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The third IAEA review of the 2200 m/s and 20°C Maxwellian neutron data for U-233, U-235, Pu-239, Pu-241 and the spontaneous neutron yield of Cf-252

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This is the Draft from early 1975 on which the summary by H.D. Lemmel was based that was presented at the Conference on Nuclear Cross Sections and Technology, Washington D.C., 3-7 March 1975. At that time, it was expected that the encountered discrepancy between 2200m/s values and 20°C Maxwellian values could soon be resolved by the improved fitting procedure by B.R. Leonard Jr. As this was not the case, and as no further manpower could be made available for this work at the IAEA, the Manuscript remained in this stage as of February 1975. An updated fit was presented at the Symposium on Neutron Standards and Applications, Gaithersburg Md, 28-31 March 1977, but the present manuscript was not updated accordingly.

Note: This Manuscript was not submitted to the co-authors for final approval. Nevertheless it will contain much useful information.

H.D. Lemmel, April 1982

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1. INTRODUCTION

In 1965 [1] and 1969 [2] consultants groups convened by the IAEA Nuclear Data Section published consistent sets of recommended best values of the thermal neutron data of the fissile nuclides. These include 2200 m/s and thermal Maxwellian averaged cross-sections, related parameters and fission-neutron yields for U-233, U-235, Pu-239, Pu-241 and of the fission-neutron yield $\bar{\nu}$ of Cf-252. The present paper is a continuation of these earlier evaluations (which will hereinafter be referred to as Paper 1 and Paper 2); the recommended values presented here supersede the earlier ones.

In 1969 it was known that the recommended data suffered mainly from two uncertainties: firstly from the spread in the experimental results for $\bar{\nu}$ of Cf-252, and secondly from the uncertainty in half-life values, especially that of U-234, which is basic to the knowledge of the U-235 fission cross-section. At that time there were arguments in favor of assuming rather high values for $\bar{\nu}$(Cf-252) and $T_{1/2}$(U-234), an assumption which meanwhile turned out to be wrong.

New measurements for both quantities obtained lower values, and consequently we believe now that the U-235 fission cross-section is significantly higher, and that the fission neutron-yields $\bar{\nu}$ are significantly lower than the values recommended in Paper 2. These changes exceed the standard-deviation errors given in Paper 2.

In addition to these two major changes a number of further adjustments became necessary concerning Westcott g-factors, standard cross-sections, mean fission spectrum energies, scattering cross-sections, and others. Therefore, a complete new evaluation of the thermal neutron cross-sections and parameters of the fissile nuclides was desirable.

It will be shown that some disturbing discrepancies encountered earlier among experimental data can be regarded as resolved, but that some other significant discrepancies, which continue to exist, require some further investigations. These will be discussed.

2. GENERAL CONSIDERATIONS

2.1 THE PROCEDURE

The general philosophy of the evaluation remained the same as in Papers 1 and 2, that is: Available experimental data are entered in a least-squares fitting program. The weight of each input datum is given by $1/e^2$, where e is the relative standard-deviation error including statistical and systematic error contributions.

Values and errors of input data were carefully reviewed; the reference standards were adjusted to up-to-date values; experimental corrections and errors were revised where possible and necessary. On this basis, values and errors were adjusted only for physical reasons inherent in the experiment. Discrepancy with other input data was in principle not recognized as a sufficient reason to increase errors. Authors of re-assessed data were contacted where possible.

Concerning the systematic errors, one must assume that these have a statistical distribution in the various experiments. Where this is not the case, error correlations were considered and reflected in the fit as far as possible.

Data with insufficient documentation, that is new data prior to publication or old insufficiently published data may be downweighted, usually by a factor of 2, that is by multiplying the error with $\sqrt{2}$.

