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STATUS OF FISSION PRODUCT YIELD DATA FOR THERMAL REACTORS

= RP 11a FPND - Panel

by

W.H. WALKER

Review Paper 11a for the I.A.E.A. Panel on Fission Product Nuclear Data, held at Bologna, Italy, November 26 to 30, 1973

(IAEA-169, vol. 1, 285 (1974))

Chalk River Nuclear Laboratories

Chalk River, Ontario

February 1974

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Données actuelles sur les rendements de fission des réacteurs thermiques*

par

W.H. Walker

*Communication 11a présentée au Colloque de l'AIEA sur les données nucléaires relatives aux produits de fission, tenu à Bologne, Italie, du 26 au 30 novembre 1973. (AIEA-169 Vol.1, 285(1974).

Résumé

Les méthodes servant à mesurer les rendements de fission font l'objet de commentaires. Des rendements en chaîne mesurés et évalués à partir de la fission, par neutrons thermiques, de ^{233}U, ^{235}U, ^{239}Pu et ^{241}Pu sont passés en revue et les rendements évalués sont comparés dans une annexe. Les rendements mesurés, directs et fractionnels, qui présentent un intérêt pour les calculs de réacteur, font l'objet de commentaires et ils sont compilés dans une annexe. Les quelques données relatives aux rendements cumulatifs de fissions obtenues par des neutrons épithermiques à faible énergie sont notées et leur intérêt pour les calculs de réacteur est estimé.

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ABSTRACT

Methods of measuring fission product yields are discussed. Measured and evaluated chain yields from thermal neutron fission of ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu are reviewed and evaluated yields are compared in an appendix. Measured fractional and direct yields of interest in reactor calculations are discussed and compiled in an appendix. The few data on cumulative yields from fission by low energy epithermal neutrons are noted and their significance in reactor calculations estimated.

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1. SUMMARY

Fission products affect reactors in many ways. Calculations of all these effects depend on fission product yields and hence on their accuracy. The dependence on accuracy may be high, as in the case of neutron absorption in ^{135}Xe and fuel burnup determinations [1] or low, as in the case of total energy release [2] [3] [4] or the average β-decay energy per fission.

Since the purpose of this meeting is to assess the current status of fission product nuclear data from the practical rather than fundamental scientific viewpoint, the end product of this review is a recommended set of chain yields for thermal fission of ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu, and an assessment of their uncertainties. Measured direct yields are not numerous enough to permit such a set. The main problem areas for both chain and direct yield measurements are noted.

1.1 Contents of Review

The bulk of this paper will discuss the data and evaluation procedures on which the recommended values are based. This is done in the context of a brief historical review of yield measurements and their development. The advantages of each type of yield measurement and their sources of systematic errors are discussed.

A comparison of yield values indicates that many data do include systematic errors and it is essential that these systematic errors be taken into account. In only a few cases can errors be assigned to a particular yield value, which may then be corrected or rejected. An evaluation procedure is proposed that will enhance the probability of recognizing the presence of unidentified systematic errors and reduce the probability of assigning too great a weight to a yield containing a large systematic error.

Five recent evaluations of cumulative yields [5] [6] [7] [8] [9] are compared to the proposed procedure. On the basis of a comparison of their recommended yields and data on which they are based, sets of cumulative yields for the thermal neutron fission of ^{233}U, ^{235}U, ^{234}Pu and ^{241}Pu are recommended.

Information on direct yields is sparse as compared to that for cumulative yields. For ^{235}U these have been reviewed recently by Wahl [10], Denschlag [11] and Amiel and Feldstein [12], primarily to establish the parameters of a semi-empirical model of charge dispersion.

In this paper only direct yields of interest in fuel burnup and decay heating calculations are considered. It is apparent many more measurements are required before we can dispense with a semi-empirical model of charge dispersion to predict direct yields, particularly in ^{233}U, ^{239}Pu and ^{241}Pu thermal fission.

Finally the few data on cumulative yields from fission by epithermal neutrons are listed and their significance is discussed briefly.

1.2 Yield Compilations and Evaluations

The remainder of this summary is intended to give the "state of the art" in compiling and evaluating and the status of measurements of chain yields, fractional yields and epithermal yields.

In compiling yield measurements for evaluation the most obvious problem is the large number to be dealt with. For example, Meek and Rider [9] list over 17000 data cards, of which about 3000 are used in calculations of cumulative and direct yields from thermal fission. Some of these data have been re-examined recently, but much similar work is required before they can all be certified as valid.

Five evaluations of cumulative yields have been published in the last two years, culminating preparatory work that in some cases began nearly ten years ago. The number is remarkable in comparison to the average rate of publication of such evaluations in the preceding two decades.

The problem presented by the large amount of yield data has been tackled in two ways. Meek and Rider [5] [9] and Crouch [6] record all their data in a computer file after assessing the accuracy of each value, and then evaluate the data by computer on a mass-by-mass basis. Walker [7] [13] and Lammer and Eder [8] concentrate on mass spectrometric measurements to establish, with relatively high precision, the dependence of yield on mass for about 90% of the yield of a particular fissile nuclide, and use radiometric data mainly to fill in the remaining 10%.

This concentration of effort on yield evaluation has not been wasteful duplication because each has contributed something significantly different in procedure or insight into the sources of disagreement. Even more valuable, from the viewpoint of this meeting, is the extensive weeding out of the inevitable errors which are more easily located when one set is compared to another. This is a process which would otherwise take many years and might never be done satisfactorily.

1.3 Status of Chain Yield Measurements

Yields of ^{235}U fission products are much the best known. Not only have they been measured more frequently, but there are fewer disagreements, perhaps an indication that the work was done more carefully.

For reactor calculations the most serious uncertainties are in the yields of the Sm isotopes. These result from a 15% spread in mass spectrometric measurements of the atom ratios of fission product Sm and Nd.

Yields from ^{235}U fission are used frequently as reference standards. They would be more reliable for this purpose if the yields so far neglected were measured, particularly in the valley between light and heavy mass peaks of the yield curve, and if the remaining disagreements were resolved.

Thermal cumulative yields for ^{233}U are acceptable. The lack of serious disagreements however, may be merely a reflection of the scarcity of measurements.

For both ^{239}Pu and ^{241}Pu additional measurements are required. These include the ^{103}Ru and ^{106}Ru yields, the Kr/Xe ratio and the Cs yields. New data are required for the Pd-In range, particularly since the yields are much higher from fissile Pu than from fissile U.

If the ^{235}U yields are established more firmly by new measurements, then relative yields measurements using Ge (Li) gamma detectors can provide a rapid and reliable method of determining additional ^{233}U, ^{239}Pu and ^{241}Pu thermal yields, as well as fast neutron yields.

1.4 Status of Direct Yield Measurements

For fission product heating calculations, direct or cumulative yields of 3 or 4 isobars are required for each mass. Even if this requirement is restricted to masses with yields exceeding 1%, nearly twice as many direct yields are required as there are chain yields.

For ^{235}U there are cumulative or direct yields for about 70% of the nuclides in this category, but even here, for a substantial fraction, either there are significant disagreements or only one measurement has been made.

For ^{233}U, ^{239}Pu and ^{241}Pu very little data exists and calculations will have to rely on a set of direct yields based on a semi-empirical model fitted to ^{235}U data.

1.5 Status of Epithermal Fission Yield Measurements

The peak-to-valley yield ratio is a measure of symmetric to asymmetric fission. Using this ratio it has been established that yields from the first resonance at 0.3 eV in ^{239}Pu are much more strongly asymmetric than for thermal fission, i.e. the yields in the valley between peaks in the mass yield curve are much reduced. Changes have also been observed for ^{235}U and ^{233}U fission, but are much smaller.

The effect of these changes on reactor calculations will be negligible if only the very small yields change appreciably, but changes in large yields near the peaks are also possible. At present, the best experimental evidence available indicates that such changes are 3% or less.

In some reactor calculations epithermal yields are found by interpolation between thermal yields and reactor spectrum yields. Since the latter are enhanced in the symmetric fission mode, such interpolations could lead to small errors if they are applied below about 100 eV.

2. FISSION PRODUCT YIELD MEASUREMENTS

2.1 A Brief History

The first yield measurements were made by Hahn and Strassman [14] when they detected the presence of radioactive Ba and thus established that their uranium target was fissioning rather than capturing when bombarded with slow neutrons.

Soon after that it became apparent that fission into fragments of approximately equal mass had a small probability, and the first phase in yield measurements was concerned with establishing quantitatively the double-humped dependence of yields on fission product mass.

These early distributions had many disagreements and certainly did not give a smooth variation of yield with mass. Initially wide deviations from a smooth curve were attributed, with good cause, to uncertainties in the measured yields, but, as techniques were refined, some anomalies persisted. These became known as "fine structure". In the second phase, beginning in the early 1950's, the main interest in yield measurements was in determining the location and magnitude of fine structure, and explaining it in terms of the shell model of the nucleus.

By the early 1960's the majority of chain yields in ^{235}U, ^{233}U and ^{239}Pu fission had been measured. In the third phase,interest, particularly among radiochemists, turned to measuring direct yields of fission products and their isobaric distribution immediately following neutron emission, and in testing several hypotheses intended to predict that distribution.

In the mid-1960's, as more and more power reactors came into operation, it became important to determine fuel burnup not only for assessing reactor performance, but also for fuel processing and safeguard inventories. Fission products can be used for this purpose if their yields are known accurately. Several nuclear energy laboratories were active in this fourth phase of yield measurements, with the most extensive work being done at Idaho Falls [15].

During the same period Ge(Li) γ-ray spectrometry was used to determine the yields of radioactive fission products having half-lives of about an hour or longer. More recently these detectors have been used to measure yields of short-

lived fission products including direct and cumulative fractional yields [90]. These measurements should have their greatest application for ^{233}U and ^{239}Pu fission since the direct yields of longer-lived nuclides is expected to be greater for these fissile nuclides than for ^{235}U and ^{241}Pu.

2.2 Methods of Yield Measurement

Each of the phases listed in the preceding outline was associated with the development of a particular method of measurement, or a significant improvement in an established method.

2.2.1 Radiochemistry, Absolute Yields

This is the oldest method of measuring yields, the method of Hahn and Strassman. It played the major role in the first phase of yield measurements.

Briefly the fissile material is irradiated and dissolved. The solution is treated chemically to separate a particular fission product element or group of elements. The separated product is placed in a radiation detector and its counting rate is measured as a function of time. The number of fission events must also be determined.

The samples are β-counted except in cases where a γ-ray emission probability is well known. Originally thin-window or thin-wall Geiger-Müller counters were used. For later β-counting the sample was placed inside a gas-flow counter with high geometry. Counts from different isotopes were resolved using half-lives and β-spectrum end-point energies (or transmission through filters).

Because radiochemical yield measurements can be made with very small samples it is the preferred method for determining low yields such as chain yields at near-symmetric and very asymmetric fission, and direct yields.

2.2.2 Radiochemistry, Relative Yields

Once the yield of one radioactive fission product is known precisely, it can be used as an internal monitor of the number of fissions. Favorite fission products to fill this role are Mo^{99}, Ba^{140} and Cs^{137}. This procedure was used for many of the later measurements of the first phase, and is the one most widely used in the determination of charge distribution.

The advent of Ge(Li) detectors and the subsequent accurate determinations of γ-ray emission probabilities for many radioactive fission products has greatly improved the ease and accuracy of relative yield determinations.

2.2.3 Radiochemistry, R-Value Method

When ^{235}U yields became reasonably well-known it was possible to eliminate one of the major sources of uncertainty in radiochemical measurements - those due to errors in estimating geometric losses and in counting corrections arising from uncertainties in the decay schemes.

To do this, samples of two fissile atoms are irradiated together and each is processed to obtain the fission product elements to be counted. Let the subscript "r" refer to the "reference" fissile nuclide, the one for which the yields are assumed known; "u" to the "unknown" fissile nuclide for which the yields are to be determined; "s" to a "standard" radioactive fission product such as ^{140}Ba; and "x" to the fission product for which the yield in the unknown is required. If A refers to a measured activity corrected to a chosen time such as the end of the irradiation and y refers to yield, then the R-value is defined as the ratio of activity ratios given by,

$$R = \frac{A_{ux}}{A_{rx}} \frac{A_{rs}}{A_{us}}$$

The required yield is given by

$$y_{ux} = R(y_{rx}\, y_{us}/y_{rs})$$

Note that the yield y_{us} must be known in addition to those of the reference fissile nuclide.

This method reduces the chance of errors due to processing losses but does not eliminate them since identical treatment of different fissile materials need not lead to equal recovery of a particular element.

For a discussion of experimental techniques with references to the original work the recent review by von Gunten is recommended [16].

2.2.4 Mass Spectrometry

Mass spectrometers have been used in fission product yield measurements since the mid-1940's. As in radiochemical measurements the irradiated fissile material must be dissolved and the various elements separated.

Mass spectrometers give the relative abundances of the isotopes of the element under study. These cannot be converted to yields without further measurements or assumptions. In the earlier work they were normalized to an assumed yield at a particular mass, usually based on a radiometric measurement. For adjacent elements with isotopes alternating in mass, for example ^{104}Ru, ^{105}Pd, ^{106}Ru(1 year), ^{107}Pd, the yields might or might not vary smoothly with mass depending on the relative magnitudes of the two normalizing yields.

This uncertainty in normalization was a serious problem in measurements of fine structure. In order to improve the relative normalization of adjacent elements, the techniques of isotope dilution and isobaric coupling were perfected, notably at McMaster University. The use of these techniques is discussed in greater detail elsewhere [7] [8] [17].

Mass spectrometry provides an accurate method of determining burnup as well as fission product element yields provided the sample is irradiated long enough to change the number of fissile atoms significantly. Lisman et al [15] used this technique to determine the absolute yields from thermal neutron fission of ^{233}U and ^{235}U.

Mass spectrometric measurements require relatively large samples and have, until recently, been restricted to the higher yield elements, Kr through Ru and Xe through Sm.

2.2.5 γ-Spectrometry

The advent of solid state detectors permitted a quite new approach to radiometric yield measurements. The essential difference from radiochemical methods is that no chemistry is performed on the irradiated samples. Rather, they remain sealed during both irradiation and counting so that there is no problem of fission product losses. If the fission products are separated chemically and then counted with a Ge(Li) detector the data is treated, in this review, as radiochemical.

Background rates in the sealed samples are quite high and this limits application of the method to yields $\gtrsim$ 1% and γ-ray emission probabilities $\gtrsim$ 10%. Both limits can be lowered if the background is reduced using Compton detectors in anti-coincidence.

γ-spectrometry can be used to determine yields either absolutely [18], or with the R-value technique of section 2.2.3 [19] [20] or by comparing fission product γ-rays from the irradiated sample with standard sources prepared chemically from relatively large samples [21]. Of these the R-value technique appears to have the greatest potential since it can be used for fast fission yields and direct or cumulative yields of short-lived nuclides.

2.2.6 Miscellaneous Methods

The following methods have been either used in special situations or developed as alternatives to the preceding methods, but have never been applied widely.

(i) Volumetric determination of rare gas fission products - the ratio of Xe to Kr was determined [22]. The claimed accuracy was high but the ratio disagrees with that for currently accepted yields by $\sim$ 11%.

(ii) Integrated current mass spectrometry - the current of ions at each mass was determined absolutely using measured ionization efficiencies for each element [23]. The method appears to have considerable potential, especially for the determination of monoisotopic fission product elements such as Tc and Pr but was never perfected. The isotopic ratios reported for multi-isotopic elements were so different from those measured by conventional mass spectrometric methods that all data must be suspect [7].

(iii) Pile oscillator - the relative yields of ^{135}I from ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu thermal fission were

determined from the relative magnitudes of the ^{135}Xe absorption transient [24] [25]. The accuracy is determined by the estimated number of fissions occuring in each sample.

(iv) Vapor phase chromatography - used by Lisman et al. [15] to determine the number of atoms of fission product Xe and Kr.

(v) Spectrophotometry - to determine the yield of ^{99}Tc [15].

(vi) On-line mass separator - a beam of fission fragments is separated according to m/e by a double-focussing mass separator and collected on photographic plates. After most of the fragments have β-decayed the plates are developed and the number of β tracks at the end of each fission fragment track are counted. From this information the charge distribution for each mass can be determined.

The method is limited to mass ranges where interference between beams with different m and e values is small. The most extensive data to date gives yields for the masses between 131 and 140 [26].

2.3 Sources of Error in Yield Measurements

2.3.1 Number of Fissions

In the early radiochemical measurement of absolute yields this was one of the most serious sources of error because both flux and fission cross section were poorly known and the number of fissile atoms was difficult to determine.

In more recent radiochemical work this problem may be less serious provided measurements of well-established yields are included. Then, even if a significant error has been made, its presence can often be recognized and corrected for by treating the measurements as relative rather than absolute yields.

In mass spectrometric work the numbers of fissions have most frequently been determined, as in radiochemistry, using a flux monitor, a determination of the number of fissile atoms and an estimate of the fission cross section. The most reliable method is mass spectrometry of the fissile sample after irradiation [15]. In evaluation of mass spectrometric yields (section 3) summing the total yields to 100% in the light and heavy masses provides a reliable alternative.

2.3.2 Normalization of Relative Yields

The use of a standard yield not only avoids determining the number of fissions directly but also provides a straightforward method of updating the measurements as knowledge of the standard yield improves. The main sources of error are:

(i) uncertainty in the standard yield

(ii) processing losses of the standard nuclide (the nuclide with the standard yield)

(iii) incorrect decay data for the standard nuclide

(iv) errors in the counting corrections for the standard nuclide.

The first can be greatly reduced if the standard nuclide has an isobar for which the yield has been determined mass spectrometrically, such as ^{140}Ba or ^{144}Ce, rather than otherwise (^{99}Tc, ^{141}Ce). Corrections can be made for the last two errors if sufficient information on the original corrections is given.

2.3.3 Processing Losses

All of the element of interest may not be recovered in the chemical extraction. In radiochemistry the amount of fission products is very small and a carrier element is usually added to facilitate extraction. Repeated extractions can be used to obtain full recovery provided the fission product is converted to the same chemical state as the carrier. In some cases losses can be monitored with a γ-detector.

R-value results may also be affected, especially if the two fissile atoms are isotopes of different elements such as U and Pu. In this case differences in chemistry may lead to different losses of a particular fission product element.

In mass spectrometry, processing losses will not affect isotope dilution measurements provided all of the fissile sample can be dissolved.

2.3.4 Contamination

Contamination with naturally occurring elements may occur in the preparation of the fissile sample, in the dissolution of the irradiated fissile sample, in the separation of a particular element during isotope dilution, or on the mass spectrometer filament.

Only the first type of contamination can affect counting measurements, but a greater range of contaminants may be troublesome since chemically similar elements may be isolated with the element of interest and interfere in the counting.

All of these sources of contamination can affect mass spectrometry and are probably the main source of error in isotope dilution measurements. In many cases, such contaminants can be recognized by the presence of isotopes not formed in fission and the necessary corrections made. Elements where this is not the case, or where such isotopes have such a low abundance in the naturally occurring element that they are very insensitive contamination monitors are Rb, Cs, Ba, and Ce.

2.3.5 Decay Data (Half-Lives, β- and γ-Energies, β- and γ-Emission Probabilities)

Corrections can readily be made for changes in these data if the experimenter lists all relevant input. Unfortunately most do not. All radiochemical measurements except those using R-values are subject to these errors. Some mass spectrometric yields must be corrected for β-decay and are therefore affected by uncertainties in the half-life involved.

2.3.6 Neutron Capture

Usually, only mass spectrometric samples are irradiated sufficiently that the measured isotopic abundances need to be corrected for neutron capture. For non-saturating fission products, such as ^{131}Xe or ^{143}Nd, this correction can be calculated accurately and is often negligible. For ^{135}Xe and ^{151}Sm, the corrections can be very large and sometimes impossible to calculate accurately. ^{149}Sm differs in having as capture product a shielded isotope, ^{150}Sm, so that the sum of the ^{149}Sm and ^{150}Sm abundances is equal to the ^{149}Sm yield except for small corrections.

2.3.7 Counting Corrections

These are the most widespread cause of error in β- and γ-counting. They include:

(i) Loss of radiation by absorption in the sample, air gap, and detector housing

(ii) Backscattering of β's from the mounting material

(iii) Counting losses in the detector (end-effects, ion recombination)

(iv) Counting losses in the associated electronics (deadtime, pile-up)

(v) Interfering activities, background subtraction.

In most experiments there may be corrections for these effects, but these depend on the state of knowledge at the time of the experiment.

The accuracy of these corrections, assuming they have been made in the data, is difficult to assess at a later date. However, it is to be expected that this accuracy will improve with time. For this reason, older radiochemical data are usually assigned a larger uncertainty than more recent results.

2.3.8 Magnitudes of Errors

The preceding review of sources of error has been qualitative for the good reason that the magnitude of a particular type of error depends as much on the experimenter as on the method. Also, although an evaluation may indicate that a certain yield contains a systematic error, the cause of the error can be identified only rarely.

