σ_{th}	2	Sg		30 /1/		radioactive
	RI	10 d)	BU		no data		
^{155}Eu	RI	10	W		D=56 /3/	0.19-3.9 eV	radioactive; D for evaluations

a) Sources of requests:

W .... WRENDA 76/77

DH .... decay heat (RP 4)

ρ .... reactivity predictions (RP 3 here and at Bologna Panel)

BU .... burnup determination (RP 6)

Sg .... safeguards (RP 6)

Table 11 (continued)

b) experimental data with ± 15%, evaluation with ± 8% accuracy

c) required to 3.5% if σ_{th} > 20b

d) required to 10% if RI > 50b

e) not in RP 6

f) not for power reactors, but for special high flux irradiations ($5 \cdot 10^{14}$ n/cm^2 s)

g) References:

/1/ BNL-325, 3rd edition (1973)

/2/ 1973 Bologna Panel, P.Ribon: RP 10 (IAEA-169,Vol.I)

/3/ This meeting, RP 7 (E. Fort)

/4/ A.L. Pope, J.S. Story, contribution to RP 10 of 1973 Bologna Meeting, IAEA-169,Vol.III, p.163

/5/ 1971 Cook Library, as quoted in /4/

/6/ G.J. Kirouac and H.M. Eiland, Phys. Rev. C11 (1975) 895

/7/ ENDF/B-III Library (1971), as quoted in /4/

D ... discrepancies

cross sections (>100mb) of all major stable FP to 15%.

As a long term goal, the calculation of the net effect of lumped FP on reactivity should be accurate to ± 7%. Calculations have been carried out in the Netherlands [76Hei] and France [77Lan] which suggest that, with the accuracies of individual cross sections as given in present evaluation, this target is already reached. However, preliminary results of experiments performed in France on irradiated fuel from PHENIX [77Lan] show integral data which are systematically about 15% lower than those calculated. On the other hand, Dutch experiences with samples of irradiated thermal reactor fuel oscillated in STEK (see RP 14) are in satisfactory agreement with the calculations. Before judgement is made, the final analysis of the French experiments must be awaited; only then it can also be decided whether new experiments on bulk FP samples are required or not.

There was some discussion about the fast capture cross section accuracies of individual FP that should be reached in order to safely fulfill the bulk requirements. Finally, the values included in Table 12 were agreed upon, which are mostly much lower than those requested at the Bologna Panel. The main argument for accepting these tight requests is that possible systematic errors in the capture cross sections of individual FP in general do not cancel statistically.

Table 12 gives for each FP the most stringent requirement, the source of the request, the status of differential (σ_γ vs. neutron energy) as well as of integral (σ_γ averaged over fast neutron spectrum) data or measurements, and remarks about planned, ongoing or recommended actions to improve the situation. As far as requests for reactivity calculations are concerned, the required accuracy relates to the capture cross section averaged over a fast breeder reactor spectrum.

(iii) Scattering data

The reactivity effect due to inelastic scattering of lumped FP is 10% to 15% of the capture effect. An accuracy of ± 30% in the bulk FP reactivity effect is wanted.

The data for inelastic scattering cross sections are mainly based on theory. Calculations performed with the data from the various recent evaluations differ by no more than about 15% in the net effect due to scattering, the agreement being probably due to partial cancellation of errors. This suggests that the 30% accuracy requirement has been achieved, but a check of the evaluations by integral measurements is recommended. Possibly, the CFRMF reactivity worth measurements could be used for such a test. If the uncertainty in the scattering effect would turn out to be lower than 20%, this would relax the demands for capture data.