2.2 THE LEAST-SQUARES FIT

The fitting program used is a general least-squares fitting program "LSF" by D. McPherson and J.H. Johnson[3]. It was adapted to the IAEA computer and slightly modified by C.L. Dunford. This program has some advantages against the one used in Paper 2, although it does in principle the same. As a test, this program had been used for fitting the input data of Paper 2, and the results from both programs were identical. In fact, McPherson's program had been used already for Paper 2 at Chalk River in parallel to the IAEA program.

The advantages of the new program against the 1969 IAEA program are:
1. The Pu-241 data are fitted in the same fit together with the other nuclides, whereas in 1969 they were fitted separately. 2. The new program is flexible in the choice of input variables, and many more parameters could be defined and fitted. The number of fitted expressions was close to 200. Among these were 51 independent variables, compared to 16 independent variables in 1969. 3. This allowed more convenience and transparency in the treatment of error correlations and thermal-Maxwellian averaged input data. (This however does not mean that there was something incorrect in the treatment of such data in the 1969 program.)

There exist a few limitations in the nature of the least-squares fitting method which must be considered. Firstly, the theory of this method requires that the input data to be fitted are statistically independent, respectively that the error correlations of the input data are known and formulated in the fit. In fact, most of the significant correlations, for example correlations between data resulting from the same experiment or from similar ones, are well reflected in the fit. However, it is certainly not possible to consider all existing correlations among

the experimental data, and consequently, the errors resulting from the fit may be slightly too small.

Secondly, the theory of the least-squares fitting method requires that the error function of the input data has a Gaussian distribution. This condition is clearly violated in certain cases, for example in the case of $T_{1/2}$(Pu-239) where existing measurements claiming high accuracy are very discrepant; or when the likelihood for possible values of a given quantity, such as a g-factor, is perhaps better described by a rectangular distribution than by a Gaussian. In such cases, the half width of the spread or of the rectangular distribution is treated in the fit as a standard deviation error. This is certainly not quite correct.

2.3. FORMULATION OF INPUT DATA

In this paper, the 2200 m/s cross-sections are denoted by σ, and thermal-Maxwellian averaged cross-sections by $\hat{\sigma} = g\sigma$.

In the least-squares fit, the following quantities, for each of the nuclides U-233, U-235, Pu-239, Pu-241, were taken as basic independent variables to be fitted:

2200 m/s cross-sections for absorption σ_a, fission σ_f and bound-atom scattering σ_{sb}; the 2200 m/s fission-neutron yields per absorption η and per fission $\bar{\nu}_p$; the Westcott g-factors, defining the ratio $\hat{\sigma}/\sigma$ of thermal-Maxwellian averaged data versus 2200 m/s data, for absorption, g_a, and fission, g_f, in a 20.4°C Maxwellian spectrum.

Other quantities were formulated as derivatives of these basic ones, for example:

20.4°C Maxwellian data were entered as the product $\sigma * g$;
the total cross-section σ_t was formulated as $\sigma_a + \sigma_s$;
the capture-to-fission cross-section ratio α as $\sigma_a/\sigma_f - 1$;
the same as a 20.4°C Maxwellian average $\hat{\alpha} = (\sigma_a g_a)/(\sigma_f g_f) - 1$;
the g-factor for capture $g_\gamma = (\sigma_a g_a - \sigma_f g_f)/(\sigma_a - \sigma_f)$;
the delayed neutron yield per fission $\bar{\nu}_d = (\eta\,\sigma_a)/\sigma_f - \bar{\nu}_p$; etc.

The fit is independent of the choice of independent variables. If one chooses σ_γ and σ_f as independent variables (instead of σ_a and σ_f), thus entering σ_a as the sum of $\sigma_\gamma + \sigma_f$, one obtains exactly the same results. In particular it has been checked that no rounding error is introduced by formulating σ_γ or $\bar{\nu}_d$ as a difference of two large numbers.

Furthermore, independent variables were introduced for the total and the prompt fission-neutron yield of Cf-252, and for the half-lives of U-233, U-234

and Pu-239. Some more variables were defined in order to take care of error correlations between different input data.