A quantitative estimate of errors by the evaluator is essential for two reasons:

TABLE 1 - Summary of Possible Errors and Estimates of Percent Error in a Single Yield

	Radiochemistry			Mass Spectrometry[a]	γ-Spectrometry		
	Absolute	Relative	R-value		Absolute	Relative	R-value
Number of fissions	x	-	-	x	x	-	-
Normalization to standard yield	-	x	x	x	-	x	x
Normalization to reference yield	-	-	x	-	-	-	x
Processing losses	x	x	x	x	-	-	-
Contamination	x	x	x	x	x	x	x
Decay data	x	x	-	x	x	x	-
Neutron capture data	-	-	-	x	-	-	-
Counting corrections, β	x	x	x	-	-	-	-
Counting corrections, γ	x	x	x	-	x	x	x
Error assignments (%)							
- maximum	20[b]	20[b]	10[b]	10[c]	10	5	5
- minimum	4	4	3-4[d]	1[e]	4	3-4[d]	2-3[d]

a Isotope dilution or isobaric coupling.

b For radiochemical data measured about 1950. Errors for intermediate dates are interpolated linearly.

c Based on the evaluation of mass spectrometric data in [7]. Most data with errors this large were discarded.

d Minimum errors will depend on the error assigned to the normalizing value.

e The estimated error in normalizing evaluated data to 100% [7]. Mass spectrometric yields will also include in their errors the uncertainties in isotopic dilution or isobaric coupling and in isotopic abundances.

First, the errors assigned by the experimenters are based on a variety of criteria. They may include an estimate of systematic errors or simply represent the statistical uncertainty in multiple measurements. The error may be the average deviation, standard deviation in the mean, the 95% confidence limit or simply half the spread between maximum and minimum results. These variations can be reduced if the evaluator assigns his own errors.

Second, a set of yields may disagree by much more than indicated by the assigned errors, indicating the presence of unidentified systematic errors. If these cannot be isolated by closer examination of the data, the most satisfactory way to deal with the data is to increase the assigned errors until the discrepancy "disappears".

Table 1 summarizes the sources of error described in the preceding sections, and then gives the percentage errors recommended for the various types of measurement. These errors are to be treated as root mean square (rms) deviations.

The procedure recommended is to assign errors to radiometric and other yields with a partial linear time dependence, say from 4% for recent measurements to 10% for early (c.1950) measurements. If these are not sufficient to account for the differences in values after rejecting obviously errant values, the upper limit should be increased so the range covers 4% to 20%. Finally, if this is still insufficient, all errors should be increased by equal amounts, added in quadrature, until the assigned errors do account for the differences.

3. EVALUATION OF CHAIN YIELDS*

In determining chain yields the evaluator must deal with a very large amount of data obtained by a variety of methods. For some fissile nuclides and some masses the yields have been measured many times, for others, never. Some data agree, others differ by many times the claimed error. How should the evaluator proceed?

The solution, in essence, is to retain the special contribution of mass spectrometric data, namely, the accurately known ratios of isotopic abundances, while at the same time making full use of the radiochemical and γ-spectrometric yields. A simple example illustrating how a mass-by-mass analysis can affect yield ratios is given below for a hypothetical element with two fission product isotopes.

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* In this section no distinction is made between chain yield and total yield at a given mass. Only for mass 136, where the shielded isobar ^{136}Cs has a direct yield of $\sim$1% of the chain yield for ^{233}U and ^{239}Pu fission, will the two differ significantly.

Mass spectrometric data	Ratio of yields	1.00±0.01
	Sum of yields(%)	10.0 ±0.5
	Each yield(%)	5.00±0.255
Radiochemical yields(%)	1st isotope	4.40±0.30
	2nd isotope	5.70±0.35
Weighted mean yields(%)	1st isotope	4.74±0.19
	2nd isotope	5.24±0.21
	ratio	1.10±0.6

In this case the final ratio differs from the measured ratio by 10 times the uncertainty in the latter. The reason is that the mass-by-mass evaluation takes no direct account of the measured ratio.

On the other hand the radiochemical data contains useful information about both the relative yields and total yield which should not be ignored. In the illustration the ratio of radiochemical yields is 1.19±.11 and the sum is (10.10±0.46)%, so that the weighted means of these and the mass spectrometric values are 1.009 and 10.05% respectively, and the individual yields are 5.00% and 5.05%. These would be better values to use than either the mass-by-mass weighted means or the straight mass spectrometric data.

In real life the radiochemical data is not so complete and the solution is not so simple. How the evaluation should proceed in this case to obtain analogous results is discussed in the following sections.

3.1 Mass Spectrometric Yield Measurements

Mass spectrometric yields have been evaluated in two recent reports [7, 8]. Both proceeded as follows:

(i) Corrections for β-decay and neutron capture were brought up to date if sufficient information was available. If updating was not possible the associated uncertainty in the value was estimated and the value was accepted, accepted with reduced weight or rejected on the basis of this estimate. Details of these corrections are given in [7].

(ii) The relative abundances of the isotopes of each fission product element were determined by comparing all relevant mass spectrometric measurements. Some values were rejected because they differed from the average of the remainder for that isotope by several times the root mean square (rms) deviation from that average.

(iii) The number of atoms of each fission product element were determined relative to a chosen standard element (e.g. neodymium) using isotope dilution and isobaric coupling measurements. Again a few values were rejected.

(iv) The mass spectrometric yields for the light and heavy mass peaks were normalized by equating them to 100% less the sum of radiochemical and inter-

polated yields. These non-mass spectrometric yields contribute from about 3% (^{235}U heavy masses) to 20% (^{239}Pu light masses), except for ^{241}Pu light masses where they contribute 55%. If this sum is accurate to 10% then the final normalization will be accurate to $\lesssim$2%, except for the ^{241}Pu light masses. A 2% uncertainty is comparable to that in normalization if the number of fissions were large enough to be measured by mass spectrometry of the fissile material. The two methods can be compared for ^{235}U and ^{233}U fission [7] and agree to $\sim$1% or better.

For most isotopic abundances of elements in the range Kr to Ru and Xe to Sm there are two or more measurements available for thermal neutron fission of ^{233}U, ^{235}U and ^{239}Pu so that errors can be estimated from differences in measured values. These errors are less than or about equal to 1% of the value in most cases, which is consistent with the occurrence of small or negligible systematic errors in these measurements. Where only one measurement is available the error can be estimated on the basis of other results if it is assumed that any systematic uncertainty remains small.

There are fewer data available for relative element yields and the agreement is poorer. An error of two percent is typical.

3.2 Non Mass Spectrometric Yield Measurements

Yields measured by radiochemical, γ-spectrometric and miscellaneous methods do not have the relative accuracy between masses that is a feature of mass spectrometric isotopic abundances and are best treated on a mass-by-mass basis. This can be done separately from the mass spectrometric analysis and then the two sets can be combined.

At each mass all non mass spectrometric yields should be compared, clearly discrepant values rejected and weighted means calculated using evaluator-assigned errors as discussed in section 2.3.8.

Where no mass spectrometric measurements are available this is as far as one can proceed normally, although there are a variety of less decisive tests, described in section 3.3 which may assist in choosing between two or three values at one mass when the discrepancy is large.

If both types of measurements have been made in a given mass range the greater precision of relative abundances can be brought into play as follows: the weighted mean of the non mass spectrometric yields for a given mass is divided by the isotopic abundance for that mass to obtain a set of yields corresponding to element yields as measured by mass spectrometer. The input data, non mass spectrometric yields and mass spectrometric isotopic abundances, can be adjusted to minimize the uncertainty in the "element" yield. The two element yields can then be averaged. These steps are

analogous to taking weighted averages of the relative yields and the sum of the yields in the example given in section 3.

Once correctable systematic errors have been corrected and errors assigned to account for recognized systematic errors which cannot be corrected (e.g. a known change in half-life, but no statement of irradiation or decay times, or the magnitude of the original correction) it should be possible to perform the remaining steps in evaluation by computer. An example using data for yields at masses 140, 141, 142 and 144 from ^{235}U thermal fission is given in Table 2.

Step 1: The evaluated mass spectrometric data for Ce [7] are listed. The procedures followed in obtaining these (section 3.1) are also amenable to computer treatment. The isotopic abundances are averages of five sets of measurements for masses 140, 142, and 144. There is only one measurement for mass 141.

The errors quoted are the rms deviations of a single value from the mean, i.e. $\left[\sum_{i=1}^{n} (x_i-\bar{x})^2/(n-1)\right]^{1/2}$. Here x_i is an individual measurement, $\bar{x}$ is the average, and n is the number of measurements. For ^{141}Ce (one measurement) an uncertainty of 2% in the isotopic abundance is estimated.

The total Ce yield is based on two isotope dilution measurements plus isobaric coupling at mass 144, all three giving the ratio of Ce to Nd with an uncertainty of 1%.

The non-mass spectrometric data are taken from the most recent Meek and Rider compilation [9]. Yield ratios that include ^{140}Ba are used to obtain a value for the other mass since the numerous ^{140}Ba yields agree well.* A value of 6.36% for ^{140}Ba is used. Other measured yield ratios are normalized to the recommended yields of [7].

To be directly comparable, measured yields of radioactive isobars should be corrected to take account of the fact that the cumulative yields may decrease with decreasing atomic number (Z) because of significant direct yields to higher Z isobars. For most nuclides used to determine chain yields the estimated fractional cumulative yield is greater than 0.99 of the chain yield. This is the case for masses 140 - 144 in ^{235}U fission so no correction is needed. For the few cases where the cumulative yield is ≤ 0.99 of the chain yield the measured cumulative yield should be divided by the fractional cumulative yield to obtain a value of the chain yield.

The errors assigned by the experimenter follow the yield preceded by ±. Errors assigned in this evaluation follow in brackets.

Step 2: Here we are concerned with rejection of discrepant data. Assigned errors depend too greatly on

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* These yields were later found to require a variety of corrections as shown in Appendix C. The agreement is not as good as indicated in Table 2.

TABLE 2 EXAMPLE OF EVALUATION USING ^{235}U YIELD DATA

Mass Chain	a	140*	a	141	a	142	a	144	Total
1. Starting Values									
Evaluated mass spectrometric data } Ce Isotopic abundances	7	0.2704±0.0032	7	0.2482±0.0050	7	0.2522±0.0043	7	0.2292±0.0030	
Ce Yields (%)	7	(6.39±0.12)		(5.86±0.15)		(5.96±0.13)		(5.41±0.11)	23.62±0.33
Non mass spectrometric yields - renormalized values (%) ± original error with evaluator assigned error in brackets		Ba		Ce		La		Ce	
	27	6.17±0.13(0.62)	36	6.0 (0.6)	18	5.70±0.21(0.23)	36	5.30 (0.53)	
	28	6.40±0.64(0.64)	15	5.46±0.34(0.34)		Ba	18	5.79±0.43(0 43)	
	29	6.25±0.13(0.59)	18	5.76±0.17(0.23)	38	5.08±0.43(0.43)			
	30	6.32±0.24(0.58)	21	5.81±0.06(0.17)					
	31	6.36±0.12(0.46)	32	5.87±0.28(0.31)					
	33	6.36±0.32(0.32)		La					
	34	6.29±0.14(0.25)	37	6.37±0.14(0.52)					
	18	6.40±0.11(0.26)		Ba					
	35	5.77±0.30	38	5.45±0.32(0.38)					
			39	4.6					
2. Average non mass spectrometric yields with rms deviation									
(a) All values (%)		6.26±0.20		5.67±0.52		5.39±0.44		5.55±0.26	
(b) With omissions (%)		6.32±0.08		5.82±0.32		---		---	
omitted values (%)		5.77		4.6					
3. Weighted mean of nms yields with omissions, using evaluator-assigned errors; ± error based on weights; in brackets, weighted deviation from mean		6.34±0.35 (±0.05)		5.78±0.26 (±0.20)		5.56±0.20 (±0.23)		5.60±0.20 (±0.13)	
4. LSF fit using nms yields of step 3									
Isotopic abundances		0.2717±0.0024		0.2481±0.0046		0.2503±0.0028		0.2299±0.0024	
Total yield (%)									23.37±0.33
5. Weighted mean of nms and mass spectrometric total yields (%)		(6.39)		(5.83)		(5.88)		(5.40)	23.50±0.23
Results from mass-by-mass evaluation									
Crouch [6]		0.2711±0.0025		0.2445±0.0075		0.2518±0.0035		0.2325±0.0050	23.31±0.21
Meek and Rider [5]		0.2679±0.0030		0.2487±0.0075		0.2525±0.0028		0.2309±0.0026	23.57±0.19
Meek and Rider [9]		0.2714±0.00		0.2394±0.00		0.2549±0.00		0.2343±0.00	23.78±0.00

* A revised set of ^{140}Ba input data is given in Appendix C. Values in steps 4 and 5 have been corrected to agree with the revised mass 140 chain yield ((6.39 ± 0.10)%).

(a) References for listed yields.

personal judgment to be reliable for this purpose so the data are simply averaged and the rms deviation calculated. The most deviant result is then omitted and the process repeated. If the omitted value differs from the average by more than three times the rms deviation it is not included in any of the following steps.

There seems to be no logical case for retaining such a discrepant value. Either it is wrong, due to a systematic error, the other measurements of the same yield are wrong, or none of them is right. In any case, no mixture obtained by judicious weighting is likely to give the correct answer. If rejections were done by computer the omitted results would be noted and the evaluator would make a personal judgment on the validity of the rejection before accepting the results.

In Table 2, two values are deleted by this criterion. At masses 142, with only 2 values available, the rejection criterion is inoperative.

Step 3: Weights are taken as the inverse squares of the evaluator-assigned errors and the weighted means calculated. Two errors are calculated for each mean, both approximately equivalent to the rms deviation. The first, following the ± sign, is based on the weights, w, and is given by

$$e_w = \left[(n-1)/\sum_{i=1}^{n} w_i\right]^{1/2}$$

The second, enclosed in brackets, is based on deviations of the individual values from $\bar{x}_w$, the weighted mean. It is given by

$$e_d = \left[\sum_i w_i (x_i - \bar{x}_w)^2 / \sum_i w_i\right]^{1/2}$$

If e_d is significantly greater than e_w, say 30%, the assigned errors should be increased following the pattern recommended in section 2.3.8 until $e_d \approx e_w$.

If $e_w >> e_d$, as for ^{140}Ba, the reverse procedure could be followed, but this is unlikely to change the weighted mean appreciably. To make $e_w \approx e_d$ in the case of ^{140}Ba, the errors assigned each value would be about 1%.

In subsequent steps the weighted means carry the larger error except for ^{140}Ba, where it is set at ±0.10.

Step 4: The weighted means of the non mass spectrometric yields from step 3 can now be combined with the mass spectrometric data. Dividing the weighted non mass spectrometric yields by the isotopic abundances from step 1 gives four estimates of the total yield of the four masses. These are 23.44±0.36%, 23.29±1.15%, 22.05±0.87% and 23.73±0.93% for masses 140 to 144 respec-

tively. These values could be combined with the mass spectrometric total yield to obtain a best value, but this would not take account of differences between ratios of the weighted means yields of step 3 and the isotopic abundances measured mass spectrometrically.

To do this both sets of data with their errors, are supplied to an iterative least squares program, LSF[40], which adjusts them to minimize the error in the non mass spectrometric total yield. The results are shown. The isotopic abundances have changed significantly to allow for the non mass spectrometric yield ratios, but by less than their assigned errors.

Step 5: The weighted mean of the two total yields (step 1 and 4) is calculated. The values in brackets on the same line are the chain yields for the four masses. They are the product of the total yield, 23.50 and the isotopic abundances of step 4.

The table is completed with 3 sets of evaluated data. Of these only one [9] is based on the complete set of non mass spectrometric data given in Table 2. Since the other two include all the mass spectrometric yields these predominate in the least squares fit, especially for masses 141, 142 and 144, so that their results would not be expected to differ greatly from the input mass spectrometric data of step 1.

3.3 Completing the Evaluation

3.3.1 Relative Yields and Iterations

Many non mass spectrometric yields are relative, and must be normalized to a preliminary value for the standard yield for inclusion in step 1 of Table 2. The final value of the standard yield may differ from the preliminary value. If this difference exceeds a pre-selected limit, say 0.5%, the relative yields should be recalculated and the evaluation repeated.

Relative yields may serve another purpose. If a systematic error occurred in the preparation or counting of the standard in one measurement of relative yields, or if the final value for the standard yield is influenced by systematic errors in one or more of the measurements on which it is based, calculating the ratios of each value derived from a relative yield to the recommended value for that yield may indicate the presence of the error.

For example, if the average yield ratio for all relative yields in one set of measurements differs significantly from unity the first type of error is indicated. If the average yield ratio for all relative yields based on one standard yield differs significantly from unity the second type of error may be the cause.

In both cases the evaluator should re-examine the data. The simplest solution for the first type of error is to use another nuclide as standard. Yields having the second type

of error will be difficult to locate since they would have been eliminated earlier in the evaluation if clearly discrepant.

3.3.2 Estimated Chain Yields

After completing the evaluation of all measured yields the most vital remaining requirement is to estimate the chain yields for masses where there are no measurements. The theoretical and empirical methods available for making these estimates are discussed by Musgrove et al. [4].

3.3.3 Normalization

The chain yields for the light and heavy fragments should each add to 100%, i.e. 2 fragments per fission. The correct division between light and heavy masses will depend on $\bar{\nu}_{sym}$, the average number of prompt neutrons emitted by fragments near symmetric fission, i.e.

$$\text{light masses} < (A_f - \bar{\nu}_{sym})/2 < \text{heavy masses}$$

where A_f is the mass of the fissioning (compound) nucleus.

Experimental results for neutron emission are uncertain in this region because of the low chain yields, but most lie between 3 and 4 neutrons per fission, at least for ^{235}U fission [10]. A value of $\bar{\nu}_{sym}=3.5$ is suggested for normalization.

3.3.4 Yield Symmetry

If all fragments emitted the same number of neutrons, the curves fitted to the light and heavy mass yields would superpose almost perfectly on reflection about the mean fission product mass.

Significant differences observed between the reflected curves are attributed to changes in $\bar{\nu}_m$, the average number of neutrons emitted at mass m.* Differences are most apparent near the yield maxima where the yields are known most accurately, ranging up to 25% (compare yields at masses 135 and 102 in ^{239}Pu fission). It would be surprising if much larger differences occurred in other mass ranges.

In cases where two or three yields differ by much more than the sum of their errors a comparison with the curve through the complementary mass may indicate that one value is much more likely to be incorrect. On this basis the relative mass spectrometric abundances of tin isotopes [43] were omitted in one evaluation [7].

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* Values of $\bar{\nu}_m$ can be determined from a comparison of fission fragment and chain yields as described by Terrell [42]. These values of $\bar{\nu}_m$ are in satisfactory agreement with measured neutron emissions for most masses in the case of ^{235}U thermal fission [10].

3.3.5 Average Number of Neutrons per Fission ($\bar{\nu}$)

The average number of neutrons per fission is equal to the difference in the number of nucleons before and after fission, i.e.

$$\bar{\nu} = A_{fission} - \sum_i y_i A_i$$

where the A's are nuclear mass numbers.

If the evaluated set of yields is correct $\bar{\nu}$ calculated in this way will equal the recommended value [44]. Unfortunately the reverse is not true, nor can a significant inequality indicate in what way the yields are incorrect.

The calculated value of $\bar{\nu}$ depends on the division into light and heavy yields discussed in section 3.3.2. The transfer of one yield from the heavy to the light group increases the calculated value by an amount comparable to the uncertainty in the recommended $\bar{\nu}$ values.

3.4 A Comparison of Recent Evaluations

This comparison is restricted to 5 recent evaluations. Lammer and Eder [8] give a good summary of earlier work. In the following section the methods used in the evaluations are discussed in the context of the proposed procedures of section 3.1 - 3.3 and the mass-by-mass comparison appears in Appendix A.

3.4.1 Meek and Rider [5]

This is the 5th revision of the earliest available computerized data library and evaluation. The data library is intended to include all yield measurements* and some evaluations. It appears to have achieved this aim. The data is not yet free of errors since it has accumulated a number of duplications and outdated values. Many of these were eliminated in succeeding revisions and the process is still going on.

Only a few corrections for changes in half-life and cross section are included in this edition. Each yield in the data file has both a measurer-assigned and evaluator-assigned error. Lower limits for the latter are 1% for mass spectrometric yields, 4% for other measured yields, and 10% for estimated yields. Yields considered discrepant are rejected. If there are no measured yields, an estimate is inserted as input data.

For each mass the weighted mean is calculated using as weights the inverse squares of the evaluator-assigned errors. All measured yields and most evaluated yields are included. The influence of the latter is usually minimized by assigning large errors.

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* For fission by thermal, reactor and high energy neutrons; direct, cumulative and chain.

Mass spectrometric relative abundances are not treated separately as recommended in section 3.2. However relative yields, in which they are included, are normalized as discussed in section 3.3.1 and the evaluation is iterative.

After each iteration the light and heavy yields are normalized to 100%. The separation between the two groups is at $(A_f-\bar{\nu})/2$. The average difference from 100% for the four thermally fissile nuclides before normalization is 0.7%, the greatest being +2.0% for the ^{233}U light masses.