Table 12: Requests and Status for fast capture data

Nuclide	Request a)	Status b) microscopic	Status b) integral	Action
^{93}Zr	20 %	only 1 resonance no keV data not met	only STEK oscill. /13/ probably met	further analysis of STEK data
^{95}Mo	10 %	many resonances new data of Musgrove /1/ <90keV status 15%	STEK oscill. PHENIX irrad. /14/ FRO oscill. /15/ (agreement) met	no action
^{97}Mo	10 %	many resonances new data of Musgrove /1/ <90keV status 15%	STEK oscill. PHENIX irrad. FRO oscill. (agreement) met	no action
^{98}Mo	20 %	many resonances new data of Musgrove /1/ <90keV bad for E >90keV status 15%	STEK oscill. CFRMF activ. /3/ ERMINE activ. (not very good agreement between STEK/CFRMF) met	no action
^{99}Mo	(ϱ(t))	Interpolation by Musgrove /1/		reevaluation is recommended
^{100}Mo	20 %	many resonances new data of Musgrove /1/ <90keV status 15%	STEK oscill. CFRMF activ. (in same direction) ERMINE activ. met	no action
^{99}Tc	10 %	only one set of data for E <50keV /2/ very discrepant calculations for E >100keV not met	STEK oscill. French oscill. /14/ CFRMF activ. FRO oscill. (discrepancies) not met	planned: resolved resonances experiments in Kiel recommended: measurement of average σ for E=1 to 500 keV; $\langle\Gamma_\gamma\rangle$ measurements; irradiation in EBR-2

Table 12 (continued)

Nuclide	Request a)	Status b) microscopic	Status b) integral	Action
^{101}Ru	10 %	many resonances unpublished RPI data /4/ not met	STEK oscill. FRO oscill. PHENIX irrad. (good agreement) probably met	analyse data of Hockenbury /4/ compare with integral data
^{102}Ru	20 %	few resonances; unpublished RPI data /4/ (very low) not met	French oscill. FRO oscill. STEK oscill. CFRMF activ. ERMINE activ. (very good agreement) met	(perhaps more resonances required) compare RPI data with integral data
^{103}Ru	20 %	no data at all very large differences between evaluations not met	no data	evaluation with new microscopic + integral data of $^{101,102,104}Ru$
^{104}Ru	20 %	see ^{102}Ru	see ^{102}Ru (no French oscill.)	see ^{102}Ru
^{106}Ru	low priority; remove from request list			
^{103}Rh	10 %	many data uncertain: 1-10keV status: 10 to 15%	French oscill. FRO oscill. STEK oscill. CFRMF activ. (good agreement) met	no action
^{105}Rh	(for time dependence of reactivity)			reevaluation recommended
^{105}Pd	10 %	resonances to 160 eV recent RPI /5/ and ORELA /6/ data in keV range; discr. near 100 keV no data for 160 eV $\leq$ E $\leq$ few keV status 20%	STEK oscill. French oscill. PHENIX irrad. (30% discrepancies between STEK and PHENIX; irradiations: difficult to obtain pure sample!) not met	planned: resolved resonances in Geel ongoing: resolved resonances in RPI recommended: microscopic data for 160 eV $\leq$ E $\leq$ 10keV; integral irradiation experiments

Table 12 (continued)

Nuclide	Request a)	Status b) microscopic	integral	Action
^{107}Pd	10 %	no data; to be published: RPI data in resolved resonance range not met	only STEK oscill. (not a very high accuracy) not met	new evaluation RPI + STEK data
^{109}Ag	10 % to 20 %	many resonances discrepant series of data in keV region data also available for ^{107}Ag, natural Ag not met	CFRMF activ. STEK oscill. French oscill. (reasonably good agreement) met	evaluations can be improved with integral + micr. data of ^{107}Ag, nat. Ag.
^{127}I	10 % (St)	new resonances (Geel /7/) many data; discrepancy between stat. model and keV data; status 20%	STEK oscill. CFRMF activ. (in agreement with most keV data) (status: met for reactor physics purposes)	more microscopic data in keV range, to become a secondary standard
^{129}I	20 %	few resonances, Γ_γ not known no keV data not met	STEK oscill. CFRMF activ. (good agreement) met	no action
^{131}Xe	20 %	no data at all; large discr. between evaluations not met	only STEK oscill. (FP mixture) not yet analyzed	analyse STEK data
^{132}Xe	30 %	no data not met	STEK oscill. (FP mixture) CFRMF activ. not yet analyzed	analyse STEK data
^{133}Cs	10 % (5 to 10% Fh)	many resonances; discrepant series of keV data; to be published: RPI data /8/, Japanese data /16/, /17/ not met	RAPSODIE irrad. /18/ CFRMF activ. STEK, French oscill. PHENIX irrad. (good agreement between STEK/French oscill., CFRMF data lower; transm. and activ. data in agreement) probably 10% met	recommended: evaluate new data