2.4. TREATMENT OF CORRELATED ERRORS

If an author determines in the same experiment a quantity for 2 or 3 nuclides, the correlation of these data can be taken into account as described in Appendix B of Paper 2: by entering in the least-squares fit the data and their ratios with appropriately increased errors.

This method was continued to be used. But in some cases, especially when more than three input data were involved, another method was used as well, namely to enter the common error source as independent variable to be fitted. In this case, the i correlated quantities σ_i are entered as $\sigma_i \; x = n_i \pm e_i$, with a separate input for $x = 1 \pm e_x$, where x represents the common error source, n_i the author's measured values of σ_i, e_i the experimental error excluding the contribution from x, and e_x the uncertainty due to x.

To mention a typical case: Such a common-error variable was introduced for the $\bar{\nu}$ data for five nuclides by Boldeman, where e_x includes all experimental error contributions common to the five $\bar{\nu}$ data.

Similarly, another common-error variable was introduced for the uncertainty due to the NPL manganese bath, on which a number of $\bar{\nu}$ data by different authors depend.

In a similar way, some reference values by which different input data are correlated, were introduced as independent variables to be fitted. These are in particular the half-lives $T_{1/2}$ for U-233, U-234 and Pu-239 on which many fission cross-section determinations depend. Often the product of fission cross-section times half-life is directly measured, and this expression which is independent from an assumed value for the half-life, is entered in the least-squares fit.

For other standard cross-sections, for example Au(n,γ), B-10(n,α) or Co-59(n,γ), the correlation of different input data depending on the same standard was negligible, because the error contribution from these standards is too small. They were therefore not entered in the fit as variables.

2.5 TREATMENT OF MEAN FISSION-SPECTRUM ENERGIES

A number of determinations of $\bar{\nu}$ are dependent on assumptions on the spectrum of fission neutrons, and corrections are applied assuming certain values for the mean fission-spectrum energies $\bar{E}$ for the five nuclides considered. All $\bar{E}$ dependent $\bar{\nu}$ input data are therefore partially correlated, and this correlation is best reflected in the least-squares fit by entering the five $\bar{E}$ values as independent variables to be fitted.

If the author's result was $\bar{\nu}_f = n_{author} \pm e_{author}$, and if the slope of the efficiency curve of his detector was s per MeV, and if the value of $\bar{E}$ he assumed was $\bar{E}_{author}$, then his result is entered in the fit as

$$\bar{\nu}_p / (1 + s\ (\bar{E} - \bar{E}_{author})) = n_{author} \pm e_o$$

where $\bar{\nu}_p$ and $\bar{E}$ are independent variables to be fitted, and e_o is the author's error excluding the error contribution which he assumed due to the uncertainty in $\bar{E}$. In this formulation, the sign in front of s must be positive if the efficiency decreases with increasing energy of fission neutrons. For $\bar{E}$, a preferred value and error is entered in the fit as a separate input.

In this formalism it is essential to distinguish between two error contributions. The one is due to the uncertainty in $\bar{E}$, and this is taken care of by entering $\bar{E}$ as a variable in the fit; this error contribution is to be excluded from e_o. The other is due to the uncertainty in the efficiency slope s, and this error contribution, which is significant in some cases, must be included in e_o.

Similarly, a $\bar{\nu}$ ratio which is dependent on assumptions on $\bar{E}$, is entered in the fit as

$$(\bar{\nu}_p^1 / \bar{\nu}_p^2) / (1 + s\ (\bar{E}^1 - \bar{E}^2 - \delta\bar{E}_{author})) = n_{author} \pm e_o$$

where the superscripts 1 and 2 denote the two nuclides involved; $\bar{\nu}_p^1$, $\bar{\nu}_p^2$, $\bar{E}^1$ and $\bar{E}^2$ are the independent variables to be fitted; $\delta\bar{E}_{author}$ is the spectrum-energy difference which was assumed when deducing the result n_{author}; e_o is the error excluding the error contribution from the uncertainty in the spectrum-energy difference.