Relative yield measurements influence the standard yields through the use of inverse ratios. These are treated as regular input data rather than as described in section 3.3.1. The inverse ratios are generally assigned large errors, apparently to avoid divergence or oscillation in successive iterations. For this reason they do not have much influence on the final values of the standard yields.

3.4.2 Crouch [6]

A computer-based data library and interrogation program have been set up under the auspices of the U.K. Chemical Nuclear Data Committee [45, 46]. A computerized evaluation procedure has been described [48] but is not yet in operation.

The data library is intended to include only measured yields that are reasonably well documented. If two results by the same author appear to be derived from the same experimental data the earlier one is omitted. No corrections for changes in half-life or cross sections are mentioned. Relative yields are normalized to preliminary estimates of the standard yields.

Errors are evaluator-assigned. Rejected values are not indicated. A computer program is used to obtain the simple average with its standard deviation and a weighted average with two errors, the one derived from the assigned weights, the other from the weighted mean deviation. Weights are the inverse squares of the assigned errors. The recommended value is usually the weighted mean and the assigned error is the greatest of the three above.

The sum of recommended values is not normalized to 100% for the light and heavy mass peaks. The average absolute difference is 1.3% and the largest is -3.35% for the ^{239}Pu light masses.

The compilation still shows effects that can be attributed to the comparatively brief period the work has been under way. Incorrect yield values and dubious error assignments are noted in Appendix A where they affect the recommended value significantly.

3.4.3 Walker [7]

The methods used are an improvement of those described at Helsinki [13] for ^{235}U fission, with the work extended to include ^{233}U, ^{239}Pu and ^{241}Pu. These evaluations are based on an assessment of the mass spectrometric data as described in section 3.1.

Fewer radiometric yields are listed than are available in Meek and Rider [9]. They are used primarily to establish yields where there are no mass spectrometric measurements. The remaining yields, for which there are no measured values, are obtained by fitting a curve to the measured data using reflected complementary yields as a guide wherever possible.

The sum of the light and heavy mass yields, divided at $(A_f - \bar{\nu})/2$, are made approximately equal to 100% by renormalizing the mass spectrometric yields. The average difference from 100% before final normalization is 0.67%, and the largest is 1.2% for the ^{235}U heavy masses.

3.4.4 Lammer and Eder [8]

This evaluation of fission product yields began at Seibersdorf in 1969 as part of the research work on fuel burnup analysis. Yields from thermal neutron fission of ^{241}Pu are not included.

The evaluation is based on mass spectrometric measurements, as in the preceding case [7], and the methods used are very similar. The description of section 3.1 applies. Here also non mass spectrometric yields are used primarily to obtain values where there is no mass spectrometric data.

In their initial evaluation the sum of yields in the light and heavy mass peaks differed from 100% by 1 or 2%. In renormalizing they retain the mass spectrometrically measured relative light and heavy element ratios and normalize to give light mass yields that sum to 100%. For ^{233}U yields additional adjustments were made in interpolated yields to make the heavy mass yield 100% as well.

3.4.5 Meek and Rider (ENDF/B(IV)) [9]

In 1972, the Cross Section Evaluation Group, which is responsible for selecting data to be used in the Evaluated Nuclear Data File (ENDF/B), appointed a task force to prepare, for ENDF/B(IV), a set of fission product data to be used in burnup and heating calculations.

A committee of the task force dealing with cumulative yields* decided that for future evaluations the computerized approach of Meek and Rider would be most satisfactory provided agreed methods of error assignment and evaluation could be developed. In the short term, for ENDF/B(IV), the following changes were made in the Meek and Rider data to eliminate the main differences between their interim evaluation and the evaluation in reference[7]:

(1) The mass spectrometric data were corrected for neutron capture and β-decay as recommended by Walker [7]. Most of the yields not used in [7] were also omitted in this evaluation.

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* Members participating were T.R. England (Los Alamos), R.P. Larsen (Argonne), W.J. Maeck (Idaho Falls), W.M. McElroy (Hanford), B.F. Rider (AE Vallecitos), and W.H. Walker (Chalk River).

(2) Where significant differences in isotopic abundances occurred, the data were reviewed. Values responsible for the differences were assigned larger errors or not used.

(3) The errors were changed to comply with the assignments recommended by the committee. These are similar to those of section 2.3.8.

(4) Evaluated values were not used except where no measurements were available.* Here the estimated values of [7] were used.

All the work involved in making the necessary changes to input data and evaluation program has been done by Meek and Rider. At this writing yields from the penultimate evaluation were not available, but they are tabulated and discussed in Appendix A. The final result, unfortunately, will not be ready until January, 1974.

3.5 Uncertainties in Current Data Requirements for Additional Measurements

In deciding what additional measurements are needed two questions should be considered -

For what masses are the yields lacking, discrepant or uncertain because only a single measurement has been made?

Is the associated uncertainty in calculations significant?

The second point will depend, of course, on the type of calculation and is considered in papers 2 through 9 at this meeting.

The main sources of uncertainty have been discussed to a greater or lesser extent in the evaluations of the preceding section, and in a discussion of the effects of yield uncertainties on fission product absorption calculations [17].

In the following sections a more detailed survey of uncertain data is presented and the measurements necessary to reduce the uncertainties are discussed.

3.5.1 Classifying Uncertain Data

Potentially the most important uncertainties are at masses for which there are no measurements but in practice there are very few unmeasured yields greater than 1% except for ^{241}Pu thermal fission.

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* This change has not been applied completely. For some small yields in the valley an evaluated value was inserted because the evaluation did not converge on the measured cumulative yield, apparently because a fractional cumulative yield was also available. Estimates have also been retained elsewhere, not necessarily to good effect. See, for example, Appendix A, note 4, for the ^{235}U heavy masses.

In this survey mass spectrometric yields are given precedence because they cover most of the light and heavy mass peaks, and because there are more measurements available. For convenience the data presented in [7] are used. Only yields not listed there will be referenced.

Uncertain data are listed in Table 3 using the following categories*:

(1) Nuclides for which the m.s. isotopic abundance is based on only one measurement
These are usually radioactive and can be checked against the m.s. yields of their stable isobars as well as n.m.s. yields. Where ^{89}Y is listed it has been normalized to ^{91}Zr using the measured $^{89}Y/^{91}Y$ abundance ratio.

(2) Nuclides for which the error in the average m.s. isotopic abundance exceeds 2%
Since most errors in the average are ∿1% or less, a significant systematic error is indicated if yields differ by appreciably more. Recommended yields are compared to n.m.s. yields where available.

(3) Elements for which the m.s. element yield is based on one measurement

(4) Elements for which the error in the average m.s. element yield exceeds 3%
For both (3) and (4) the yields of isotopes of the elements can be checked against n.m.s. yields.

(5) Chain yields based on n.m.s. measurements only, the yield exceeding 0.5%
Smaller yields may be poorly measured but the uncertainty is not likely to be important in calculations. If more than one measurement has been made the highest and lowest yield values are shown.

(6) Masses for which no yields have been measured
These are listed with their estimated yields to indicate their importance. The total of estimated yields is also listed.

3.5.2 ^{235}U Yields

The uncertainty likely to cause most trouble is that for the Sm yield since two isotopes (149 and 151) have very large cross sections. Although the ^{147}Sm yield agrees with that for ^{147}Nd the latter is the result of a single m.s. measurement. Radiometric yields at masses 147 and 149 also agree, but their accuracy is not high. Additional isotope dilution determinations of the element yield are required as well as another determination of the ^{147}Nd relative abundance and a γ-spectrometric measurement of the mass 149 yield.

The yield of ^{103}Rh, an important non-saturating fission

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* Here and in Table 3, m.s. ≡ mass spectrometric,
n.m.s. ≡ non mass spectrometric.

product which was previously assigned an error of 6 1/2% [7], has recently been measured by γ-spectrometry of ^{103}Ru [18] [21] [35]. The average value is 3.09, with an r.m.s. error of 4.4%. Additional measurements are still required.

Yields at masses 129 and 130 show a large spread and should be remeasured. In addition, as many as possible of yields in groups [6] should be measured.

3.5.3 ^{233}U Yields

The number of yield measurements for ^{233}U is much smaller than ^{235}U. No major discrepancies are apparent. The disagreements in mass spectrometric measurement for ^{102}Ru, ^{104}Ru and ^{150}Nd may be due to contamination but apparently not by the naturally occurring element [7]. The accuracy of the ^{148}Nd yield, of possible importance in burnup measurements, does not seem to be affected.

The low γ-spectrometric yield for ^{135}Xe [19] should be weighed against three measurements of the ^{135}I yield which agree with the value obtained by deducting the large direct Xe yield (see section 4.4) from the mass spectrometric yield. It is possible that the γ-spectrometric measurement was affected by failing to take this direct yield into account. Because of the importance of ^{135}Xe in thermal reactors, additional measurements are recommended, with either mass or gamma spectrometer.

There is a serious gap in our knowledge of yields from mass 102 to 130 inclusive. The mass 103 and 106 yields should certainly be measured again. Also the yields from mass 126 to 130 should be determined since their estimated values contribute the bulk of the total estimated yield.

3.5.4 ^{239}Pu Yields

There are more measurements of ^{239}Pu yields than of ^{233}U yields but the agreement is much poorer. This may be because of unexpected difficulties in Pu chemistry, particularly in the earlier radiometric measurements.

The mass spectrometric yields of Ba should be remeasured. All three experimenters reported large corrections for natural Ba contamination, identified by the presence of ^{136}Ba, apparently present on the mass spectrometer filament. It does not appear possible that these corrections could have been in error enough to explain the 15% spread in measured yields. The isobaric coupling technique would avoid some difficulties, but there is also a 7% difference for the ^{138}Ba yield from ^{241}Pu where two such links were used. R-value γ-spectrometry using ^{138}Cs would give a more direct check.

There are two recent sets of γ-spectrometric ^{239}Pu yields [20][35] which can be used to check some of the single m.s. yields noted in Table 3. The results of Ramaniah [20] are R-values, using ^{235}U yields as reference. Those of Larsen et al.[35] are given as absolute ^{235}U and ^{239}Pu yields, but are here converted to R-values. In this way all dependence on γ-ray emission probabilities is eliminated.

Their yields are compared below with the recommended yields of [7] which are based on mass spectrometric data only. The values shown are the ratios $y_i[35]/y_i[7]$ with both sets of yields normalized to the same value at mass 140, and $y_i[20]/y_i[7]$ with both sets normalized at mass 144.*

Mass	95	97	103	106	131	132	133	135	142	143
[35]/[7]	0.95	1.01	1.22	--	1.09	--	--	--	--	--
[20]/[7]	1.05	0.99	1.12 1.18	0.91	1.08	1.02	1.03	0.96	1.11	0.90
No. of m.s. measurements	1	1	1	2	2	2	1	1	4	5

* Different normalizing yields are used because the mass 140 yield of [20] appears to be about 7% too low, while reference [35] has no mass 144 yield. Masses 140 and 144 are chosen because they are both measured mass spectrometrically as isotopes of Ce.

TABLE 3

CHAIN YIELDS BASED ON SINGLE, DISCREPANT OR NIL MEASUREMENTS

(1) U ISOTOPES

FISSILE ISOTOPE	^{235}U						^{233}U				
(1) Yields based on only a single m.s. isotopic abundance.											
Fission product	^{89}Sr	^{89}Y	^{91}Sr	^{95}Zr	^{95}Mo		^{89}Sr	^{90}Zr	^{95}Zr	^{136}Xe	^{135}Cs
Checks from other m.s.	Yes	Yes	Yes	Yes	Yes		--	Zr	Yes	--	--
yields[a] n.m.s.	Yes		Yes	Yes			Yes	Not Used	Yes	--	Yes/No
Uncertainty in checks[b]	-1%		-4%	-1%			-7%		-1%	--	Text
Fission product	^{136}Xe	^{137}Ba	^{139}Ba	^{140}Ba	^{141}Ce	^{147}Nd					
Checks from other m.s.	--	Yes	--	Yes	--	Yes					
yields[a] n.m.s.	--	Yes	Yes	Yes	Yes	Yes					
Uncertainty in checks[b]	--	-1%	-2%	<1%	-5%	-6%					
(2) Yields for which m.s. isotopic abundances agree poorly (assigned error >± 2%).											
Nuclide (error)	^{154}Sm (2.7%) (one measurement rejected)						^{102}Ru(2.6%)	^{104}Ru(2.7%)	^{105}Nd(3.8%)		
n.m.s. check[a]	--						Yes	--	--		
Uncertainty in check[b]	--						-3%	--	--		
(3) Element yields based on a single m.s. measurement.											
Element	Kr			Xe			Kr	Rb	Ru	Xe	
Isotopes with n.m.s. check	83	84	85	131	132	133	83	85	106	131	132
n.m.s. check[a]	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes
Uncertainty in check[b]	+5%	-7%	-3%[18]	-1%[18][21]	-5%[18]	-2%[18]	-5%[50]	+14%[19]	-14%	-5%	-10%
(4) Element yields that agree poorly (assigned error >±3%).											
Element (error)	Sm(6%)				Eu(6%)		None				
Isotopes with n.m.s. check	147	149			153						
n.m.s. check[a]	Yes	Yes			Yes/No (2 values)						
Uncertainty in check[b]	-6%	-4% (both including [18])			-5%/-13%						
(5) Yields >0.5% based on n.m.s. measurements only.											
Mass	99	103	105	129	130		99	103	105	127	
Highest value (%)	6.24±.12	3.22±.09[18]	.83±.20	1.12±.18	2.0±0.5		5.06±.13	2.46±.20	.18±.04	.72±.10	
Lowest value (%)	6.03±.08	2.95±.09[35]		.50±.04[49]			4.96±.15	1.60±.20			
(6) Estimated yields, no measurements available.											
Mass	80	82	108	110	113	114	116 - 120	78	79	80	82	107	108
Estimated yield (%)	.12	.33	.07	.022	.012	.100	~.010	.06	.16	.26	.60	.13	.07
Mass	122	124	126	Total				110	113	114	116	122	123	124
Estimated yield (%)	.013	.020	.053	0.7				.029	.015	.014	.014	.025	.037	.060
Mass								126	128	129	130	155	Total	
Estimated yield (%)								.26	1.0	1.7	2.5	0.23	7.0	

a M.s. yields can be checked as follows: if the nuclide is stable the only check possible is an n.m.s. yield of a radioactive isobar; if the nuclide is radioactive there may be any or all of the following - an m.s. yield for the stable isobar, an n.m.s. yield of the nuclide itself or an n.m.s. yield of a radioactive isobar. "Yes" shows that the check agrees with the yield being checked, "No" that it does not. A blank (--) shows that no check is available.

b If the uncertainty is " X%", then the check, or average if there is more than one, has an uncertainty of X% and is close to the yield being checked.
If the uncertainty is "+Y%" or "-Y%" then the check, or average if there is more than one, is Y% greater or less than the yield being checked. If "Yes" in the line above, the uncertainty in the check exceeds the difference.

c The value recommended is 0.53%

For masses 95 and 97, measured mass spectrometrically as Mo isotopes, the γ-spectrometric yields support the m.s. values, although the two γ-spectrometric measurements differ by 10% at mass 95.

There are appreciable discrepancies in the mass spectrometric measurements of Ru. The two isotopic abundances for ^{106}Ru differ by 8 1/2% while the two measurements of element yield differ by 4%. The ^{103}Ru yield is based on a single measurement of the 103/106 ratio that was corrected in [7] by a 7.7% increase, tentatively ascribed to a calculational error in the original paper.

If the high isotopic abundance of ^{106}Ru and the high element yield were both omitted the mass spectrometric yield for mass 106 would decrease by more than 6% and would then be in reasonable agreement with the single γ-spectrometric value. However, the yield for mass 103, which is tied to mass 106 by the ratio measurement, would also decrease by

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TABLE 3

CHAIN YIELDS BASED ON SINGLE, DISCREPANT OR NIL MEASUREMENTS

(2) Pu ISOTOPES

Fissile Isotope	^{239}Pu	^{241}Pu
(1) Yields based on only a single m.s. isotopic abundance		
Fission product	^{89}Sr ^{89}Y ^{95}Zr ^{95}Mo ^{97}Mo ^{98}Mo	All isotopes of Kr, Rb, Sr, Zr and Ru. The few n.m.s. measts. available agree with recommended yields except for mass 91 (-10%) ^{133}Xe
Checks from other m.s.	differ by 5% Used to normalize -- --	Yes
yields[a] n.m.s.	Yes Mo Yes Yes --	--
Uncertainty in checks[b]	~3% ~4% ~5% --	--
Fission product	^{100}Mo ^{103}Ru ^{133}Xe ^{136}Xe ^{135}Cs	^{135}Xe ^{135}Cs ^{136}Xe ^{138}Xe ^{140}Ba ^{141}Ce
Checks from other m.s.	-- -- Yes Yes See below	^{135}Xe -- -- Text Text --
yields[a] n.m.s.	-- No Yes --	Not Used No -- Yes Yes No
Uncertainty in checks[b]	-- Text ~4% --	Text -- ~3% ~6% ~6%
(2) Yields for which m.s. isotopic abundances agree poorly (assigned error >±2%)		
Nuclide (error)	^{106}Ru (4.3%) ^{135}Cs (2.2%)	^{150}Nd (3.0%)
n.m.s. check[a]	No Yes (sum of 135, 136 agree	
Uncertainty in check[b]	Text with separate m.s. measurements)	
(3) Element yields based on a single m.s. measurement		
Element	Mo	Kr, Rb, Sr, Zn, Ru Sm
Isotopes with n.m.s. checks	See (1) above	See (1) above 147 149 151
n.m.s. checks[a]		No Yes Yes
Uncertainty in check[b]	Note: Xe/Kr ratio does not agree [51]	+7% ~4% ~4%
(4) Element yields that agree poorly (assigned error >±3%)		
Element	Ba Two values agree, assigned error +2.1%. Third value is 15% greater. No n.m.s. check at mass 138	Ba Two values differ by 7.5%. Single R-value measurement at mass 138 depends on ^{239}Pu yield for ^{138}Ba (also uncertain).
(5) Yields >0.5% based on n.m.s. measurements only		
Mass	99 105 109 139 141	95 97 99 111 153
Highest value (%)	6.47±.18 5.47±.06 1.56±.20 5.98±.15 5.67±.18	3.9±.09 4.83±.14 6.26±.16 .54±.04 .52
Lowest value (%)	5.61±.33 1.13±.06 5.55±.07 4.70±.26	3.97±.15 4.64±.14 6.15±.16 ±.02
(6) Estimated yields, no measurements available		
Mass	79 80 82 107 108 110 114	79 80 81 82 89 98 100 103 105
Estimated yield (%)	.05 .12 .22 3.5 2.3 .65 .049	.016 .033 .065 .12 1.2 5.2 6.2 6.65 6.75
Mass	116-120 122 123	107 108 109 110 112 114 115-124 126
Estimated yield (%)	.035 .038 .044	5.3 4.0 2.5 1.2 .28 .075 <0.4 .08
Mass	124 126 128 129 130 158 Total	127 128 129 130 139 158 Total
Estimated yield (%)	.055 .20 .85 1.5 2.5 .041 12.2	.17 .38 .80 1.7 6.3 .090 49.3

a M.s. yields can be checked as follows: if the nuclide is stable the only check possible is an n.m.s. yield of a radioactive isobar; if the nuclide is radioactive there may be any or all of the following - an m.s. yield for the stable isobar, an n.m.s. yield of the nuclide itself or an n.m.s. yield of a radioactive isobar. "Yes" shows that the check agress with the yield being checked, "No" that it does not. A blank (--) shows that no check is available.

b If the uncertainty is " X%", then the check, or average if there is more than one, has an uncertainty of X% and is close to the yield being checked.
If the uncertainty is "+Y%" or "-Y%" then the check, or average if there is more than one, is Y% greater or less than the yield being checked. If "Yes" in the line above, the uncertainty in the check exceeds the difference.

this amount and would then differ by about 25% from the mean of the γ-spectrometric values. Clearly additional mass and γ-spectrometric measurements are required at mass 103 and 106.

Like ^{103}Rh, ^{131}Xe is an important slowly saturating neutron absorber. As with Ru, there are disagreements in the Xe m.s. yields. Two determinations of both the Kr and Xe element yields give ratios that differ by 7 1/2%. If the higher Kr yield [15] were adopted, along with the Xe/Kr ratio based on isotope dilution with a calibrated Xe/Kr spike [51], then all Xe yields (masses 131, 132, 133 and 134) would increase 5%. This would bring the m.s. yields for ^{131}Xe into reasonable agreement with the two γ-spectrometer values, retain the agreement at mass 132 and give a ^{133}Xe yield (based on one m.s. measurement) equal to the γ-spectrometric yield of [20].

This procedure could be extended a step further. If the ^{133}Xe yield obtained above is used to give a Cs element yield via its isobar, ^{133}Cs, this element yield agrees with the value obtained by Lisman et al.[15]. Two other measurements of the Cs yield are 3% and 5% lower. The use of this higher yield would increase the discrepancy at mass 135, but here one can speculate that the γ-spectrometric measurement is in error because it did not take account of the large direct yield to ^{135}Xe.