Table 12 (continued)

Nuclide	Request a)	Status b) microscopic	integral	Action
^{135}Cs	10 %	no data at all planned: Kiel /9/ mixed FP resolved res. not met	only STEK oscill. (sample not very good) not met	recommended: integral activation measurements evaluation with Cs133,136 data
^{139}La	20 %	many resonances many keV data nearly met?	STEK oscill. CFRMF activ. (good agreement) met	no action
^{144}Ce		low priority; remove from request list		
^{141}Pr	20 %	many resonances many keV data discr. at high E not met	STEK oscill. CFRMF activ. French oscill. ERMINE oscill. (good agreement) met	no action
$^{143-150}Nd$	10 % (BU)	resolved res. known recent data of Musgrove et al. E= 1 to 19 keV /10/ status: ≈15%	STEK oscill. (not yet analyzed) Nd145: PHENIX irrad. in progress: stable Nd143-150 EBR-2 irrad. and RAPSODIE (meas'ments completed) planned: Nd143 PHENIX irrad. status: not known	evaluate Musgrove's data; analyse STEK data
^{147}Pm	10 %	many resonances no keV data, evaluations in good agreement, not met	STEK oscill. (not analyzed) CFRMF activ. French oscill. FRO oscill. (good agreement) not met	microscopic keV data required planned: integral activ. ERMINE
^{148m}Pm	Dh	no data at all probably met with ENDF/B-IV	no data	no action
^{149}Pm	($\rho(t)$)	no data		reevaluation recommended

Table 12 (continued)

Nuclide	Request a)	Status b) microscopic	integral	Action
^{147}Sm		low priority; remove from request list		
^{149}Sm	10 %	many resonances; Russian keV data /11/ to be published: RPI keV data /4/ not met	FRO oscill. STEK oscill. PHENIX irrad. EBR-2 irrad. (to be analyzed) discrepancy between STEK and recent keV data not met	recommended: evaluate new data
^{151}Sm	10 %	many resonances no keV data not met	STEK oscill. (not accurate) PHENIX irrad. (perhaps new PHENIX irrad. in future) not met	keV data required
^{152}Sm	20 %	many resonances few activation data /12/ not met	STEK oscill. CFRMF activ (good agreement) probably met	
^{153}Eu	20 %	resonances up to 100eV discrepant keV data to be published: JAERI data probably met with new data	STEK oscill. (not analyzed) CFRMF activ. French oscill. probably met	analyse STEK, JAERI data
^{155}Eu	20 %	no data at all planned: data from Kiel /9/ not met	no data	
^{151}Eu ^{152}Eu ^{153}Eu ^{154}Eu Eu nat	5 % 20 % 5 % 20 % ?	required for control rod materials	for several isotopes there are data from STEK, CFRMF and EBR-2 (to be analyzed)	

Table 12 (continued)

a) Source of requests:

All requests are for reactivity calculations, except where stated otherwise:

$\rho(t)$	...	is a request for the time dependence of reactivity at reactor shutdown (Sect.III.2.2.(iii)
Fh	...	Fuel handling (request made at Bologna Panel)
BU	...	burnup monitors
Dh	...	decay heat calculation
St	...	secondary standard

b) References:

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/3/ Y.D. Harker, in "Progress in FPND", INDC(NDS)-86, p. 77-83 (1977)

/4/ Hockenbury; Bull.Am. Phys. Soc. 20 (1976)560 (abstract, no data); see also EXFOR 10552