It should be noted that the purpose of this method is not to obtain from the fit values for $\bar{E}$ which are better than the input values chosen; this is not possible, because the representation of the fission spectrum by a single parameter $\bar{E}$ is a too rough approximation. This approximation may however be good enough to express the correlation of different $\bar{\nu}$ data, and this is the only purpose of formulating the five $\bar{E}$ values as independent parameters in the fit.

3. REFERENCE VALUES

Standard cross-sections used for the derivation of input data, and half-lives which are entered directly in the fit, are discussed in the following. Some more reference values used will be mentioned in the text where the input data concerned are discussed.

3.1 STANDARD CROSS-SECTIONS

The standard cross-sections used are listed in Table 1. There are some changes since Paper 2.

The hydrogen (n,γ) cross-section was left unchanged.

The B-10 absorption cross-section was reviewed by Story [R5] who suggests to reduce the scattering cross-section slightly to $\sigma_{bound} = 2.66 \pm 0.08$ b and therefore recommends a value which is about 0.1% higher than the value previously recommended by Gubernator and Moret [R4]. This is mainly relevant to the fission cross-sections measured by Deruytter.

The Na-23 activation cross-section was reduced by 0.8%[R5]. This affects the fission cross-sections by Popovic.

The knowledge of the Co-59 activation cross-section (leading to 1925.5 day Co-60) was much improved by the precise measurement of Dilg et al.[R2] and our new preferred value is 0.8% lower than that in Paper 2. This reduces the absolute measurements of the Maxwellian capture and absorption cross-sections by Cornish, Halperin and Cabell, and also the fission cross-sections by Keith.

In the same paper by Dilg et al.[R2] a precise determination of the gold capture cross-section is given which leaves our value of Paper 2 unchanged but reduces its error. The fission cross-sections by Bigham and Raffle, and Green's absorption cross-section, which were measured relative to gold, need therefore no revision of their standard compared to Paper 2.

3.2 HALF-LIVES

The present situation with the half-lives, on which many fission cross-section measurements depend, was recently reviewed by Vaninbroukx [H19]. For some nuclides, existing unexplained discrepancies between measured values make a reliable evaluation of "best" half-life values still rather difficult.

For U-233 the situation as of 1969 was reviewed in Paper 2 page 8 and table IIa. At that time disturbingly low values for the U-233 half-life had just been reported by Keith $(1.553 \pm 0.010)\ 10^5$y [H8] and Oetting $(1.554 \pm 0.003)\ 10^5$y [H14], which

were in disagreement with previously accepted values and in particular with the value of (1.621 ± 0.003) 10^5y by Ihle [H3]. Since then three new measurements have been performed by Durham [H2], by Vaninbroukx et al. at Geel [H18] and by Jaffey et al. at Argonne [H5], which are in excellent agreement close to 1.590 * 10^5y (see table 2). These were adopted as input values in the least-squares fit. The first two of them are downweighted (error times 1.4) because of their insufficient respectively preliminary state of publication. The error quoted by Jaffey reflects only the scatter between four runs, and does not reflect any systematic errors common to the four runs. We therefore assigned it, arbitrarily, an error which gives it same weight as the Geel value.

The excellent agreement between the ANL and Geel values, based on carefully and accurately performed measurements using several independent methods, solves the 4% discrepancy between the values determined before 1968, and it seems justified to ignore these earlier values although the reason for their large spread is not known.

It is worth-while to mention that Jaffey et al. [H5] revised the U-233 half-life determined by Bigham et al. [F1] by updating its reference value of the natural uranium specific activity [H4] and obtained (1.590 ± 0.003) 10^5y in good agreement with the recent half-life values.

For U-234, a half-life value seems now to be established which is 1.7% lower than that assumed in Paper 2. The three recent measurements by Meadows [H11], Lounsbury and Durham [H9], and by de Bièvre et al. [H1] were entered in the fit (see table 2).