The preceding is, of course, highly speculative, and additional mass spectrometric measurements of the Xe/Kr yield ratio and the Cs yield, as well as γ-spectrometric measurements at masses 131, 133 and 135, are clearly required.

The mass spectrometric yields at masses 142 and 143 are based on several measurements that agree well. Only the final normalization to 100% is in doubt because of the uncertainties in the Xe and Cs yields. If these were increased as discussed above, the remaining yields would have to be decreased by about 2%. Since this is far short of removing the disagreement it appears probable that the γ-spectrometric yields are in error.

Returning to Table 3, the review of n.m.s. yields in part (5) shows that there is disagreement at all masses where there is more than one measurement. The γ-spectrometric results of [20] when normalized at mass 144, give a mass 99 yield in good agreement with 2 of the 3 other yields, with an average value of 6.32, so that it would be reasonable to omit the low value in Table 3. For the other masses in part (5) plus masses 107 to 130 inclusive, for most of which no data is available, additional yield measurements should be made.

3.5.5 ^{241}Pu Yields

There are many fewer measurements of ^{241}Pu yields so that the greater number fall in the "no measurement" or "single measurement" categories. The most important region that is undermeasured is the mass range 100 to 130 which includes the maximum of the light mass peak. There is one mass spectrometric measurement, of the Ru isotopes, but

it is not normalized by isotope dilution [15]. Outside this range yields at masses 100 (∿6.2%) and 139 (∿6.3%) should also be measured.

The mass spectrometric Ba yields again disagree. One value, based on two isobaric links at masses 138 and 140 [52] differs from the isotope dilution measurement by 7% [15]. If the latter is correct then the Ba isotope yield ratios normalized to it would give yields at masses 138 and 140 that differed by 7% from Xe and Ce measurements. Further measurements are also required at these masses.

At mass 135 two pile oscillator measurements [53] [54] of the ^{135}I yield agree well. They are 13% greater than the value obtained by subtracting the small direct Xe yield from the m.s. yield. Again further measurements are essential.

4. CUMULATIVE AND DIRECT (INDEPENDENT) FRACTIONAL YIELDS

The stable and long-lived β-active nuclides used to determine chain yields represent a negligible fraction of those present immediately following fission and fragment de-excitation by prompt neutron and gamma emission. Most of these are short-lived β-active nuclides that are important in reactor heating, radiation damage, and delayed neutron production. Fortunately for reactor physicists they are also important to scientists interested in understanding the fission process, and it is the latter who have done almost all the measurements of direct and cumulative fractional yields.

4.1 Cumulative Yields, Direct Yields and β-decay

The cumulative fractional yield, c_{ij}, of the i^{th} isobar at mass j, is related to the direct fractional yields, d_{ij}, by

$$c_{ij} = \sum_{k=i}^{\infty} d_{kj}$$

A typical direct yield distribution as a function of the atomic number, Z, is given in the following hypothetical example.

Atomic no. of isobar, Z_{ij}	Z_s*	Z_s-1	Z_s-2	Z_s-3	Z_s-4	Z_s-5	Z_s-6
Direct yields, d_{ij}	<.003	.023	.405	.517	.054	.0007	∿0
Cumulative yield, c_{ij}	1.000	∿1.00	.977	.572	∿.055	∿.0007	
Half-life of Isobar	∞	∿1 day	∿1 hr	∿3 min	∿20 s	∿2 s	
Total Energy (MeV/decay)	∿1	∿2	∿4	∿5.5	∿7	∿8.5	∿10

* stable isobar

The features of main interest for reactor applications are that the direct yield distribution-in-Z peaks sharply, typically for nuclides with half-lives in the range of a few minutes to a few hours, and that the cumulative yield is close to unity for the last two β-decays ($Z_s-2 \rightarrow Z_s-1 \rightarrow Z_s$). When the reactor has run long enough for this isobaric chain to reach equilibrium the decay rate for each isobar will be proportional to its cumulative yield, c_{ij}, and the corresponding rate of energy release will be proportional to c_{ij} times the MeV/decay for that isobar.

The average β-decay chain length for mass j, $\bar{n}_{\beta j}$, is given by

$$\bar{n}_{\beta j} = \sum_i d_{ij}(Z_{sj}-Z_{ij}) \qquad (\bar{n}_{\beta j} = 2.61 \text{ decays/fission in the example})$$

The average β-decay chain length over all masses is given by

$$\bar{n}_{\beta} = \sum_j y_j \bar{n}_{\beta j}/200$$ where y_j is the chain yield of the j^{th} mass in percent.

A value of $\bar{n}_{\beta}$ can also be deduced by equating the atomic number before fission, $Z_{fissile}$, to the average atomic number of the stable fission products, i.e.

$$\bar{n}_{\beta} = \sum_j (y_j Z_{sj}/200) - Z_{fissile}$$

Using the recommended yields of Appendix A the values of $\bar{n}_{\beta}$ are:

Fissile nuclide	^{235}U	^{233}U	^{239}Pu	^{241}Pu
decays/fission	6.07	5.20	5.50	6.30

Values of $\bar{n}_{\beta j}$ will average $\bar{n}_{\beta}/2$ but considerable variation is expected depending on nuclear structure, particularly the displacement of Z_s from the atomic number of the most stable nuclide for that mass.

4.2 Measurements of Direct and Cumulative Yields

The methods for measuring direct and cumulative yields are similar to those described in section 2, except that, for the great majority, the nuclides studied are relatively short-lived. They can be expected to include greater systematic errors.

Direct yields are measured either by isolating the nuclide before its parent decays to an appreciable extent or by measuring its cumulative yield and that of its parent. The direct yield is then just the difference $c_{ij} - c_{(i-1)j}$. If $c_{(i-1)j}$ is very small ($Z_{i-1} << Z_s$) it may suffice to estimate its value.

Direct and cumulative yields are measured relative to some standard yield, so that the ratio of the chain yield to the same standard must also be determined before the fractional yield can be obtained.

4.3 Compilations of Direct and Cumulative Yields

There are several recent compilations of direct and cumulative yields. The reviews by Wahl et al. [10] and Amiel and Feldstein [12] treat only the relatively abundant ^{235}U measurements, while Denschlag [11] also includes ^{233}U and ^{239}Pu fission.

The data library of Meek and Rider [5] [9] includes direct and cumulative yields in addition to chain yields and they are used in their evaluation of the direct yield distribution at each mass.

From the discussion and illustration of section 4.1 it can be seen that the fractional cumulative yield is the most important factor determining isobaric contributions to β-decay energy release and radioactivity for a given mass chain. Isobars with Z_{ij} close to Z_{sj} have values of c_{ij} close to unity and are, therefore, subject to only small uncertainties while, if $Z_{ij} >> Z_{sj}$, values of c_{ij} are negligibly small. Thus the main uncertainty in reactor calculations will come from isobars between these extremes. For the purpose of this meeting a survey of direct yields is required that is confined to this region of uncertainty and is up-to-date, easily read and widely accessible. None of the current surveys is satisfactory in all these respects.

Appendix B is a compilation of direct and cumulative yields for all fission products with $y_j \gtrsim 1\%$ and $d_{ij} \gtrsim 0.05$. The first limit eliminates yields that are so small the excluded nuclides make only minor contributions in calculations, and for which there are very few data anyway. The second limit corresponds to $1.0 > c_{ij} > 0.05$. The data library of Meek and Rider [9] has been used with certain deletions, and with additions from the other compilations [10] [11] [12] and unpublished measurements.

It requires only a brief look at Appendix B to see that many more direct and cumulative yield measurements are required. For ^{235}U there are some data available for about 65% of the fission products listed, but for about half of these either there is only a single measurement or the spread between values is large.

For ^{233}U and ^{239}Pu there are so few measurements that evaluation is impossible. For ^{241}Pu they hardly exist and its yields are not included in Appendix B. With very few exceptions, almost all direct yields for these 3 fissile nuclides must be estimated using a semi-empirical model as discussed by Musgrove et al. [41].

4.4 An Evaluation for Mass 135

There are insufficient data for most fission products to carry out a satisfactory evaluation, even for ^{235}U thermal fission, and such an evaluation will not be attempted. One region where measurements are relatively abundant is between masses 131 and 135, due to the relative ease of extraction of Xe and I isotopes.

TABLE 4

YIELDS OF MASS 135 ISOBARS

Fissile Nuclide	^{235}U		^{233}U		^{239}Pu		^{241}Pu	
	Cum.	Direct	Cum.	Direct	Cum.	Direct	Cum.	Direct
Cs (chain yield)	6.60±.16 [7]		6.21±.15[7]		7.69±.26[7]		7.06±.24 [7]	
Xe (Z = 54)	.89±.09 [18]	.025±.025 [56]	.92±.10 [19]	.099±.013*[60]	.955±.025 [20]	.129±.022 [59]		.049±.038[59]
	1.02±.02[18]	.041±.012 [55]		.154±.014 [59]		.151±.004 [61]		.032±.002[61]
		.027±.010 [57]		.218±.005 [61]				
		.035±.010 [58]						
		.024±.017 [59]						
		.019±.013 [60]						
		.036+.002 [61]						
Weighted mean	1.01±.04	.035±.0035	.92±.10	.21±.02	.955±.025	.150±.004		.032±.002
Recommended	1.00	.035	>0.99	.21	>0.99	.150	1.00	.032
I (Z = 53)	.88±.09 [62]	.70±.17*[64]	.78±.02 [53]	.606±.024 [71]	.75±.08 [71]	.608±.017 [71]	1.05±.10 [73]	
	.99±.08 [63]	.43±.10 [65]	.76±.08 [70]		.85±.02 [53]		1.02±.03 [53]	
	.96±.07 [18]	.55±.09 [66]	.85±.07 [54]		.86±.02 [54]		1.14±.08 [54]	
		.47±.02 [67]			.25±.04†[69]			
		.44±.07 [68]						
		.27+.03†[69]						
Average	.94±.06	.47±.05	.80±.05	.606±.024	.82±.06	.608±.017	1.07±.06	
Recommended	.965	.47	.79	.61	.85	.61	.968	(~.45)
Te (Z = 52)	.52±.07 [68]	.23±.15 [64]				.48±.04 (69)		
	.50+.04 [74]	.50+.04 [69]						
Average	.51±.01	.37				.48±.04		
Recommended	.50	(~.47)	.18	(~.18)	.24	(~.23)		(~.48)
Sb (Z = 51)		.20 [69]				.24 [69]		
Recommended		(~.03)		(~0)		(~.01)		(~.04)

* Value not used in obtaining weighted mean or average (using rejection criterion of section 3.2).

† Sum of Xe and I. Value not used as * above.

Mass 135 is of particular interest because of the importance of ^{135}Xe as a neutron absorber, and, in particular, the dependence of reactor stability on the direct yield of ^{135}Xe and the cumulative yield of ^{135}I.

The measurements are presented in Table 4 as fractional yields. Absolute yields have been converted to fractional yields by dividing by the Cs (chain) yields listed in the first line. Errors are evaluator-assigned.

The evaluation proceeds as in section 3.2 except that, for I and Te, averages are calculated rather than weighted means. The recommended cumulative yields for I are equal to the difference between the cumulative and direct yield of Xe ($c_{Xe,135} - d_{Xe,135}$) since this has a smaller error than the average of the measured yields. The recommended cumulative yields for Te are obtained in the same way. In all cases the value obtained as a difference between cumulative and direct yields differs from the average of the measured cumulative yields by appreciably less than the rms deviation in the latter.

Bracketed yields are estimates extrapolated from the recommended yields of the higher Z isobars assuming that the distribution is sharply peaked as in the example of section 4.1.

Measured yields are rejected if they differ from the average of the remainder by more than 3 times the rms deviation from the average. All rejected yields except one were obtained from the recent paper by Gunther et al.[69]. These measurements were done with an on-line double-focussing mass separator as described in section 2.2.6.

A major finding of this investigation is that the direct yield distribution-in-Z for ^{239}Pu is almost identical to that for ^{235}U for all masses investigated (131 to 139 inclusive). At mass 135 this is clearly in disagreement with the radiochemical and γ-spectrometric measurements and the pile oscillator results (section 2.2.6) for the cumulative I yields.

This can be seen more readily in Fig. 1 in which the recommended yields of Table 4 and the measurements of [69] are plotted. In the latter the photographic plates were examined before an appreciable fraction of 6.6-h ^{135}I and 9.2-h ^{135}Xe could decay, so that the direct yield corresponding to no observed β-decays includes both isobars. This is indicated in Fig. 1 by the horizontal bar.

On the basis of the mass 135 evaluation all results of reference [69] must be suspect. It is possible that the direct yields observed are dictated by the conditions of the experiment rather than the actual yields. In discussing a similar discrepancy at mass 132, Naeumann et al.[74] suggested that selection of a restricted range of fission fragment energies for analysis in the mass separator may account for the difference.

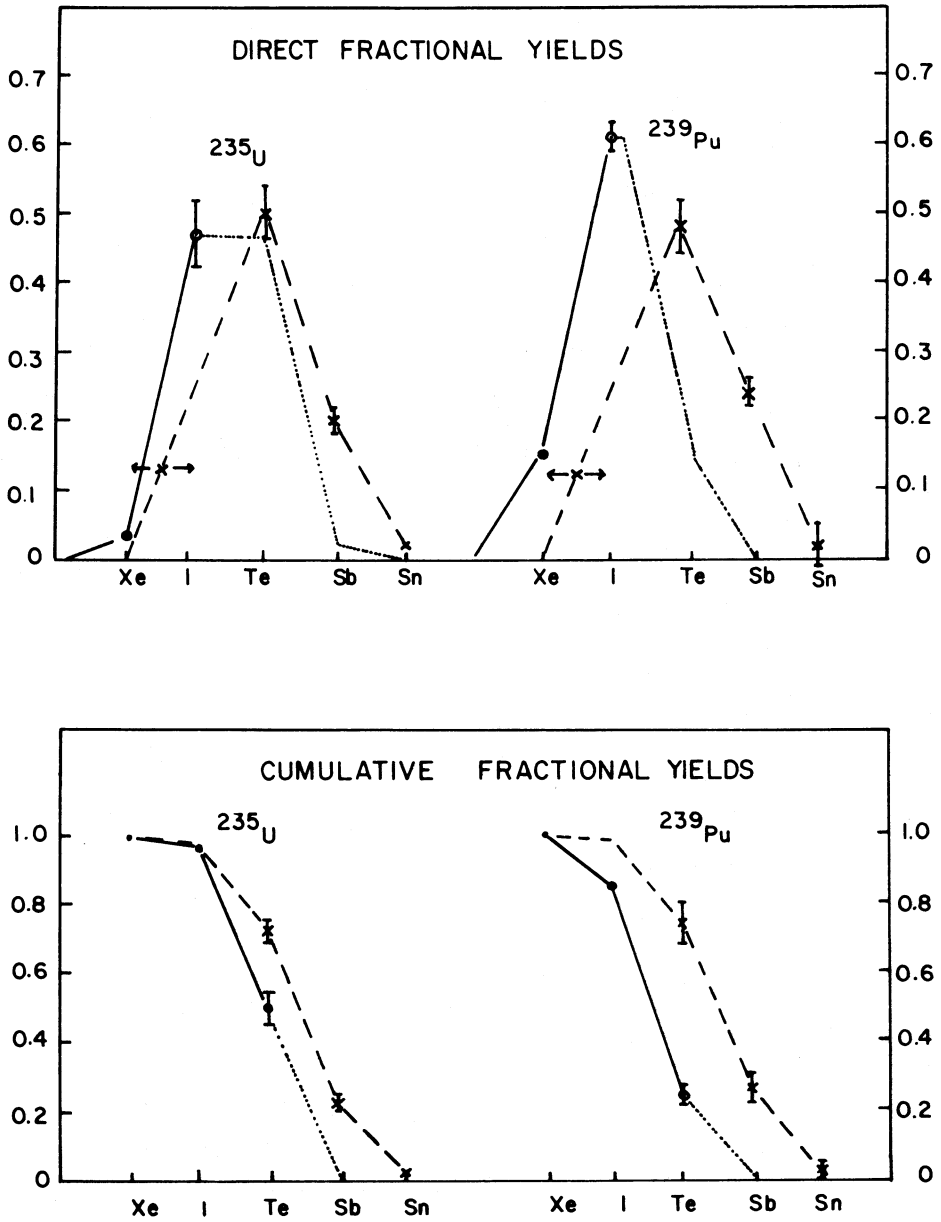

Figure 1 Direct and Cumulative yields for mass 135 isobars in the thermal neutron fission of ^{235}U and ^{239}U

—o—o— recommended experimental yields of Table 4

····· extrapolation of recommended yields

—x—x— experimental yields of reference [69]

5. YIELDS FROM FISSION BY EPITHERMAL NEUTRONS

It is now well established that yields in the valley near symmetric fission vary appreciably with neutron energies in the resolved resonance region [75] [76] [77]. An effect can also be seen using epithermal neutrons obtained by filtering a reactor flux with Cd or Sm.

The effect can be explained empirically by the two-mode fission hypothesis originated by Turkevich and Niday in 1951 [78]. It supposes that the observed yield is composed of two distributions, an asymmetric two-humped mode which is independent of neutron energy and a symmetric mode with a maximum for symmetric fission whose magnitude varies with neutron energy. In the epithermal region this dependence on energy varies from resonance to resonance between limits which appear to be related to the fission width and, to some extent, the spin of the compound nucleus [76] [77]. At much higher neutron energies, beyond the scope of this paper, the symmetric mode increases monotonically with energy [79].

5.1 The Symmetric Mode in the Epithermal Fission of ^{239}Pu

^{239}Pu shows the largest yield changes attributable to resonance absorption. Cowan et al. [76] used ^{115}Cd and ^{99}Mo to monitor these changes for resonances from 15 to 82 eV. Their results fall into three groups, based on the ratio of thermal to resonance yield, with averages of 2.7±0.2, 1.8±0.1 and 0.67±0.02 for this ratio. In thermal fission about 48% of the fissions are due to the resonance at 0.3 eV and the remainder to a bound level. These contributions are compatible with a ratio of 2.7 for the 0.3 eV level and 0.67 for the bound level.

Sm, with a large resonance at 0.098 eV, can be used to filter a reactor spectrum so that most ^{239}Pu fissions are caused by resonances at energies from 0.3 eV up. The work of Regier et al. [80] who obtained a thermal/epi-Sm ratio of 2.41±0.15 for ^{115}Cd confirms this expectation.

A survey of measured thermal/epi-Sm ratios as a function of fission fragment mass will, therefore, give a good indication of the width and magnitude of the symmetric mode and the total yield of fission products that change with neutron energy. The summary by Tong et al. [81] is used.

F.P.Mass	Th/Epi-Sm Ratio	Chain Yield(%)	Epi-Sm Yield(%)	Symmetric Mode Yield(%)
72	1.44±.05[82]	0.00011[9]	0.000076	0.000034
77	1.08±.04[81]	0.0059[9]	0.00546	0.00044
112	1.32±.08[82]	0.11[7]	0.083	0.027
115	2.41±.15[80]	0.038[7]	0.016	0.022
121	2.34±.06[80]	0.038[7]	0.016	0.022
125	1.79±.06[80]	0.10[7]	0.056	0.044
166	1.45±.07[81]	0.000068[9]	0.000047	0.000021

In the table the epi-Sm yield is the quotient of the chain yield and the measured ratio, and the difference from the chain yield, shown in the last column, is attributed to the energy dependent mode. If the result for mass 125 is correct the energy dependent mode does not peak at the mean mass.

To make a rough estimate of the fraction of the total yield that varies with energy assume that the energy dependent mode is symmetric, with a constant value of 0.025% from 100 to 138, and a value that decreases linearly outside this range to the measured values at masses 72 to 166. For this distribution the fraction of the yield in the energy-dependent symmetric mode is 1.65% out of 200%, or about 0.01.

For a mass having a thermal neutron chain yield of about 6% which is typical of the yields in the light and heavy mass peaks, the epithermal yield will be about $(6.00 - 0.025)\% \times 1.01 \cong 6.03\%$. The renormalization factor, 1.01, is required because the symmetric mode decreases for epithermal fission and the yields must total 200%.

5.2 Peak Yields in Epithermal Fission of ^{239}Pu

In the preceding section it was assumed that only the symmetric mode changed with neutron energy. It is also possible that peak yields will change relative to each other, contrary to the assumption of the two-mode hypothesis.

The effect of neutron energy on peak yields has recently been measured by Tong et al.[81] for ^{239}Pu. They measured the thermal/epi-Sm and thermal/epi-Cd ratios for a total of 19 nuclides representing 7 mass chains between masses 85 and 105 and 7 between 131 and 147 and found them to be constant with an uncertainty of less than 3% for a series of 5 irradiations (3 epi-Sm, 2 epi-Cd).*

The recent measurements of Popa et al.[83] using ^{235}U under a Cd filter show significant increases in peak yields relative to thermal neutron fission. For example, they report an epi-Cd/thermal yield of 1.2 at mass 131. Their total observed increase in the heavy mass peak alone is 2.3% over thermal fission for the 9 mass chains for which results are listed. This is about four times greater than the change that could be accounted for by assuming complete loss of a symmetric mode with a peak equal to the yield at mass 117 ($\sim$0.01%), i.e. by assuming that, in epi-Cd fission, valley yields are about zero.