/5/ Hockenbury, NBS-Spec. Publ.-425 (1975 Washington Conf.) p. 904

/6/ see INDC(NDS)-86 ("Progress in FPND") p.72 (1977)

/7/ G. Rohr et al, Int. Conf. on Interactions of Neutrons with Nuclei; Lowell, Massachusetts, 6-9 July 1976; p.1249

/8/ Hockenbury, Bull. Am. Phys. Soc. 21 (1976)537 (abstract no data)

/9/ see INDC(NDS)-86 ("Progress in FPND") p.10 (1977)

/10/ A.R. Musgrove, to be published in Nucl. Phys. See also EXFOR 30360

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/13/ J.J. Veenema, A.J. Janssen, "Small sample reactivity worths of FP isotopes and some other meterials measured in STEK", ECN-10(1976)

Table 12 (continued)

/14/ Langlet and Martin-Deidier, contribution to RP 14 of this meeting . Published in INDC(NDS)-87 (1978). ("French oscill." means: ERMINE and MASURCA oscillation experiments)

/15/ T.L. Anderson, AE-428 (1971)

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/17/ N. Yamamuro, private communication 1977

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IV.5.2. Recommendations

(i) - New measurements of differential fast capture cross sections are recommended for the following FP (see also Table 12, "actions"):

Tc99, (Ru102,104), Pd105, I127, Pm147, Sm151;

- Additional integral irradiation measurements of fast neutron capture cross sections would be of value for:

Tc99, Ru101, Pd105, Pd107, Cs135 and Sm151;

- New evaluations are recommended for all FP whose differential or integral capture cross sections do not meet the required accuracies. Some nuclides like Ru103 and Cs135 have isotopic neighbours whose capture cross sections have been measured recently. In these cases the required data may be deduced from systematics; nevertheless the determination of some data (e.g. resolved resonances) of the nuclides themselves would improve the quality and reliability of the systematics and the evaluated data.

(ii) Because evaluations of fast neutron cross sections are partly based on nuclear models, the following recommendations are considered as important:

- The methods of determining average parameters from resolved resonance parameters should be improved. This could for instance be done through an intercomparison of available methods by computer simulation, preferably on an international basis. It was suggested that P. Ribon could act as coordinator of such an international project, with the support of IAEA/NDS.

- Strong support should be given to the evaluators of level scheme data.

- It is recommended that IAEA/NDS organize a specialist meeting on the systematics of all parameters needed in model calculations of 'neutron cross sections'.

- Evaluators should make use of the recent developments in nuclear theory, in close cooperation with fundamental physicists. Important developments are e.g.: recent statistical model improvements, SPRT method for optical model parametrization [75Del] and inclusion of direct collective effects to calculate inelastic scattering cross sections (see also the recommendations of the Consultants Meeting on Nuclear Theory in Neutron Nuclear Data Evaluation, Trieste 1975 [75Tri]).

(iii) There is a large number of recent microscopic capture cross section data which have not yet been included in the present evaluations. Moreover many experiments on differential and integral data are ongoing. It is therefore recommended that:

- A specialist meeting on the status of capture cross sections for FP should be organized in a few years time. Both experimentalists and evaluators should re-examine the cross section status.

(iv) With respect to the role of integral data the following recommendations are made:

- It is recommended to use various integral data obtained at different facilities to derive adjusted capture cross sections.

- For the convenience of the cross section data users, the results of integral measurements should be incorporated in evaluated point cross section libraries, preferably in one of the well-known formats.

- It is recommended that further integral measurements, in particular irradiation measurements in fast power reactors (or prototypes) are performed for a number of important unstable FP nuclides (see Table 12).

- For the estimate of the bulk FP effect on sodium void reactivity, integral experiments would be of help; the necessity of such experiments must however be confirmed by feasibility studies.

- As "standard" for integral measurements the nuclide Rh103 is suggested. Also I127 could be used but the microscopic data for this nuclide have to be improved first.

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