For Pu-239, experimental half-life values looked consistent in our 1969 evaluation (see Paper 2 page 35), where a value of 24380 ± 50y was adopted. However, lateron Oetting withdrew [H15] his calorimetric result of 24310 ± 50y which he had obtained in 1967 [H13]

obtained in 1967 [H13] because the Pu-238 content of the sample used in this experiment was not known with sufficient accuracy. In an improved experiment he obtained in 1970 [H14] a new calorimetric result of 24065 ± 50y. This supported his earlier low value of 24181 ± 125y from 1965 [H12]. Yet all results by alpha counting are around 24400 ± 50y [Paper 2], except for the ones by Sellers et al. [H17] who obtained 24100 ± 58y, and by Westrum et al. [H21] who obtained 24000 ± 70y. See the recent review by Oetting [H22].

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A new calorimetric experiment is being performed at the Mound Laboratory with a preliminary result of 24170y [H7]. Mound scientists are confident that the Pu-239 half-life as determined calorimetrically by specific activity is reliable having in mind that the calorimetrically measured Am-241 half-life, which used to be even 5.5% lower than corresponding alpha-counting values was now confirmed around 433.8y using three different methods: direct decay, integrated decay curve of Pu-241 into Am-241 using the initial weight of Pu-241 and directly by specific activity [H7]. The calorimetric Am-241 half-life value was also confirmed by a new measurement made in USSR by alpha-counting [H16].

Three indirect determinations [H10] of the Pu-239 half-life compiled in a paper appended to a still unpublished report of the American National Standards Institute yield values of 24213 ± 100y, 24062 ± 100y, 24134 ± 100y respectively, and thus support a low value of the half-life.

Finally, it will be shown later in this paper that a fit of the existing 2200 m/s fission data is significantly more consistent if a low half-life value is adopted for Pu-239.

All these are indications for a low Pu-239 half-life value of 24100 ± 50y. However, for the purpose of the present review, we found it premature to use this low value and prefer to use the mean between the high value used in Paper 2 and the new low value and thus adopt for input 24240 ± 140y, where the error represents the spread between the old and new values.

The error function of the Pu-239 input value is clearly not a Gaussian as required by the least-squares fitting method. One would expect that either the old high or the new low value is close to the correct one, but not the mean of both, and the input value chosen is an unsatisfactory compromise. A confirmation by new experiments is urgently needed. New measurements are presently being performed by Jaffey [H6] at Argonne and by Vaninbroukx [H20] at Geel, but the results are not yet available. Mound Laboratory is coordinating a cooperative half-life measurement program of five US laboratories [H7]. In particular it will be investigated whether the geometry factor is the most likely source of error of previous alpha-counting measurements.

For Pu-241, the half-life value assumed and the corresponding corrections in Pu-241 data have been left the same as in Paper 2.

4. 2200 m/s INPUT DATA

4.1 SCATTERING, TOTAL AND ABSORPTION CROSS-SECTIONS

The scattering cross-sections have been studied in detail in Paper 2. Some new measurements have become available since then. A new evaluation by B.R. Leonard Jr. [S3] suggested an increase in the scattering cross-section for U-233 and a decrease for U-235.

The thermal-energy scattering cross-sections σ_s and therefore also the total cross-sections σ_T depend on the structure of the sample, and corresponding corrections were made to the experimental total cross-section data, similar as in Paper 2. Depending on the sample type, the total cross-sections were formulated as either $(\sigma_a + \sigma_{sb})$ or $(\sigma_a + \sigma_{sm})$, where the bound-atom scattering cross-section used for liquid and powdered-metal samples is denoted as σ_{sb} and that for rolled-metal or unspecified-metal samples as σ_{sm}. Total cross-section data obtained on other sample types were reduced, for input in the fit, to one of the above sample types, using the corrections listed in table 3. For further details see the notes to table 3. For Pu-241 the scattering cross-sections were left as in Paper 2.