Thus the only way in which these results could be consistent with a total yield of 200% would be for other peak yields to decrease by similar amounts. Clearly such decreases would have to be measured before the results of Popa et al.[83] can be accepted. The results of

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* Their results, converted to ratios relative to the mean value of the thermal/epithermal ratio for each irradiation, are given in Appendix C.

Balcarczyk et al. [84] for ^{235}U and ^{233}U under Cd show no signficant changes at masses 137, 103 or 106, which were not measured by Popa et al. [83].

5.3 Effects of Epithermal Yield Variations on Fission Product Absorption

From the preceding two sections it is apparent that changes in yields due to variations in the symmetric mode are small compared to uncertainties in measurements of the ratio of thermal to epi-Sm or epi-Cd yields. This will also be true for ^{233}U and ^{235}U since changes in the peak-to-valley ratio with neutron energy for those nuclides are several times smaller than for ^{239}Pu.

To decide whether there is any significant effect on fission product absorption due to changes in yields with neutron energy, it would be necessary to measure very accurately the changes for such important absorbers as ^{103}Rh, ^{131}Xe, ^{135}Xe, ^{143}Nd, ^{147}Pm, ^{149}Sm and ^{151}Sm.

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APPENDIX A

COMPARISON OF EVALUATED YIELDS FROM THE THERMAL NEUTRON FISSION OF ^{235}U, ^{233}U, ^{239}Pu and ^{241}Pu

The evaluated yields of Meek and Rider [5] [9], Crouch [6], Lammer and Eder [8] and Walker [7] are listed in Tables A1 to A8. Light and heavy mass yields are tabulated separately, with light masses defined as those less than 1/2 (fissioning mass - 3.5).

The first three (^{241}Pu) or four yield columns list published evaluated values with their error assignments [5] [6] [7] [8]. The next column, headed ENDF/B, is the unpublished interim set based on the Meek and Rider yield library and evaluated by them [9], as discussed in section 3.4.5.

The last yield column gives a set of recommended values. The recommended yields are averages of the preceding columns with the following exceptions:

(i) The Meek and Rider [5] values are not included since the ENDF/B set is based on the same data library except for recent additions and corrections.

(ii) The Crouch [6] values are used infrequently for two main reasons: the Idaho Falls values are taken from a preliminary publication [85] and often differ significantly from the final yields [15]; the sums of light and heavy mass yields do not add to 100% and will introduce a bias into the evaluation. Where these differences are particularly large a note is appended.

(iii) Where an explanatory note is indicated in the last column.

For each set, values of $\sum_i y_i$, $\sum_i y_i A_i$, $\bar{A}_L$, and $\bar{A}_H$ are included. Here A is the nucleon number and the average values are given by $\bar{A} = \sum_i y_i A_i / \sum_i y_i$. The calculated value of $\bar{\nu}$ (= fissioning mass - $\bar{A}_L$ - $\bar{A}_H$) is given at the bottom of each heavy mass table (A2, A4, A6, A8).

The recommended yields do not sum to 100%, the difference from 100% depending on how closely they follow the evaluated yields. Before use, each value should be divided by the appropriate value of $\sum_i y_i$.

In view of the many discrepancies discussed in section 3.5, it may seem surprising that the evaluations disagree so infrequently. This only indicates that the evaluators have usually responded in similar ways when faced with a discrepancy, and should not be taken as an indication that the problem has been resolved and the correct value determined.

TABLE A1

EVALUATED CHAIN YIELDS FROM ^{235}U
THERMAL NEUTRON FISSION - LIGHT MASSES

Mass	Meek & Rider	Crouch	Lammer & Eder	Walker	ENDF/B	Recommended	Note
<73	0.000038 (16%)	~0.000025 (15%)	~0.000025	↑	0.000038 (16%)	0.00003	
73	0.00010 (32%)	0.00010 (15%)	0.00010	↑	0.00010 (23%)	0.00010 (20%)	
74	0.00034 (32%)	0.00034 (15%)	0.00035	0.005*	0.00035 (32%)	.00035 (20%)	
75	0.00121 (32%)	—	0.001*	↓	0.00125 (32%)	0.0012*	
76	0.0035 (64%)	—	0.003*	—	0.0038 (45%)	0.0035*	
77	0.0092 (.0007)	0.0081 (.0009)	0.008	0.0083 (.0008)	0.0077 (.0010)	0.0082 (.001)	1
78	0.0203 (.0032)	0.020 (.002)	0.020	0.020 (.002)	0.0184 (.0041)	0.020 (.002)	
79	0 055 (.009)	0.055 (.006)	0.056	0.056 (.006)	0.058 (.001)	0.056 (.006)	
80	0.095 (.032)	0.11*	0.11*	0.120 (.024)*	0.128 (.031)	0.12*	
81	0.197 (.016)	0.21 (.02)	0.22	0.20 (.02)	0.216 (.034)	0.21 (.02)	
82	0.243 (.076)	0.333*	0.35	0.33 (.06)*	0.344 (.076)	0.34*	
83	0.535 (.005)	0.515 (.005)	0.532	0.535 (.013)	0.532 (.003)	0.533 (.013)	2
84	0.997 (.010)	0.959 (.007)	1.000	0.986 (.023)	0.987 (.010)	0.986 (.023)	2
85	1.331 (.027)	1.30 (.04)	1.328	1.33 (.03)	1.315 (.010)	1.32 (.03)	2
86	1.937 (.019)	1.89 (.13)	1.97	1.96 (.05)	1.953 (.020)	1.95 (.05)	2
87	2.553 (.051)	2.64 (.13)	2.56	2 53 (.06)	2.548 (.071)	2.55 (.07)	3
88	3.646 (.072)	3.69 (.18)	3.62	3.59 (.07)	3.640 (.072)	3.62 (.07)	3
89	4.809 (.096)	4.77 (.07)	4.84	4.74 (.09)	4.891 (.192)	4.80 (.10)	
90	5.930 (.119)	5.89 (.65)	5.91	5.82 (.11)	5.896 (.165)	5.89 (.11)	
91	5.912 (.118)	5.90 (.12)	5.93	5 95 (.11)	5.928 (.083)	5.93 (.11)	
92	5.987 (.120)	5.95 (.06)	5.98	5.98 (.07)	5.974 (.085)	5.97 (.07)	
93	6.407 (.128)	6.34 (.19)	6.39	6.41 (.07)	6.386 (.090)	6.40 (.07)	
94	6.449 (.129)	6.41 (.13)	6.45	6.43 (.07)	6.431 (.090)	6.44 (.07)	
95	6.499 (.130	6.45 (.13)	6.54	6.53 (.10)	6.473 (.091)	6.50 (.09)	
96	6.279 (.125)	6.23 (.12)	6.29	6.30 (.07)	6.264 (.088)	6.28 (.07)	
97	5.941 (.119)	5.87 (.15)	6.00	6.07 (.10)	5.901 (.059)	6.03 (.10)	4
98	5.788 (.116)	5.77 (.12)	5.81	5.81 (.10)	5.789 (.161)	5.79 (.10)	4
99	6.130 (.061)	6.14 (.05)	6.11	6.14 (.09)	6.128 (.061)	6.13 (.06)	
100	6.283 (.125)	6.24 (.19)	6.32	6.31 (.11)	6.264 (.175)	6.30 (.11)	4
101	5.097 (.102)	5.05 (.25)	5.05	5.07 (.07)	5.051 (.141)	5.05 (.07)	
102	4.206 (.084)	4.19 (.04)	4.19	4.19 (.06)	4.215 (.117)	4.19 (.06)	
103	3.103 (.124)	3.03 (.18)	2.95	3.05 (.20)	3.124 (.043)	3.12 (.04)	5
104	1.832 (.036)	1.82 (.05)	1.83	1.83 (.03)	1.826 (.051)	1.83 (.03)	
105	0.946 (.040)	0.96 (.04)	0.90	0.95 (.20)	0.927 (.037)	0.927 (.040)	6
106	0.391 (.008)	0.39 (.05)	0.387	0.390 (.006)	0.393 (.011)	0.390 (.006)	
107	0.191 (.061)	0.166*	0.17*	0.16 (.04)	0.206 (.030)	0.17*	
108	0.0704 (.022)	0.070*	0.057*	0.070 (.014)*	0.0743 (.022)	0.070*	
109	0.0274 (.0044)	0.030 (.001)	0.024	0.030 (.006)	0.0267 (.029)	0.030 (.003)	7
110	0.0200 (.0064)	0.0195*	0.017*	0.022 (.004)*	0.0230 (.005)	0.020*	
111	0.0182 (.0014)	0.0170 (.0003)	0.014	0.018 (.003)	0.0161 (.0019)	0.017 (.001)	
112	0.0128 (.0020)	0.0085 (.0001)	0.010	0.014 (.003)*	0.0120 (.0010)	0.012 (.001)	8,9
113	0.0129 (.0020)	0.0086*	0.004	0.012 (.003)*	0.0138 (.020)	0.012*	9
114	0.0129 (.0040)	0.0090*	0.012	0.011 (.002)*	0.0122 (.080)	0.011*	9
115	0.0105 (.0008)	0.0095 (.0014)	0.011	0.0104 (.002)	0.0109 (.0016)	0.0109 (.0016)	8
116	0.0111 (.0075)	0.0097*	0.011	0.0105 (.002)*	0.0122 (.051)	0.011*	9
Total	99.9999	99.48307	99.98548	99.9982	100.019	100.0493	
$\Sigma A_i y_i$	9489.581	9438.137	9483.413	9488.697	9489.025	9492.555	
$\bar{A}_L$	94.896	94.872	94.848	94.889	94.872	94.879	

* Interpolated yield

1. The ENDF/B value is low because the error assignment favors a recent measurement of the yield of 13-s ^{77}Ga. The earlier measurement using longer-lived isobars is probably as accurate, so the higher value is preferred.

2. The Crouch yields for Kr are 2 1/2% lower and not included in the average.

3. The Crouch yields are high due to the inclusion of early mass spectrometric data [86]. These have isotopic abundances very different from later results (summarized in [7]) and probably should not be used. At mass 88 the listed input does not give the weighted and simple means.

4. There are three mass spectrometric measurements of the abundances of Mo isotopes (masses 97, 98, 100). These agree to better than 1% [7] and the ratios have therefore been retained in the recommended yields.

5. The ENDF/B value is chosen since it is the only one based on a complete set of data.

6. The recommended value is based on yields listed in the ENDF/B library, but excludes one yield (used in the ENDF/B evaluation) that is 25% lower than the recommended value.

7. The ENDF/B evaluation uses an unpublished yield that is assigned a high weight; the Lammer and Eder value is also smaller than most measured yields. Both are omitted in taking the average.

8. The Crouch evaluation assigns low errors (and hence greater weight) to a 1957 measurement while the ENDF/B evaluation favors a 1970 measurement. The latter set is preferred.

9. The Lammer and Eder and ENDF/B evaluations use a preliminary set of mass spectrometric yields that have not been corrected for capture in ^{113}Cd. It is recommended that a smooth curve be assumed until final values are available.

TABLE A2

EVALUATED CHAIN YIELDS FROM ^{235}U

THERMAL NEUTRON FISSION - HEAVY MASSES

Mass	Meek & Rider	Crouch	Lammer & Eder	Walker	ENDF/B	Recommended	Note
117	.0161 (.0025)	.0100 (.0002)	.011	.0105 (.0020)*	.0103 (.0008)	.011*	1
118	.0147 (.0047)	.0100 (.0002)	.011	.0105 (.0020)*	.0116 (.0027)	.011*	1
119	.0126 (.0040)	.0110 (.0002)	.012	.0105 (.0020)*	.0113 (.0025)	.011*	1
120	.0131 (.0042)	.0110 (.0002)	.013	.011 (.002)*	.0118 (.0025)	.012*	1
121	.0178 (.0014)	.0111 (.0004)	.014	.0130 (.0017)	.0144 (.0008)	.014 (.001)	1
122	.0151 (.0048)	.0130 (.0003)	.015	.013 (.003)*	.0143 (.0044)	.014*	1
123	.0239 (.0019)	.0140 (.0003)	.0164	.016 (.001)	.0158 (.0009)	.016 (.001)	1
124	.0178 (.0114)	.0170 (.0003)	.024	.020 (.004)*	.0223 (.0070)	.022*	1
125	.0253 (.0010)	.0296 (.0027)	.028	.029 (.004)	.0305 (.0017)	.030 (.002)	1
126	.0523 (.0334)	0.100 (.002)	.063	.053 (.010)*	.0563 (.031)	.055*	1
127	.139 (.005)	0.250 (.005)	0.11	0.124 (.010)	.125 (.008)	.125 (.008)	1
128	.402 (.064)	0.500 (.010)	0.36	0.34 (.03)	.348 (.014)	.35 (.02)	1
129	.853 (.130)	1.00 (.02)	0.64	0.88 (.30)	.653 (.051)	.65 (.15)	1,2
130	2.003 (.64)	2.00 (.04)	2.00	1.7 (0.5)	1.442 (.157)	1.7 (.3)	1,3
131	2.771 (.028)	2.85 (.03)	2.82	2.80 (.07)	2.832 (.056)	2.82 (.07)	
132	4.124 (.041)	4.26 (.04)	4.20	4.17 (.09)	4.231 (.060)	4.20 (.09)	
133	6.760 (.068)	6.72 (.03)	6.73	6.79 (.16)	6.771 (.068)	6.75 (.16)	
134	7.187 (.072)	7.76 (.08)	7.67	7.61 (.17)	7.683 (.107)	7.65 (.17)	
135	6.720 (.268)	6.45 (.13)	6.55	6.60 (.16)	6.636 (.132)	6.60 (.16)	
136	6.123 (.061)	6.54 (.13)	6.18	6.13 (.14)	6.292 (.125)	6.18 (.14)	4
137	6.224 (.062)	6.27 (.06)	6.26	6.24 (.16)	6.277 (.031)	6.26 (.16)	
138	6.741 (.135)	6.80 (.17)	6.82	6.76 (.18)	6.827 (.095)	6.80 (.17)	
139	6.583 (.263)	6.44 (.13)	6.55	6.53 (.12)	6.477 (.091)	6.50 (.12)	
140	6.316 (.063)	6.32 (.03)	6.37	6.36 (.14)	6.320 (.063)	6.36 (.06)	5
141	5.862 (.234)	5.70 (.17)	5.85	5.87 (.12)	5.575 (.118)	5.82 (.06)	5
142	5.952 (.060)	5.86 (.06)	5.91	5.96 (.13)	5.935 (.084)	5.87 (.06)	5
143	5.987 (.060)	5.89 (.12)	5.92	5.95 (.08)	5.978 (.042)	5.95 (.08)	
144	5.444 (.054)	5.42 (.11)	5.44	5.43 (.10)	5.458 (.055)	5.39 (.06)	5
145	3.950 (.020)	3.87 (.04)	3.91	3.93 (.06)	3.946 (.028)	3.93 (.06)	
146	2.996 (.030)	2.95 (.06)	2.96	2.98 (.04)	2.995 (.021)	2.97 (.04)	
147	2.253 (.022)	2.17 (.08)	2.22	2.26 (.04)	2.274 (.046)	2.25 (.04)	
148	1.689 (.008)	1.69 (.02)	1.67	1.68 (.03)	1.694 (.012)	1.68 (.03)	
149	1.070 (.011)	1.01 (.06)	1.05	1.08 (.07)	1.091 (.022)	1.07 (.06)	
150	0.649 (.006)	0.637 (.006)	0.644	0.652 (.009)	0.648 (.007)	0.648 (.009)	
151	0.435 (.009)	0.410 (.008)	0.407	0.419 (.027)	0.422 (.006)	0.420 (.027)	6
152	0.265 (.003)	0.234 (.011)	0.262	0.268 (.017)	0.272 (.016)	0.270 (.017)	6
153	0.163 (.006)	0.150 (.005)	0.163	0.167 (.011)	0.163 (.007)	0.164 (.010)	
154	.0712 (.0007)	.0652 (.005)	.072	.0743 (.0051)	.0754 (.0086)	.075 (.005)	7
155	.0332 (.0013)	.0294 (.0015)	.032	.0321 (.0022)	.0331 (.0019)	.0325 (.002)	1
156	.0133 (.0011)	.0156 (.0003)	.014	.0131 (.0007)	.0136 (.0011)	.0133 (.0011)	1
157	.00642 (.00050)	.00677 (.00041)	.0062	.0061 (.0004)	.0065 (.00072)	.0064 (.00072)	1
158	.00428 (.00035)	.0020 (.0003)	.0031	.0031 (.0006)	.0032 (.00086)	.0031 (.0006)	1
159	.00109 (.00009)	.00101 (.00003)	.00105	.0010 (.0001)	.00102 (.00008)	.00102 (.00008)	1
160	.00033 (64%)	----	.00035*	↑	.00035 (45%)	.00035*	
161	.000084 (8%)	.000080 (7%)	.00009	.0007	.000088 (8%)	.000088 (8%)	
>161	.000040 (32%)	~.00004	~.00004	↓	.000040 (32%)	.000040*	
Σy_i	99.9996	100.4981	100.0022	99.9969	99.9975	99.705	
$\Sigma A_i y_i$	13867.711	13924.239	13866.384	13868.302	13871.689	13828.315	
$\bar{A}_H$	138.678	138.552	138.661	138.687	138.720	138.693	
$\bar{\nu}$	2.426	2.576	2.491	2.424	2.408	2.428	8

* Interpolated yield

1. The Crouch evaluation assigns low errors to estimated yields of Farrar and Tomlinson [87].

2. The Walker value is not based on all the measurements available.

3. The ENDF/B evaluation uses only a 1973 measurement, while the others are based only on earlier measurements. The recommended yield uses all data, as shown in Table A9.

4. The recommended value of Crouch is greater than any listed yield; the ENDF/B value is also higher than listed measured yields, but lower than 3 estimated values. The recommended value retains the mass spectrometric yield ratio to other Xe isotopes (131, 132, 134).

5. The evaluated yields from Table 2 (section 3) are used.

6. The ratio of ^{151}Sm to ^{152}Sm yields is affected by capture in ^{151}Sm in the results of Lisman et al, [15] and after correction still differs from other measurements (summarized in [7]). The Walker and ENDF/B evaluations take this into account and are used to obtain the recommended yield.

7. The Walker and ENDF/B yields are preferred because the very low ^{154}Sm value of [15] is omitted in the evaluation.

8. The value of $\bar{\nu}$ recommended by Hanna et al [44] is 2.4229 ± 0.0066. Only the evaluated yields of Meek and Rider and Walker, and the recommended yields give $\bar{\nu}$ values that agree within the error limits. The variation in $\bar{\nu}$ is mainly due to the very different yield values used for masses 129 to 130.

TABLE A3

EVALUATED CHAIN YIELDS FROM ^{233}U
THERMAL NEUTRON FISSION - LIGHT MASSES

Mass	Meek & Rider	Crouch	Lammer & Eder	Walker	ENDF/B	Recommended	Note
<73	0.000043	——	~0.00015*		0.000107	0.00013*	
73	0.00019 (32%)	——	0.00033*		0.00027 (32%)	0.0003*	
74	0.00064 (32%)	——	0.0009*		0.00053 (32%)	0.0009*	
75	0.0023 (32%)	——	0.0023*	0.010	0.00085 (45%)	0.0023*	
76	0.0068 (64%)	——	0.0068*		0.0062 (32%)	0.0065*	
77	0.0177 (.0028)	0.020 (.003)	0.02	0.020 (.004)	0.0178 (.0075)	0.019 (.005)	
78	0.098 (.031)	0.04*	0.04*	0.060 (.012)*	0.056 (.017)	0.06*	1
79	0.186 (.059)	0.08*	0.09*	0.16 (.03)*	0.152 (.007)	0.16*	1
80	0.253 (.081)	0.07*	0.18*	0.26 (.05)*	0.244 (.074)	0.26*	1
81	0.356 (.057)	0.33 (.04)	0.33	0.34 (.04)	0.316 (.049)	0.33 (.04)	
82	0.702 (.225)	0.61*	0.60*	0.60 (.12)*	0.562 (.171)	0.60*	
83	1.008 (.020)	1.09 (.04)	1.023	1.00 (.02)	1.017 (.010)	1.013 (.020)	
84	1.689 (.034)	1.81 (.07)	1.69	1.66 (.04)	1.702 (.034)	1.68 (.04)	
85	2.213 (.044)	2.32 (.16)	2.19	2.18 (.05)	2.197 (.016)	2.19 (.05)	
86	2.890 (.058)	3.06 (.12)	2.86	2.80 (.06)	2.870 (.081)	2.84 (.06)	
87	3.990 (.080)	4.18 (.29)	4.01	3.98 (.09)	4.004 (.113)	4.00 (.09)	
88	5.561 (.112)	5.47 (.11)	5.54	5.53 (.09)	5.498 (.154)	5.52 (.09)	
89	7.186 (.29)	6.12 (.30)	6.41	6.33 (.10)	6.267 (.174)	6.33 (.10)	
90	6.481 (.129)	6.33 (.25)	6.88	6.81 (.10)	6.804 (.195)	6.83 (.10)	2
91	6.421 (.064)	6.56 (.13)	6.52	6.49 (.08)	6.521 (.131)	6.51 (.08)	
92	6.423 (.064)	6.66 (.20)	6.65	6.67 (.09)	6.617 (.131)	6.64 (.09)	
93	6.838 (.068)	7.06 (.21)	7.04	7.05 (.09)	7.006 (.139)	7.04 (.09)	
94	6.541 (.065)	6.80 (.21)	6.81	6.75 (.09)	6.810 (.133)	6.79 (.09)	
95	6.197 (.124)	6.27 (.31)	6.21	6.19 (.10)	6.264 (.353)	6.22 (.10)	
96	5.520 (.055)	5.78 (.17)	5.73	5.66 (.09)	5.686 (.112)	5.71 (.09)	
97	5.449 (.108)	5.57 (.28)	5.39	5.36 (.09)	5.450 (.077)	5.40 (.09)	3
98	5.134 (.102)	5.24 (.37)	5.14	5.10 (.08)	5.159 (.145)	5.13 (.08)	
99	5.023 (.100)	5.08 (.15)	4.89	5.01 (.10)	4.969 (.283)	4.99 (.10)	
100	4.369 (.087)	4.50 (.72)	4.38	4.36 (.08)	4.412 (.124)	4.38 (.08)	
101	3.189 (.063)	3.10 (.09)	3.19	3.21 (.08)	3.224 (.090)	3.21 (.08)	
102	2,414 (.048)	2.31 (.07)	2.42	2.44 (.08)	2.453 (.069)	2.44 (.08)	
103	1.796 (0.72)	1.61 (.23)	1.60	1.8 (.3)	1.702 (.068)	1.70 (.10)	
104	1.023 (.020)	1.00 (.03)	1.02	1.030 (.033)	1.043 (.029)	1.03 (.03)	
105	0.414 (.132)	0.52*	0.54*	0.53 (.10)	0.506 (.111)	0.53*	
106	0.256 (.005)	0.262 (.008)	0.255	0.253 (.006)	0.257 (.010)	0.255 (.010)	
107	0.118 (.038)	0.105*	0.12*	0.130 (.026)*	0.122 (.037)	0.12*	
108	0.069 (.022)	0.087*	0.065*	0.070 (.014)*	0.066 (.020)	0.070*	
109	0.039 (.006)	0.052 (.008)	0.04	0.047 (.005)	0.045 (.004)	0.045 (.005)	
110	0.029 (.019)	0.032*	0.03*	0.029 (.006)*	0.027 (.008)	0.030*	
111	0.023 (.004)	0.020 (.001$_4$)	0.021	0.023 (.004)	0.020 (.002)	0.021 (.002)	
112	0.015 (.002)	0.013 (.001)	0.015	0.015 (.001)	0.015 (.002)	0.015 (.002)	
113	0.020 (.006)	0.014*	0.015*	0.015 (.003)*	0.014 (.004)	0.015*	
114	0.020 (.012)	0.015*	0.020*	0.014 (.003)*	0.013 (.004)	0.015*	
115	0.0215(.008)	0.019 (.002)	0.021	0.017 (.003)	0.020 (.003)	0.019 (.003)	
Σy_i	100.00161	100.319	100.0055	100.003	100.1318	100.2781	
$\Sigma A_i y_i$	9332.143	9366.964	9338.181	9339.700	9351.917	9359.004	
$\bar{A}_L$	93.320	93.372	93.377	93.394	93.396	93.360	

* Interpolated Yield

1. The recommended yields follow the curve through the complementary heavy masses as indicated in Fig. 1 of [7].

2. The Crouch value is very low because of the large weights assigned to mass spectrometric measurements that give $^{88}Sr/^{90}Sr$ yield ratios that are very different from other measurements (as summarized in [7]). The recommended yield is the average of the latter.

3. In the Crouch evaluation the listed yields and weights do not give the weighted mean. The most heavily weighted value may be a misprint.

TABLE A4

EVALUATED CHAIN YIELDS FROM ^{233}U

THERMAL NEUTRON FISSION - HEAVY MASSES

Mass	Meek & Rider	Crouch	Lammer & Eder	Walker	ENDF/B	Recommended†	Note
116	.010 (.006)	.0154*	.021*	.014 (.003)*	.013 (.004)	.015*	
117	.028 (.004)	.015 (.001)	.022	.014 (.003)	.013 (.002)	.015*	1
118	.030 (.005)	.015 (.001)	.022	.0145 (.003)	.013 (.002)	.015*	1
119	.030 (.005)	.015 (.001)	.023	.015 (.003)	.014 (.002)	.015*	1
120	.033 (.005)	.017 (.001)	.025	.016 (.003)	.015 (.002)	.017*	1
121	.045 (.029)	.020 (.003)	.027*	.018 (.004)	.017 (.010)	.018 (.003)	
122	.038 (.006)	.019 (.001)	.030	.025 (.005)*	.024 (.008)	.024*	1
123	.040 (.013)	.024*	.038*	.037 (.007)*	.036 (.008)	.036*	
124	.065 (.010)	.031 (.002)	.050	.060 (.012)*	.057 (.018)	.058*	1
125	0.114 (.009)	.116 (.013)	0.110	0.116 (.013)	0.112 (.018)	0.114 (.015)	
126	0.215 (.034)	.262*	0.18*	0.26 (.05)*	0.247 (.079)	0.26*	
127	0.59 (.10)	.59 (.09)	0.50*	0.62 (.12)	0.678 (.108)	0.65 (.10)	
128	1.046 (.335)	1.04*	1.00*	1.00 (.20)*	0.947 (.303)	1.00*	
129	1.694 (.542)	1.61*	1.56*	1.70 (.34)*	1.612 (.366)	1.60*	
130	2.326 (.744)	2.40*	2.40*	2.50 (.50)*	2.373 (.759)	2.40*	
131	3.505 (.070)	3.51 (.07)	3.54	3.53 (.08)	3.502 (.049)	3.52 (.08)	
132	4.835 (.096)	4.81 (.29)	4.84	4.82 (.11)	4.803 (.096)	4.82 (.11)	
133	5.958 (.060)	5.88 (.12)	6.03	5.99 (.21)	6.040 (.085)	6.02 (.21)	
134	6.154 (.123)	6.14 (.18)	6.15	6.14 (.14)	6.105 (.086)	6.13 (.14)	
135	6.098 (.244)	5.81 (.18)	6.27	6.21 (.15)	6.259 (.357)	6.24 (.15)	
136	7.386 (.295)	6.89 (.34)	6.82	6.88 (.16)	6.900 (.552)	6.87 (.16)	
137	6.560 (.066)	6.12 (.18)	6.85	6.76 (.16)	6.798 (.095)	6.80 (.16)	2
138	6.372 (.127)	5.96 (.18)	6.00	5.84 (.14)	5.890 (.165)	5.92 (.16)	
139	6.092 (.244)	6.20 (.18)	6.34	6.41 (.14)	6.441 (.258)	6.40 (.20)	
140	6.417 (.128)	6.32 (.19)	6.45	6.39 (.12)	6.452 (.367)	6.43 (.12)	3
141	5.918 (.119)	6.16 (.37)	6.56	6.62 (.50)	6.603 (.264)	6.60 (.50)	
142	6.579 (.132)	6.61 (.26)	6.61	6.60 (.12)	6.643 (.171)	6.61 (.12)	3
143	5.953 (.060)	5.83 (.18)	5.88	5.85 (.10)	5.885 (.082)	5.86 (.10)	
144	4.685 (.047)	4.52 (.18)	4.64	4.62 (.09)	4.664 (.065)	4.61 (.09)	3
145	3.412 (.034)	3.39 (.10)	3.39	3.38 (.06)	3.375 (.047)	3.38 (.06)	
146	2.547 (.025)	2.46 (.07)	2.53	2.55 (.04)	2.548 (.036)	2.53 (.04)	
147	1.869 (.374)	1.82 (.11)	1.80	1.70 (.05)	1.755 (.070)	1.76 (.07)	
148	1.285 (.013)	1.24 (.05)	1.30	1.30 (.022)	1.288 (.018)	1.28 (.02)	
149	0.766 (.023)	0.773 (.02)	0.76	0.766 (.021)	0.771 (.044)	0.77 (.02)	
150	0.532 (.021)	0.503 (.010)	0.501	0.508 (.020)	0.502 (.010)	0.503 (.020)	
151	0.338 (.067)	0.338 (.010)	0.32	0.314 (.008)	0.324 (.013)	0.314 (.020)	4
152	0.193 (.038)	0.198 (.008)	0.22	0.213 (.006)	0.209 (.012)	0.214 (.010)	4
153	0.126 (.020)	.099 (.013)	0.107	0.105 (.005)	0.109 (.009)	0.107 (.009)	
154	.047 (.002)	.046 (.002)	.0449	.0456 (.0012)	.046 (.003)	.046 (.002)	
155	.030 (.019)	.0231*	.026	.023 (.005)*	.022 (.007)	.023*	
156	.012 (.002)	.0114 (.0011)	.012	.0116 (.0003)	.0119 (.0010)	.0117 (.0010)	
157	.0077 (.0012)	.0067 (.0007)	.0072	.0065 (.0005)	.0069 (.0008)	.0068 (.0007)	
158	.0014 (.0009)	.00235*	.0024*	↑	.00127 (.00057)	.0024*	
159	.012 (.008)	.00091 (10%)	.00091	↑	.00091 (.0007)	.00091 (.0007)	
160	.0029 (32%)	.00031*	.00035*	.004	.00028 (32%)	.0003*	
161	.00013 (16%)	.00012 (10%)	.00012	↓	.00013 (8%)	.00012 (10%)	
>161	.000029 (32%)	----	----	↓	.000026	~.00003*	
Σy_i	99.9999	97.8613	100.0099	99.9962	100.1255	100.0163	
$\Sigma A_i y_i$	13812.626	13518.870	13817.286	13811.350	13832.340	13815.602	
$\bar{A}_H$	138.126	138.143	138.159	138.119	138.151	138.134	
$\bar{\nu}$	2.554	2.485	2.464	2.487	2.453	2.505	5

* Interpolated yield

†The recommended yields do not take the Crouch values into account. These sum to only 97.9% suggesting the possibility of renormalization. However, differences from the other sets are not consistent, since about half the 1.4% difference occurs for the Cs isotopes, masses 133, 135 and 137.

1. The Crouch and Lammer and Eder evaluations use the mass spectrometric measurements of relative Sn yields by de Laeter and Thode [43]. These differ markedly from radiometric yields, and their use is not recommended until they are confirmed by additional measurements.

2. The mass spectrometric yield ratio of 137 to 133 is retained in the recommended yields.

3. The mass spectrometric Ce isotopic abundances are retained (masses 140, 142, 144).

4. The yield ratio of Walker for ^{151}Sm and ^{152}Sm is retained in the recommended yields for the reasons given in note 6 for Table A2.

5. The value of $\bar{\nu}$ recommended by Hanna et al.[44] is 2.4866 ± 0.0069. The value given by the recommended set differs by less than 3 standard deviations. This is considered acceptable in view of the large uncertainties in the yields between masses 116 and 130.

TABLE A5

EVALUATED CHAIN YIELDS FROM ^{239}Pu
THERMAL NEUTRON FISSION - LIGHT MASSES

Mass	Meek & Rider	Crouch	Lammer & Eder	Walker	ENDF/B	Recommended†	Note
<73	0.00017			↑	0.00016 (45%)	0.00016*	
73	0.00025 (32%)	0.00026*	0.00025*	↑	0.00024 (16%)	0.00025*	
74	0.00060 (32%)	0.00059*	0.00062*	0.004	0.00059 (32%)	0.0006*	
75	0.0014 (.0004)	0.0013*	0.0016*	↓	0.0014 (.0004)	0.0014*	
76	0.031 (.0020)	0.003*	0.0035*	↓	0.0031 (.0014)	0.0033*	
77	0.0086 (.0007)	0.0071 (.0007)	0.0075	0.0073 (.0015)	0.0071 (.0011)	0.0073 (.001)	
78	0.029 (.002)	0.026 (.003)	0.028	0.025 (.005)	0.025 (.004)	0.026 (.004)	
79	0.025 (.008)	0.036*	0.06*	0.050 (.010)*	0.050 (.002)	0.05*	
80	0.048 (.031)	0.08*	0.11*	0.12 (.02)*	0.121 (.019)	0.11*	
81	0.182 (.029)	0.182 (.018)	0.186	0.18 (.02)	0.184 (.029)	0.183 (.020)	
82	0.167 (.107)	0.24*	0.24*	0.22 (.04)*	0.224 (.036)	0.23*	
83	0.293 (.006)	0.295 (.009)	0.298	0.295 (.007)	0.297 (.006)	0.297 (.007)	
84	0.470 (.009)	0.478 (.019)	0.482	0.477 (.011)	0.481 (.013)	0.482 (.011)	
85	0.601 (.012)	0.559 (.034)	0.566	0.558 (.013)	0.565 (.015)	0.563 (.013)	
86	0.746 (.015)	0.77 (.08)	0.764	0.758 (.017)	0.761 (.021)	0.761 (.020)	
87	0.952 (.019)	0.968 (.069)	0.980	0.970 (.022)	0.946 (.038)	0.98 (.02)	1
88	1.351 (.027)	1.36 (.09)	1.385	1.37 (.02)	1.372 (.027)	1.375 (.02)	
89	1.674 (.033)	1.67 (.05)	1.74	1.74 (.04)	1.733 (.035)	1.74 (.04)	
90	2.129 (.042)	2.09 (.10)	2.13	2.11 (.03)	2.124 (.042)	2.12 (.03)	
91	2.440 (.049)	2.47 (.10)	2.53	2.54 (.05)	2.521 (.035)	2.54 (.05)	
92	2.937 (.059)	3.01 (.06)	3.05	3.06 (.04)	3.036 (.085)	3.05 (.04)	
93	3.793 (.076)	3.91 (.08)	3.92	3.92 (.05)	3.935 (.079)	3.92 (.05)	
94	4.311 (.086)	4.45 (.09)	4.48	4.45 (.06)	4.466 (.089)	4.47 (.06)	
95	4.912 (.098)	4.90 (.025)	5.07	4.98 (.08)	4.979 (.139)	5.01 (.08)	
96	4.950 (.099)	5.08 (.11)	5.12	5.12 (.07)	5.132 (.102)	5.12 (.07)	
97	5.601 (.224)	5.54 (.17)	5.70	5.58 (.10)	5.737 (.229)	5.59 (.10)	2
98	5.725 (.458)	5.59 (.56)	5.93	5.81 (.10)	5.914 (.166)	5.88 (.10)	
99	6.456 (.129)	6.20 (.19)	6.33	6.10 (.36)	6.187 (.353)	6.32 (.20)	3
100	6.898 (.552)	6.74 (.67)	7.16	7.00 (.12)	7.154 (.572)	7.10 (.12)	
101	6.061 (.242)	6.05 (.48)	6.01	6.04 (.19)	5.993 (.168)	6.01 (.19)	4
102	6.108 (.244)	6.00 (.42)	6.09	6.15 (.19)	6.138 (.246)	6.13 (.19)	4
103	6.998 (.280)	5.51 (.39)	5.86	5.94 (.29)	5.818 (.116)	6.95 (.29)	5
104	6.056 (.242)	5.99 (.54)	6.03	6.10 (.19)	6.079 (.243)	6.07 (.19)	4
105	5.409 (.222)	5.47 (.55)	5.47	5.47 (.16)	5.291 (.423)	5.47 (.16)	
106	4.271 (.170)	4.34 (.17)	4.64	4.45 (.22)	4.344 (.174)	4.48 (.22)	4
107	3.06 (.98)	2.70*	3.3*	3.5 (.7)*	3.374 (.540)	3.5*	6
108	2.53 (.81)	1.70*	2.0*	2.3 (.5)*	2.307 (.738)	2.3*	6
109	1.385 (.111)	1.08 (.05)	1.13	1.3 (.2)	1.424 (.082)	1.3 (.2)	
110	0.74 (.48)	0.53*	0.57*	0.65 (.13)*	0.654 (.209)	0.62*	
110	0.27 (.04)	0.267 (.013)	0.27	0.28 (.01)	0.269 (.022)	0.27 (.02)	
112	0.117 (.009)	0.094 (.004)	0.11	0.11 (.02)	0.116 (.007)	0.11 (.01)	
113	0.084 (.013)	0.065 (.011)	0.65	0.076 (.006)	0.079 (.051)	0.072 (.010)	
114	0.055 (.035)	0.052*	0.41*	0.049 (.010)*	0.049 (.016)	0.048*	
115	0.037 (.003)	0.0371 (.0038)	0.036	0.038 (.002)	0.038 (.003)	0.037 (.003)	
116	0.037 (.024)	0.038*	0.035*	0.036 (.007)*	0.036 (.012)	0.036*	
117	0.036 (.011)	0.039*	0.035	0.035 (.007)*	0.035 (.006)	0.035*	
118	0.0350 (.0112)	0.039*	0.035	0.035 (.007)*	0.035 (.011)	0.035*	
Σy_i	100.0007	96.6675	99.9996	100.0033	100.0356	101.4030	
$\Sigma A_i y_i$	9896.230	9543.167	9881.418	9890.598	9891.228	10031.897	
$\bar{A}_L$	99.003	98.732	98.815	98.902	98.877	98.931	

* Interpolated Yield

† The recommended yields do not take the Crouch values into account because of the large renormalization required. The difference appears, in part, to be due to the use of yields attributed to Farrar and Tomlinson [91] that are about 4% less than the values in their paper.

1. The mass spectrometric yield ratio of ^{85}Rb to ^{87}Rb [7] normalized to the mass 85 yield is used to obtain the recommended yield.

2. The ENDF/B value is not consistent with the listed yields of Meek and Rider [5] [9]. The recommended yield is the average of the Meek and Rider and Walker values.

3. The recommended yield is taken from section 3.5.4.

4. The uncertainties in the mass spectrometric Ru yields, particularly for ^{101}Ru, are discussed in section 3.5.4. The evidence favoring a revision of the evaluated yields is not considered conclusive.

5. The γ-spectrometric yields are assumed correct (section 3.5.4). The recommended yield is 1.17 times the Walker value.

6. The estimated yields of Walker are used since these give better agreement between the calculated and recommended $\bar{\nu}$ values.