The total and absorption cross-section data used are shown in table 4. The data and their re-assessments are the same as in Paper 2 but adapted to the new formulation of input. For Gerasimov the error was further increased by a factor 1.4 for lack of documentation of systematic errors.

4.2 FISSION CROSS-SECTIONS

There are two important new determinations of fission cross-sections using monoenergetic neutrons, for U-235 and Pu-239. These were made by Deruytter et al. [F9, F10] at Geel and by Petrascu et al. [F2, F3, F17] at Bucarest. In both cases the sample assay was made by alpha counting. Therefore, the results are half-life dependent, and the product of $\sigma_f\ T_{1/2}$ is entered in the fit (see table 5b). Both measurements are relative to boron, but the Romanian group did not use the B-10(n,α) cross-section as standard but measured the activation of Li-7*, using the accurately known B-10(n,α) branching ratio. Both measurements agree very well.

These new experiments determine significantly the present knowledge of the U-235 and Pu-239 2200 m/s fission cross-sections. It is regrettable that the result of a similar experiment for U-233 which is being planned at Geel [F26], was not yet available for the present evaluation, and that the Pu-239 half-life is not yet sufficiently well known.

In Paper 2 the input data for σ_f(U-235) looked rather discrepant, and an additional error was introduced in the fit to represent the discrepancy of data.

Much of this discrepancy has disappeared, partially due to the revised value of the U-234 half-life, and partially due to a careful review by Deruytter [F7] who found the reason for the previously encountered discrepant results of the experiments by Şaplakoğlu and Maslin et al. The value by Friesen et al. [F12] was withdrawn by the authors [F15].

For further details see the notes to tables 5a and 5b.

4.3 NEUTRON YIELD PER ABSORPTION

Since the new measurements of $\bar{\nu}$(Cf-252) made it evident that the $\bar{\nu}$ values of Paper 2 were too high, considerable effort has been given to the critique of η data. It seemed that the low $\bar{\nu}$ values were not consistent with the relatively high experimental η values.

The experiments concerned are those by Smith et al. [E16, E17, E18, E19] with monoenergetic neutrons, and by Macklin et al. [E11, E12] in a thermal neutron spectrum. The latter is entered in the fit as 2200 m/s result, because the data were reduced by Monte Carlo calculations without using g-factors.

Axton, among others, performed re-evaluations of these experiments. His results in the case of Smith were even insignificantly higher, rather than lower. Revised corrections for manganese resonance absorption, neutron leakage and capture in oxygen and sulfur resulted in a net increase of +0.17%, +0.13%, +0.22%, +0.22% for U-233, U-235, Pu-239, Pu-241 respectively. Also, the authors' errors due to fast fission, assumed as only 6% of the corresponding correction, may be considered as too optimistic.

Recently, Monte Carlo calculations for the corrections in the U-233 and U-235 experiments were repeated at the Bettis Laboratory [E7, E20]. The fast effect could not be extracted in a form comparable to the original corrections used. The other corrections agreed within 0.1% except in two cases: The Bettis calculations predicted about 0.3% less absorption in the aluminium sample holder than was measured, and 0.22% less loss of high-energy neutrons to oxygen and sulfur. Smith concludes [E17] that the Bettis calculation may be more reliable in the latter case since it used more recent oxygen cross-sections, but that it under-predicts the aluminum absorption, assuming the presence of pure aluminum. Consequently, Smith suggests that the MTR η values could be lowered by 0.2 or 0.3%, this being within the claimed accuracy of the experiment. Thus, we reduced the MTR η values by 0.25% but kept, after consultation with Smith, the authors' errors unchanged.- A reduction of the MTR values by 0.4% as suggested by De Volpi [C5] could not be verified.