TABLE A6

EVALUATED CHAIN YIELDS FROM ^{239}Pu

THERMAL NEUTRON FISSION - HEAVY MASSES

Mass	Meek & Rider	Crouch	Lammer & Eder	Walker	ENDF/B	Recommended†	Note
119	.036 (.012)	.040*	.036	.035 (.007)*	.035 (.006)	.035*	
120	.037 (.012)	.042*	.038	.035 (.007)*	.035 (.006)	.036*	
121	.053 (.034)	.042±.006	.041*	.038 (.008)	.038 (.024)	.039 (.008)	
122	.047 (.030)	.049*	.045	.038 (.008)*	.038 (.012)	.040*	
123	.056 (.018)	.058*	.055*	.044 (.009)*	.044 (.007)	.05*	
124	0.158 (.025)	.078*	.075	.055 (.011)*	.055 (.018)	.06*	
125	0.109 (.009)	0.116 (.014)	0.110	0.100 (.015)	0.100 (.016)	.106 (.015)	
126	0.218 (.070)	0.24*	0.23*	0.20 (.04)*	0.200 (.064)	.22*	
127	0.526 (.042)	0.513 (.102)	0.55	0.45 (.09)	0.494 (.079)	.50 (.09)	
128	0.844 (.270)	0.83*	1.0*	0.85 (.17)*	0.849 (.272)	.85*	
129	1.689 (.541)	1.38*	1.65*	1.50 (.30)*	1.501 (.240)	1.5*	
130	2.684 (.859)	2.30*	2.6*	2.50 (.50)*	2.503 (.800)	2.5*	
131	3.890 (.078)	3.69 (.07)	3.73	3.73 (.09)	3.759 (.075)	3.74 (.09)	1
132	5.164 (.103)	5.11 (.15)	5.25	5.21 (.12)	5.281 (.148)	5.23 (.12)	1
133	6.839 (.068)	6.76 (.33)	6.94	6.92 (.19)	6.974 (.140)	6.92 (.19)	1
134	7.226 (.145)	7.24 (.22)	7.43	7.41 (.17)	7.417 (.148)	7.42 (.17)	1
135	7.223 (.144)	7.08 (.28)	7.48	7.69 (.26)	7.326 (.205)	7.69 (.26)	1,2
136	6.655 (.532)	6.33 (.63)	6.83	6.47 (.15)	6.723 (.188)	6.47 (.15)	1,2
137	6.535 (.065)	6.48 (.39)	6.62	6.72 (.18)	6.687 (.094)	6.65 (.18)	1
138	5.692 (.114)	5.71 (.28)	5.46	5.74 (.37)	5.718 (.457)	5.73 (.37)	3
139	5.842 (.234)	5.77 (.29)	5.82	5.74 (.22)	5.719 (.458)	5.72 (.30)	4
140	5.504 (.111)	5.57 (.28)	5.53	5.62 (.09)	5.583 (.078)	5.59 (.09)	5
141	5.963 (.238)	5.78 (.23)	5.24	5.27 (.35)	5.340 (.214)	5.34 (.25)	4
142	4.977 (.095)	5.05 (.30)	4.97	5.02 (.08)	5.001 (.070)	5.00 (.08)	5
143	4.460 (.045)	4.42 (.22)	4.48	4.53 (.06)	4.553 (.046)	4.51 (.06)	6
144	3.775 (.075)	3.85 (.23)	3.76	3.81 (.08)	3.833 (.027)	3.80 (.08)	5
145	3.017 (.030)	3.14 (.19)	3.04	3.06 (.03)	3.070 (.031)	3.05 (.03)	6
146	2.481 (.025)	2.52 (.21)	2.49	2.53 (.03)	2.536 (.025)	2.52 (.03)	6
147	1.947 (.039)	2.07 (.13)	2.09	2.16 (.07)	2.102 (.042)	2.13 (.07)	7
148	1.659 (.016)	1.71 (.08)	1.68	1.69 (.03)	1.699 (.017)	1.69 (.03)	
149	1.245 (.025)	1.24 (.08)	1.24	1.30 (.05)	1.282 (.025)	1.29 (.05)	7
150	0.998 (.020)	0.97 (.03)	0.97	0.989 (.018)	0.996 (.010)	0.99 (.02)	
151	0.765 (.015)	0.791 (.048)	0.76	0.814 (.031)	0.787 (.011)	0.80 (.03)	7
152	0.576 (.012)	0.575 (.058)	0.58	0.619 (.023)	0.606 (.017)	0.61 (.02)	7
153	0.384 (.061)	0.385 (.039)	0.44	0.38 (.01)	0.374 (.030)	0.38 (.01)	8
154	0.275 (.005)	0.26 (.03)	0.273	0.286 (.011)	0.281 (.006)	0.285 (.010)	7
155	0.207 (.066)	0.216 (.03)	0.17	0.17 (.02)	0.171 (.027)	0.17 (.02)	
156	.083 (.007)	.086 (.011)	0.12	0.120 (.010)	0.120 (.096)	0.120 (.010)	
157	.076 (.048)	.075 (.011)	.080	.076 (.004)	.076 (.006)	.077 (.006)	
158	.042 (.027)	.04*	.045*	.041 (.008)*	.041 (.013)	.04*	
159	.022 (.007)	.021 (.002)	.022	.021 (.001)	.021 (.002)	.021 (.002)	
160	.012 (.004)	.01*	.011*	↑	.0096 (.0031)	.010*	
161	.0045 (32%)	.0047 (12%)	.0051	↑	.0050 (.0004)	.0050 (.0004)	
162	.0024 (32%)	.0022*	.0025*	↑	.0024 (.0011)	.0023*	
163	.00098 (32%)	.00106*	——	.015	.00096 (32%)	.0010*	
164	.00039 (64%)	.00042*	——	↓	.00037 (45%)	.0004*	
>164	.0003	~.0003	——	↓	.00023	.00025*	
Σy_i	100.00020	98.6457	99.9904	99.996	99.9868	99.9380	
$\Sigma A_i y_i$	13812.882	13538.727	13810.271	13820.651	13817.822	13810.519	
$\bar{A}_H$	138.129	137.246	138.116	138.212	138.196	138.191	
$\bar{\nu}$	2.868	4.022	3.069	2.886	2.927	2.878	9

* Interpolated yield

† The recommended yields do not take the Crouch values into account because of renormalization difficulties.

1. The uncertainties in the mass spectrometric Xe yields are discussed in section 3.5.4. The evidence favoring a revision of the evaluated yields is not considered conclusive.

2. The sum of the mass 135 and 136 yields of Fickel and Tomlinson [91] agree with that obtained by Lisman et al [15]. The 135 and 136 yield ratio of the former, as used by Walker, is used to give the recommended yields.

3. The Lammer and Eder value is apparently based on the smaller of the discrepant values discussed in section 3.5.4. The recommended value uses the evaluated yields based on the average of the discrepant results.

4. Only the ENDF/B evaluation uses all data and is recommended.

5. The mass spectrometric yield ratios for Ce are retained. For the recommended yields they are normalized at mass 144.

6. As in 5, for Nd.

7. The Lammer and Eder evaluation is apparently based on the lower of two isotope dilution measurements of the Sm yield. The recommended value is the average of the Walker and ENDF/B values, both of which use both measurements.

8. The high value of Lammer and Eder is not included in the average.

9. The value of $\bar{\nu}$ recommended by Hanna et al [44] is 2.8799 ± 0.0090. The good agreement with the recommended yield is largely due to the choice of the high γ-spectrometric yield at mass 103.

TABLE A7

EVALUATED CHAIN YIELDS FROM ^{241}Pu
THERMAL NEUTRON FISSION - LIGHT MASSES

Mass	Meek & Rider	Crouch	Walker	ENDF/B	Recommended	Note
<75	0.000026 (32%)	—	↑	0.000025 (32%)	0.00010*	
75	0.000067 (32%)	—	↑	0.000066 (32%)	0.00025*	
76	0.000195 (64%)	—	0.005	0.00019 (45%)	0.0008*	
77	0.00052 (.00004)	0.00045 (.00007)	↓	0.00037 (.00004)	0.0025*	1
78	0.0092 (.008)	0.0086 (.0013)	0.0082 (.0005)	0.0082 (.0007)	0.0083 (.0007)	
79	0.0116 (.0068)	0.018*	0.016 (.003)*	0.0164 (.0005)	0.017*	
80	0.0296 (.0095)	0.034*	0.033 (.007)*	0.0330 (.0075)	0.033*	
81	0.055 (.018)	0.063*	0.065 (.013)*	0.0637 (.0145)	0.064*	
82	0.069 (.044)	0.105*	0.120 (.024)*	0.114 (.026)	0.115*	
83	0.198 (.008)	0.201 (.006)	0.202 (.005)	0.205 (.006)	0.203 (.006)	
84	0.343 (.014)	0.353 (.018)	0.360 (.008)	0.357 (.014)	0.357 (.008)	
85	0.379 (.015)	0.387 (.040)	0.392 (.009)	0.396 (.016)	0.392 (.009)	
86	0.588 (.024)	0.601 (.060)	0.608 (.014)	0.613 (.035)	0.607 (.014)	
87	0.725 (.029)	0.741 (.074)	0.750 (.017)	0.756 (.043)	0.749 (.017)	
88	0.934 (.037)	0.954 (.095)	0.966 (.015)	0.973 (.055)	0.966 (.015)	
89	0.760 (.024)	1.19*	1.20 (.24)*	1.182 (.378)	1.19*	
90	1.498 (.060)	1.53 (.15)	1.55 (.02)	1.555 (.089)	1.55 (.02)	
91	1.778 (.071)	1.76 (.09)	1.84 (.03)	1.839 (.074)	1.82 (.03)	
92	2.183 (.087)	2.23 (.22)	2.26 (.03)	2.273 (.128)	2.25 (.03)	
93	2.829 (.113)	2.90 (.29)	2.93 (.04)	2.965 (.169)	2.93 (.04)	
94	3.260 (1.30)	3.33 (.33)	3.37 (.05)	3.402 (.194)	3.37 (.05)	
95	3.859 (.154)	4.00 (.16)	3.98 (.09)	3.982 (.227)	3.99 (.09)	
96	4.252 (.170)	4.33 (.43)	4.39 (.06)	4.438 (.252)	4.39 (.06)	
97	4.587 (.183)	4.75 (.14)	4.73 (.12)	4.762 (.271)	4.75 (.14)	
98	5.924 (1.896)	5.5*	5.2 (.5)*	5.173 (.828)	5.3*	
99	6.267 (.251)	6.14 (.18)	6.20 (.12)	6.231 (.249)	6.19 (.12)	
100	6.221 (1.991)	6.0*	6.2 (.6)*	6.173 (.988)	6.1*	
101	5.683 (.909)	5.94 (.59)	5.91 (.32)	5.968 (.674)	5.94 (.32)	
102	6.047 (.968)	6.32 (.63)	6.29 (.34)	6.344 (.717)	6.32 (.34)	
103	6.023 (1.927)	6.60*	6.65 (.7)*	6.571 (.742)	6.60*	
104	6.506 (1.041)	6.80 (.68)	6.77 (.37)	6.823 (.771)	6.80 (.37)	
105	5.925 (.948)	6.60*	6.75 (.7)*	6.667 (1.067)	6.67*	
106	5.936 (.475)	6.08 (.61)	6.05 (.33)	6.116 (.489)	6.08 (.40)	
107	4.937 (1.580)	5.15*	5.3 (.8)*	5.245 (1.191)	5.25*	
108	3.950 (1.264)	4.15*	4.0 (.8)*	3.94 (1.26)	4.05*	
109	3.778 (.604)	2.9*	2.5 (.5)*	2.48 (.28)	2.6*	
110	2.172 (1.390)	1.4*	1.2 (.24)*	1.18 (.26)	1.3*	
111	1.017 (.325)	0.49 (.07)	0.55 (.04)	0.51 (.08)	0.51 (.07)	
112	0.911 (.292)	0.32*	0.28 (.05)*	0.28 (.09)	0.30*	
113	0.167 (.013)	0.147 (.022)	0.153 (.008)	0.15 (.08)	0.15 (.02)	
114	0.059 (.019)	0.065*	0.075 (.015)*	0.074 (.024)	0.075*	
115	0.0350 (.0224)	0.037*	0.040 (.010)*	0.044 (.010)	0.040*	
116	0.0267 (64%)	0.033*	0.030 (.010)*	0.029 (.009)	0.030*	
117	0.0227 (32%)	0.031*	0.026 (.010)*	0.026 (.006)	0.028*	
118	0.0207 (32%)	0.030*	0.025 (.010)*	0.025 (.011)	0.027*	
119	0.0197 (32%)	0.029*	0.025 (.010)*	0.025 (.006)	0.026*	
Σy_i	99.99601	100.2484	99.9992	100.0090	100.1410	
$\Sigma A_i y_i$	10064.698	10064.220	10032.047	10030.717	10048.110	
$\bar{A}_L$	100.651	100.393	100.321	100.298	100.340	

* Interpolated yield

1. The measured yield at mass 77 is about 1/20th that at mass 78. Since such a large ratio is encountered nowhere else the recommended yields are obtained by extrapolating at rates consistent with other measurements (approximately x 0.3 per mass).

TABLE A8

EVALUATED CHAIN YIELDS FROM ^{241}Pu

THERMAL NEUTRON FISSION - HEAVY MASSES

Mass	Meek & Rider	Crouch	Walker	ENDF/B	Recommended	Note
120	.0250 (.0080)	.029*	.025 (.010)*	.024 (.008)	.026*	
121	.0250 (.0080)	.030*	.025 (.010)*	.024 (.008)	.026*	
122	.0250 (.0160)	.031*	.025 (.010)*	.024 (.008)	.027*	
123	.0260 (.0083)	.032*	.027 (.008)*	.025 (.008)	.028*	
124	.0311 (.0200)	.036*	.031 (.006)*	.029 (.009)	.032*	
125	.0414 (.0066)	.042 (.006)	.042 (.005)	.041 (.007)	.042 (.006)	
126	.0930 (.0300)	0.1*	.080 (.016)*	.077 (.017)	.085*	
127	0.700 (.112)	0.21*	0.17 (.04)*	0.164 (.052)	.18*	
128	0.494 (.158)	0.41*	0.37 (.08)*	0.354 (.113)	.38*	
129	1.008 (.323)	0.82*	0.80 (0.16)*	0.773 (.175)	.80*	
130	1.818 (.582)	1.65*	1.70 (0.34)*	1.637 (.524)	1.65*	
131	3.092 (.062)	3.14 (.09)	3.12 (.07)	3.131 (.088)	3.13 (.08)	
132	4.589 (.092)	4.59 (.14)	4.64 (.11)	4.658 (.130)	4.64 (.12)	
133	6.611 (.132)	6.64 (.20)	6.72 (.20)	6.715 (.134)	6.72 (.20)	
134	7.990 (.160)	7.99 (.24)	8.08 (.18)	8.102 (.227)	8.09 (.20)	
135	7.293 (.146)	7.08 (.35)	7.06 (.24)	7.180 (.143)	7.11 (.24)	
136	7.210 (.288)	7.04 (.35)	7.30 (.17)	7.290 (.292)	7.29 (.17)	
137	6.562 (.131)	6.52 (.20)	6.50 (.20)	6.650 (.186)	6.58 (.20)	
138	6.594 (.264)	6.54 (.20)	6.71 (.25)	6.519 (.261)	6.60 (.25)	
139	5.882 (1.882)	6.30*	6.3 (0.6)*	6.195 (.991)	6.3*	
140	5.860 (.117)	5.83 (.17)	5.91 (.11)	5.932 (.166)	5.92 (.14)	
141	4.972 (.199)	4.78 (.14)	4.98 (.08)	4.863 (.136)	4.88 (.10)	
142	4.752 (.190)	4.77 (.14)	4.84 (.07)	4.835 (.135)	4.83 (.10)	
143	4.412 (.088)	4.40 (.13)	4.52 (.06)	4.514 (.090)	4.51 (.08)	
144	4.058 (.081)	4.09 (.08)	4.18 (.06)	4.163 (.083)	4.17 (.08)	
145	3.120 (.062)	3.14 (.06)	3.22 (.04)	3.212 (.064)	3.21 (.06)	
146	2.665 (.053)	2.65 (.05)	2.72 (.04)	2.748 (.055)	2.70 (.05)	
147	2.182 (.087)	2.26 (.07)	2.20 (.06)	2.267 (.045)	2.24 (.06)	
148	1.871 (.037)	1.87 (.04)	1.92 (.03)	1.926 (.053)	1.90 (.04)	
149	1.432 (.006)	1.47 (.04)	1.44 (.04)	1.471 (.029)	1.46 (.04)	
150	1.187 (.024)	1.16 (.05)	1.17 (.04)	1.198 (.034)	1.18 (.04)	
151	0.886 (.071)	0.903 (.054)	0.882 (.024)	0.905 (.025)	0.90 (.03)	
152	0.707 (.028)	0.741 (.030)	0.697 (.019)	0.719 (.020)	0.72 (.02)	
153	0.536 (.172)	0.54 (.02)	0.522 (.022)	0.529 (.015)	0.53 (.02)	
154	0.370 (.014)	0.379 (.019)	0.378 (.010)	0.381 (.030)	0.38 (.02)	
155	0.293 (.094)	0.231 (.020)	0.231 (.022)	0.232 (.008)	0.23 (.01)	
156	0.209 (.067)	0.170 (.009)	0.167 (.005)	0.170 (.027)	0.17 (.01)	
157	0.146 (.093)	0.130 (.007)	0.130 (.006)	0.132 (.008)	0.13 (.01)	
158	0.101 (.064)	.086*	0.090 (.018)*	.087 (.007)	.087*	
159	.068 (.043)	.0462 (.0023)	0.046 (.002)	.047 (.015)	.046 (.002)	
160	.046 (.030)	.024*	0.020 (.004)*	.019 (.002)	.020*	
161	.015 (.010)	.00814 (.00040)	.0082 (.0003)	.0083 (.0026)	.0082 (.0003)	
162	.0021 (32%)	----	↑	.0038 (.0003)	.0038*	
163	.0021 (32%)	----	~.005	.00095 (.00042)	.0010*	
164	.00032 (32%)	----	↓	.00030 (.00010)	.0003*	
>164	.0002 (32%)	----		.00019 (.00006)	.0002*	
Σy_i	100.00012	98.91334	100.0012	99.9755	99.9625	
$\Sigma A_i y_i$	13864.152	13721.767	13873.600	13872.208	13868.503	
$\bar{A}_H$	138.641	138.725	138.734	138.756	138.737	
$\bar{\nu}$	2.708	2.882	2.945	2.946	2.923	1

* Interpolated yield

1. The value of $\bar{\nu}$ recommended by Hanna et al. [44] is 2.934 ± 0.012.

TABLE A9

^{235}U YIELDS AT MASS 130

Isobar	Cumulative Yields		Chain Yields (%)	
	Absolute (%)	Fractional		
stable ^{130}Te	1.43 ± 0.18[88]	∿1.000	1.43 ± 0.20	Weighted mean 1.7 ± 0.3
6.6 min. ^{130}Sb	2.17 ± 0.4[63] 2.2 ± 0.5[89]	0.86 ± 0.04*	2.5 ± 0.5 2.5 ± 0.6	
3.7 min. ^{130}Sn	0.89 ± 0.10[88]	0.50 ± 0.10[90]	1.8 ± 0.4	

* ^{130}Sn does not decay to ^{130}Sb so the fractional cumulative yield of 6.6-min. ^{130}Sb is 1.00 less the direct yield to 33-min. ^{130}Sb (average of [88] [90]) less the direct yield to ^{130}Te [90].

APPENDIX B

A SURVEY OF FRACTIONAL DIRECT AND CUMULATIVE YIELDS FOR REACTOR APPLICATIONS

As noted in the main text, this survey is limited to masses for which the chain yields are about 1% or greater, and, at each mass, to isobars with direct yields about 5% or greater. The latter restriction ensures that all excluded nuclides have cumulative yields that are negligibly small or essentially unity. In the first case uncertainty in the direct yield will have no significant effect on calculations; in the second, its effect on the cumulative yield will be small compared to that due to the uncertainty in the chain yield.

The main source of data is the yield library of Meek and Rider [9], augmented by unpublished yields listed in other surveys [10] [11] [12] and other recent material. An attempt has been made to report each measurement only once since duplications give the impression of a higher degree of agreement than the data warrant. The commonest ways duplications occur are when preliminary values are listed and then the final values are listed following publication, or when cumulative yields are calculated from measured direct yields and both are listed as though they were independent measurements.

Measurements of delayed neutron emission can be converted to cumulative yields if the fraction of the isobar decaying by neutron emission is known. However, the latter are poorly known and yields based on these measurements do not appear in Table B1.

The data is presented in a format that makes unmeasured and undermeasured yields needed for reactor calculations readily apparent. For each mass, measurements for ^{235}U, ^{233}U, and ^{239}Pu are listed in that order to facilitate the isobaric comparison noted in (4) below.

The validity of listed yields, particularly where there is disagreement, can often be checked using the tests listed below. Here c_{ij} and d_{ij} are the cumulative and direct fractional yields, respectively, of the i^{th} isobar of mass j, where i = 1 is the stable isobar at the end of the decay chain.

(1) For each mass $\sum_i d_{ij} \leq 1.00$

(2) For any isobar $c_{ij} \approx \sum_{k=i}^{\infty} d_{kj} \approx d_{ij} + c_{(i+1),j}$

(3) Because the average number of β-decays is smaller for ^{233}U and ^{239}Pu than for ^{235}U, $c_{ij}(^{235}U)$ should be greater than both $c_{ij}(^{233}U)$ and $c_{ij}(^{239}Pu)$ for most isobars.

No evaluation is attempted here. The Meek and Rider evaluation for ENDF/B uses as input both measured yields and calculated yields and by least squares fitting works out a complete set of direct yields. The calculated yields are

based on a new set of most probable yields* that take into account the systematic odd-even effect investigated by Amiel and Feldstein [12]. Table B1 will provide a useful check on the ENDF/B values when they become available.

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* Prepared by Dr. K. Wolfsberg

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TABLE B1 FRACTIONAL DIRECT AND CUMULATIVE YIELDS FROM THERMAL NEUTRON FISSION

Mass	Stable Isobar (Z)	a	Chain Yield (%)	Fractional Yields of Radioactive Isobars x 100										
				b	Cum.	Direct	b	Cum.	Direct	b	Cum.	Direct	b	Direct [c]
83	Kr(36)	25	0.533	Br (35)			Se,m (34),g	64±4 [1]	64±4 [1]	As (33)	80±8 [4]		Ge (32)	
							g	39 [2]			76±6 [5]			
							m/g	42±4 [1]						
							m+g	1.5±.1 [3]						
								≥93 [5]						
		23	1.013				g	39±3 [1]						
							m/g	1.6±.1 [3]						
		49	0.297				g	53±7 [3]						
							m/g	.92±.12 [3]						
84	Kr(36)	25	.986	Br (35)			Se (34)	99 [6]		As (33)	17±2[d] [4]		Ge (32)	
								97±2 [5]			15±1[d] [5]			
										m+g	40±6 [5]			
		23	1.68											
		49	0.482											
85	Rb(37)	25	1.32	Br (35)			Se (34)	87±9 [6]		As (33)			Ge (32)	
								82±7 [5]						
		23	2.19											
		49	0.563											
86	Kr(36)	25	1.95	Br			Se			As			Ge	
		23	2.84	(35)			(34)			(33)			(32)	
		49	0.761											
87	Rb(37)	25	2.55	Kr (36)		14±1[15]	Br (35)	106 [6]	47±12 [8]	Se (34)	46±6 [10]		As (33)	4±2[e] [13]
								95±4 [11]	43±11 [9]		26±5 [12]			1.8±.9[e] [5]
											41±7 [13]			
											25±5 [14]			
		23	4.00					56±4 [10]	75±20 [8]		19±4 [10]			
		49	0.98					83±7 [10]			33±6 [10]			

a Fissile isotope; 25 = ^{235}U, 23 = ^{233}U, 49 = ^{239}Pu
b Radioactive isobar and atomic number, Z, in brackets
c For these isobars the cumulative yield is approximately equal to the direct yield
d 5.3s ^{33}As. It may be either the ground state or metastable.
e. The yield given in the original paper [13] is an absolute value equal to .04 of the recommended chain yield (2.55%). The same authors later quote their result as .018[5]. Smaller changes also occur for ^{87}Se and ^{88}Se; the values listed in [5] are, respectively, 7% greater and less than those in [13].

TABLE B1, continued (All references are for the Appendix B reference list)

Mass	Stable Isobar (Z)	a	Chain Yield (%)	Fractional Yields of Radioactive Isobars x 100											
				b	Cum.	Direct	b	Cum.	Direct	b	Cum.	Direct	b	Direct[c]
88	Sr(38)	25	3.62	Rb (37)			Kr (36)	104±6 [16]	37±3 [15]	Br (35)		56±23 [9]	Se (34)	24±6[e] [13] 11±1 [12] 13±2 [14]
		23	5.52								47±6 [10]	52±13 [8]		
		49	1.375								61±3 [10]			
89	Y (39)	25	4.80	Rb (37)		4.7±1.6 [22] 4.0±.8 [18]	Kr (36)		69±4 [15]	Br (35)		44±10 [8] 48±7 [9]	Se (34)	2.3±.8 [12]
		23	6.33					86±1 [19]			19±9 [10]			
		49	1.74					86±1 [19]			63±25 [10]			
90	Sr(38)	25	5.89	Rb		13±1 [18] 13±1 [22]	Kr	86±2 [20]	63±8 [15]	Br			Se	
		23	6.83	(37)			(36)	67±1 [19]		(35)	10±3 [10]		(34)	
		49	2.12					64±1 [19]			10±4 [10]			
91	Zr(40)	25	5.93	Sr (38)		3±3 [17]	Rb (37)	93±5 [23]	40±2 [22] 39±3 [18]	Kr (36)	59±1 [20]	54±2 [15]	Br (35)	7.5±7 [9]
		23	6.51		98±4 (Av.)						33±1[d] [19]			
		49	2.54		95±2 (Av.)						31±1[d] [19]			
92	Zr(40)	25	5.97	Sr (38)			Rb (37)		62±16 [21] 40±3 [18] 55±2 [22]	Kr (36)	31±1 [20]	25±1 [15]	Br (35)	<3. [9]
		23	6.64								13±1 [19]			
		49	3.05								11±1 [19]			
93	Zr(40)	25	6.40	Sr (38)			Rb (37)		48±3 [22] 49±3 [18]	Kr (36)	7.8±.8 [23]	8.3±.5 [15]	Br (35)	
		23	7.04								2.3±.1 [19]			
		49	3.92								2.1±.1 [19]			
94	Zr(40)	25	6.44	Y (39)	6±2 [68]		Sr (38)			Rb (37)		23±1 [22] 27±2 [18]	Kr (36)	1.5±.6 [23] 4.0±.3 [15]
		23	6.79											
		49	4.47											

a Fissile isotope; 25 = ^{235}U, 23 = ^{233}U, 49 = ^{239}Pu
b Radioactive isobar and atomic number, Z, in brackets
c For these isobars the cumulative yield is approximately equal to the direct yield
d Multiplied by fractional cumulative yield of ^{91}Sr
e See footnote e on preceding page

TABLE B1, continued (All references are for the Appendix B reference list)

Mass	Stable Isobar (Z)	a	Chain Yield (%)	Fractional Yields of Radioactive Isobars x 100										
				b	Cum.	Direct	b	Cum.	Direct	b	Cum.	Direct	b	Direct [c]
95	Mo(42)	25	6.50	Zr	99±1 (Av)	.4±.2 [24]	Y Y		13±6 [25]	Sr			Rb	10±.5 [22] 12±1 [18]
		23	6.22	(40)	100±3 (Av)	3.4±.6 [24]	(39)			(38)			(37)	
		49	5.01		99±2 (Av)									
96	Zr(40)	25	6.28	Rb (37)		2.0±.1 [22] 3.0±.5 [18]	Kr (36)			Br (35)			Se (34)	
		23	5.71											
		49	5.12											
97	Mo(42)	25	6.03	Zr (40)			Y (39)			Sr (38)			Rb (37)	0.5±.1 [22] 1.6±.6 [18]
		23	5.40											
		49	5.59											
98	Mo(42)	25	5.79	Zr			Y			Sr			Rb	
		23	5.13	(40)			(39)			(38)			(37)	
		49	5.88											
99	Tc(43)	25	6.13	Mo (42)		6±1 [26]	Nb,m (41) g	33±3 [26] 31±2 [27] 61±11 [26]	 30 [28]	Zr (40)	1.9±1 [26]		Y (39)	
		23	4.99				m		29±1 [27]					
		49	6.32											
100	Mo(42)	25	6.30	Zr			Y			Sr			Rb	
		23	4.38	(40)			(39)			(38)			(37)	
		49	7.10											
101	Ru(44)	25	5.05	Mo			Nb			Zr			Y	
		23	3.21	(42)			(41)			(40)			(39)	
		49	6.01											
102	Ru(44)	25	4.19	Mo			Nb			Zr			Y	
		23	2.44	(42)			(41)			(40)			(39)	
		49	6.13											

a Fissile isotope; 25 = ^{235}U, 23 = ^{233}U, 49 = ^{239}Pu
b Radioactive isobar and atomic number, Z, in brackets
c For these isobars the cumulative yield is approximately equal to the direct yield

TABLE B1, continued (All references are for the Appendix B reference list)

Mass	Stable Isobar (Z)	a	Chain Yield (%)	Fractional Yields of Radioactive Isobars x 100										
				b	Cum.	Direct	b	Cum.	Direct	b	Cum.	Direct	b	Direct [c]
103	Rh(45)	25	3.12	Tc			Mo			Nb			Zr	
		23	1.70	(43)			(42)			(41)			(40)	
		49	6.95											
104	Ru(44)	25	1.83	Mo			Nb			Zr			Y	
		23	1.03	(42)			(41)			(40)			(39)	
		49	6.07											
105	Pd(46)	25	0.927	Ru			Tc	76±3 [29]		Mo	98±2 [30]		Nb	
		23	0.53	(44)			(43)			(42)			(41)	
		41	5.47					72±8 [29]						
106	Pd(46)	25	0.390	Ru			Tc			Mo	107±9 [30]		Nb	
		23	0.255	(44)			(43)			(42)			(41)	
		49	4.48					80±10 [29]						
107	Pd(46)	25	0.17	Ru			Tc	33±5 [29]		Mo			Nb	
		23	0.12	(44)			(43)			(42)			(41)	
		49	3.5					41±5 [29]						
129	I(53)	25	0.65	Sb (51)		11±5 [32]	Sn,m (50) g	53±3 [32] 36±3 [32] 31±1 [34]		In (49)			Cd (48)	
		23	1.60											
		49	1.5											
130	Te(52)	25	1.7	Te (52)		3 [28]	Sb,m (51) g		37 [28] 20±3 [32] 9 [28] 14±3 [32]	Sn (50)	50 [28] 52±6 [32]		In (49)	
		23	2.4											
		49	2.5											

a Fissile isotope; 25 = ^{235}U, 23 = ^{233}U, 49 = 239Pu
b Radioactive isobar and atomic number, Z, in brackets
c For these isobars the cumulative yield is approximately equal to the direct yield

TABLE B1, continued (All references are for the Appendix B reference list)

Mass	Stable Isobar (Z)	a	Chain Yield (%)	Fractional Yields of the Radioactive Isobars x 100											
				b	Cum.	Direct	b	Cum.	Direct	b	Cum.	Direct	b	Direct [c]
131	Xe(54)	25	2.82	Te,m (52)	16[e] [35] 15[e] [36]	2.5±2.5 [37] 11 [38] 8±1 [39] 51±10 [36] 1.5±1.5 [37] 4.4±.7 [39] 12 [28]	Sb (51)	64±2 [36] 91±9 [40]	59±14 [41] 52 [28]	Sn (50)	28 [42] 35 [28] 33±6 [32] 45±7 [41]		In (49)	
		23	3.52	m g	98 [43]	23 [38]								
		49	3.74	m		18±5 [38]								
132	Xe(54)	25	4.20	Te (52)	102±5 [Av]	20±2 [41] 38±2 [44] 2 [45]	Sb (51)	72 [40]	66±8 [41] 49±1 [44] 16±2 [45]	Sn (50)	14±4 [41] 14±1 [44] 20 [42] 32±3 [46]	56 [45]	In (49)	25±2 [45]
		23	4.82			64±4 [44]			27±3 [44]		2.5±.5 [44]			
		49	5.23		100±5 [Av]	2 [45]			9±7 [45]			61 [45]		27±5 [45]
133	Cs(55)	25	6.75	I (53)		26 [36] 2.5±2.5 [37] 2.2±.8 [41] 12 [47] 2.5±.8 [48] 2±2 [49] 2.5±1.4 [50] 2 [45]	Te,m (52)g m+g	71 [36]	29±4 [41] 5±5 [37] 28±4 [41] 45±7 [45]	Sb (51)	56 [36] 42±10 [51]	46 [41] 51±5 [45]	Sn (50)	3 [45]
		23	6.02			14±1 [52] 21±1[f] [53]								
		49	6.92			15±3 [52] 6 [45]			40±7 [45]			49±5 [45]		5 [45]

a Fissile isotope, 25 = ^{235}U, 23 = ^{233}U, 49 = ^{239}Pu
b Radioactive isobar and atomic number, Z, in brackets
c For these isobars the cumulative yield is approximately equal to the direct yield
e About 7% of ^{131}Sb decays to ^{131m}Te[39] so that most of the cumulative yield is formed directly
f Revised to 15.5±1 (private communication from H.O.Denschlag, 1974)

TABLE B1, continued (All references are for the Appendix B reference list)

Mass	Stable Isobar (Z)	a	Chain Yield (%)	Fractional Yields of the Radioactive Isobars x 100											
				b	Cum.	Direct	b	Cum.	Direct	b	Cum.	Direct	b	Direct
134	Xe(54)	25	7.65	I (53)		13 [54] 11±2 [37] 12 [47] 10±1 [28] 12±2 [49] 12±1 [50] 35±5 [45]	Te (52)	89±1 [56] 90 [28]	52±6 [45]	Sb (51)	4.2±.5 [55] 3.8 [51]	16 [45]	Sn (50)	1 [45]
		23	6.13			33±2 [52] 37±2 [53]								
		49	7.42			34±3 [52] 15±7 [45]			51±6 [45]			23 [45]		5 [45]
135[d]	Cs(55)	25	6.60	Xe	100	3.5	I	96.5	47	Te	50	(47)	Sb	(3)
		23	6.24	(54)	>99	21.0	(53)	79.0	61	(52)	18	(18)	(51)	(∿0)
		49	7.69		>99	15.0		85.0	61		24	(23)		(∿1)
136	Xe(54)	25	6.18	Xe (54)		21±4 [57] 24±18 [58] 34±5 [45]	I (53)	65±15 [58]	67±25 [57] 21±8 [48] 35±5 [45]	Te (52)		10±3 [57] 24±4 [45]	Sb (51)	5±3 [45]
		23	6.87											
		49	6.47			32±5 [45]			33±3 [45]			25±4 [45]		5±3 [45]
137	Cs(55)	25	6.26	Xe (54)	97.8±.3 [23]	33±5 [57] 48±6 [15]	I (53)		53±6 [57] 28±6 [59] 46±7 [9]	Te (52)		8 [57]	Sb (51)	1 [57]
		23	6.80		90±1 [19]			28±3 [10]						
		49	6.65		92±1 [19]			42±2 [10]			16±4 [10]			
138	Ba(56)	25	6.80	Cs (55)		4.7±.2 [23] 4.8±.1 [60] 14 [45]	Xe (54)		74±8 [15] 56±5 [45]	I (53)		17±3 [45] 12±3 [59]	Te (52)	4±2 [45]
		23	5.92					83±1 [19]			10±1 [10]			
		49	5.73			22 [45]		85±1 [19]	55±7 [45]		14±9 [10]	15±3 [45]		4±2 [45]

a Fissile isotope; 25 = ^{235}U, 23 = ^{233}U, 49 = ^{239}Pu
b Radioactive isobar and atomic number, Z, in brackets
c For these isobars the cumulative yield is approximately equal to the direct yield
d Recommended fractional yields from Table 4

TABLE B1, continued (All references are for the Appendix B reference list)

Mass	Stable Isobar (Z)	a	Chain Yield (%)	Fractional Yields of the Radioactive Isobars x 100											
				b	Cum.	Direct	b	Cum.	Direct	b	Cum.	Direct	b	Direct
139	La(57)	25	6.50	Ba (56)		1.1±.4 [23] 5±5 [69]	Cs (55)		24±2 [22] 20±3 [60] 18±2 [18]	Xe (54)	82±2 [56]	79±7 [15] 13±3 [69]	I (53)	12±5 [9] 7±4 [59] 2±1 [69]
		23	6.40			8.4±.7 [61]					48±1 [19]			≤11 [10]
		49	5.72								55±1 [19]			5.4±3.4[10]
140	Ce(58)	25	6.36	Ba (56)		4.6±3.0[23]	Cs (55)	93±3 [23]	31±2 [22] 33±3 [18]	Xe (54)	60±1 [56]	46±6 [15]	I (53)	3.4±2.1 [9]
		23	6.43			27±4 [61]					23±1 [19]			
		49	5.59								30±1 [19]			
141	Pr(59)	25	5.82	La (57)		.30±.04[62] .37±.13[23]	Ba (56)		26±5 [23]	Cs (55)		55±1 [22] 45±7 [60] 52±4 [18]	Xe (54)	21±2 [20] 20±3 [15]
		23	6.60											5.1±.3 [19]
		49	5.34											7.9±.4 [19]
142	Ce(58)	25	5.87	La (57)		1.7±.4 [23]	Ba (56)			Cs (55)		41±1 [22] 25±7 [60]	Xe (54)	6±5 [63] 11±2 [15]
		23	6.61											1.0±.1 [19]
		49	5.00											1.7±.1 [19]
143	Nd(60)	25	5.95	Ce (58)		.53±.03[23] 12±3 [64]	La (57)	70 [65]		Ba (56)	88±6 [66]		Cs (55)	25±1 [22] 17±3 [60] 29±3 [18]
		23	5.86											
		49	4.51											
144	Nd(60)	25	5.39	Ce (58)		1.2±1.2[67]	La (57)			Ba (56)	78±6 [66]		Cs (55)	5.2±1.6[22] 22±3 [18]
		23	4.61											
		49	3.80											

a Fissile isotope; 25 = ^{235}U, 23 = ^{233}U, 49 = ^{239}Pu
b Radioactive isobar and atomic number, Z, in brackets
c For these isobars the cumulative yield is approximately equal to the direct yield

TABLE B1, continued (All references are for the Appendix B reference list)

Mass	Stable Isobar (Z)	a	Chain Yield (%)	Fractional Yields of Radioactive Isobars x 100										
				b	Cum.	Direct	b	Cum.	Direct	b	Cum.	Direct	b	Direct [c]
145	Nd(60)	25	3.93	Ce		61 [64]	La			Ba			Cs	7±2 [18] 2.5±1.2[60]
		23	3.38	(58)			(57)			(56)			(55)	
		49	3.05											
146	Nd(60)	25	2.97	Pr			Ce			La			Ba	
		23	2.53	(59)			(58)			(57)			(56)	
		49	2.52											
147	Sm(62)	25	2.25	Pr			Ce	96±5 [17]		La			Ba	
		23	1.76	(59)			(58)			(57)			(56)	
		49	2.13											
148	Nd(60)	25	1.68	Pr			Ce			La			Ba	
		23	1.28	(59)			(58)			(57)			(56)	
		49	1.69											
149	Sm(62)	25	1.07	Nd			Pr			Ce			La	
		23	0.77	(60)			(59)			(58)			(57)	
		49	1.29											

a Fissile isotope; 25 = ^{235}U, 23 = ^{233}U, 49 = ^{239}Pu
b Radioactive isobar and atomic number, Z, in brackets
c For these isobars the cumulative yield is approximately equal to the direct yield

APPENDIX C

MISCELLANEOUS TABLES

Two tables were prepared for the oral presentation which may be of general interest.

Table C1 shows revisions to the ^{140}Ba yields of Table 2. The investigation was initiated by a letter from M. Lammer noting that the result of Santry and Yaffe [31] required renormalization. The remaining β-counting measurements, with one exception, required corrections for flux depression. The changes increase the weighted mean by 0.8%.

Table C2 is a revised table of the thermal/epithermal counting rates given in Tong et al.[81]. The purpose of the data as originally presented was intended to show that for each irradiation this ratio was constant within experimental error for many radioactive fission products in the peak region.

In Table C2 each measured ratio is divided by the mean ratio for the same irradiation so that the numbers all lie within a few percent of unity and those in the bottom line are, of course, exactly one. These ratios of ratios are then averaged for each nuclide with the average values and their rms deviations listed in the right hand column. Only for mass 140 does the average value deviate from unity significantly. Even here 2 of the 3 measurements differ by appreciably less than the assigned error of 4%.

TABLE C1

MASS 140 YIELDS FROM ^{235}U FISSION

Ref. year	Chain Yields (%) Table 2	Corrected	Comments
27 (1951)	6.17±.13(.62)	6.51±.62	Fission chamber; 2πβ counting of ^{140}Ba + ^{140}La. Counting correction by Glendenin quoted in [30]. Target thickness equivalent to ~ 20 mil foil; no correction for flux depression, estimated correction (3±0.5)%.
28 (1952)	6.37±.18(.64)	6.55±.64	Fission chamber; 2πβ counting of ^{140}Ba + ^{140}La. Target 20 mil foil; no correction for flux depression; estimated correction (3±0.5)%.
29 (1953)	6.25±.13(.59)	6.25±.59	2πβ counting relative to ^{89}Sr absolute yield. Same authors give absolute yields of ^{97}Zn, ^{99}Mo very different from evaluated values so results are questionable.
30 (1954)	6.32±.24(.58)	6.55±.58	Flux from m.s. analysis of B^{10}/B^{11} in B monitor; 2πβ counting. Correction is for flux depression as calculated by Petruska et al (CJP33,693).
31 (1960)	6.36±.12(.46)	6.68±.46	Co monitor; 2πβ counting. Renormalized to $\sigma_f(^{235}U)$=557b; $\sigma_a(^{59}Co)$=37.2b
33 (1968)	6.36±.32(.32)	6.36±.32	Fission chamber; Ge(Li)γ-detector; counted ^{140}La γ-ray against ^{140}Ba ^{140}La standard.
34 (1971)	6.29±.14(.25)	6.29±.25	Fission chamber; Ge(Li)γ-detector; counted ^{140}La γ-ray against irradiated ^{139}La; ^{140}La decays of std. determined by 2πβ counting.
18 (1971)	6.40±.11(.26)	6.40±.26	Fission chamber; Ge(Li)γ-detector; counted ^{140}La γ-rays and obtained absolute disintegration rate using calibrated detector efficiency.
35 (1973)	5.77±.30	not used	Mica fission track recorder; Ge(Li) γ-detector; counted ^{140}La standard; weight of fission foil not given; no correction for flux depression.
Weighted means	6.34±0.35(0.05)	6.39±0.37(0.10)	

TABLE C2

RELATIVE (THERMAL/SHIELDED) ACTIVITY RATIOS
FOR ^{239}Pu FISSION PRODUCTS

Experiment No.	1	2	3	4	5	
Shield Material	Sm	Cd	Cd	Sm	Sm	Av
Kr-85m		0.991				0.991
Sr-91	1.029	1.021				1.013±.012
Y-91m	0.994	1.013	1.01			
Sr-92	1.012					1.012
Zr-97	1.000	1.013	0.994			1.004±.012
Nb-97	1.012	1.017	0.994			
Tc-99m			0.989	1.017		1.003±.014
Ru-103				1.008	0.986	.997±.011
Ru-105	1.029	1.019				1.017
I-131			1.029	1.000	1.021	1.017
Te-132	0.987	0.991	0.989	1.008	1.021	1.004±.015
I-132		1.017	1.022	1.000	1.007	
I-133	1.000	0.983	1.017	0.992	0.992	0.997±.013
I-135	1.017	1.026	1.006	0.967	0.986	1.006±.023
Xe-135	0.982	0.995	0.977			
Ba-140				0.959		0.971±.011
La-140				0.975	0.979	
Ce-143	0.997	0.966	1.011	0.983	0.979	0.987±.018
Nd-147			1.006	0.967	0.986	0.986±.020
Weighted average	1.000	1.000	1.000	1.000	1.000	
	±.023	±.021	±.029	±.025	±.029	

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