For the data by Macklin et al. the corrections for cross-sections curve shapes were left as in Paper 2, but the error due to these corrections was slightly increased. For the corrections for manganese resonance absorption, fast-neutron

capture in oxygen, fast-neutron escape, and fast fission, Axton performed detailed re-calculations. The resulting net corrections, which are shown in table 6, reduced the authors' values slightly, but not as much as suggested by De Volpi [5].

Also shown in table 6 are the U-233 η data as reviewed and revised by Steen [G7]. His results, in particular that for Macklin, are a bit larger than the values we adopted.

5. 20°C MAXWELLIAN INPUT DATA

Cross-sections measured in a thermal neutron spectrum were converted to a 20°C Maxwellian spectrum in the same way as in Paper 2. The new fitting program allowed direct input of the expression $\hat{\sigma}$ (20°C Maxwellian) $= g\,\sigma$, combined with a separate input for the 20°C g-factors using estimated best values and errors.

5.1 FISSION CROSS-SECTIONS

The data available in Paper 2 have mostly been left unchanged except for the different formulation of input data with respect to g-factors and half-lives. See table 7 and the corresponding notes for details.

The measurement of $\hat{\sigma}_f$(U-233) bei Keith[F14] was treated in Paper 2 as half-life independent, since Keith measured $\hat{\sigma}_f * T_{1/2}$(U-233) and $T_{1/2}$(U-233). Having the new measurements of $T_{1/2}$(U-233), we must conclude that Keith's half-life measurement must have been wrong, and we use only his result of $\hat{\sigma}_f * T_{1/2}$.

The contrary occurred to Bigham's[F1] experiment, since his result of $T_{1/2}$(U-233) was meanwhile confirmed, after revising it for its reference value of the specific uranium activity (see section 3.2). Despite of this confirmation, we increased the errors of this experiment arbitrarily, in order to avoid that the fit of Maxwellian data is determined by the dominating weight of Bigham's results, of which the possible systematic errors are insufficiently documented.

Of the experiment by Lounsbury et al. [C11] only preliminary results were available in Paper 2, and the final results are now used.

There are new determinations of $\hat{\sigma}_f$(U-233/U-235), half-life independent, by Vidal et al. [F24], and of $\hat{\sigma}_f$(Pu-239/U-235), half-life dependent, by Sweet[F23]. See table 7 and the corresponding notes.

5.2 20°C MAXWELLIAN ALPHA, CAPTURE AND ABSORPTION DATA

The treatment of the input data for $\hat{\alpha}$, $\hat{\sigma}_\gamma$ and $\hat{\sigma}_a$ is based on Paper 2. There is an important new measurement of $\hat{\sigma}_\gamma$(U-233) by Cabell and Wilkins[C3]. See tables 8a and 8b and the relevant notes.

The absolute values of $\hat{\sigma}_\gamma$ and $\hat{\sigma}_a$ were reduced by 0.8% due to the revised lower value of the cobalt activation cross-section standard as explained in section 3.1.

The accuracy of the $\hat{\alpha}$ and $\hat{\sigma}_\gamma$ values of the uranium isotopes is much suffering of the insufficient knowledge of the lowest energy curve shape of the capture cross-section, which makes the temperature correction $g(20°C)/g(T)$ rather uncertain. For a measurement made at 100°C (e.g. Cabell 1966), the uncertainty may be 2% in $\hat{\alpha}$,

and even for an experiment made at 37.5°C (Lounsbury) the uncertainty is still 0.5%; see section 7.5.

5.3 RATIOS FOR $\hat{\eta}$, $\hat{\sigma}_a$, $\hat{\eta}\hat{\sigma}_a$, $(\hat{\eta}^{-1})\hat{\sigma}_a$ $(\hat{\eta}-1)\hat{\sigma}_a$

Ratio data for the neutron-yield per absorption in thermal neutron spectra, are listed in table 9 and discussed in the Notes 9.1 to 9.4.

The revised results of Gwin + Magnuson's reactivity and liquid critical experiments published in 1971 [E13] had been available already in Paper 2, but some further revisions based on a study by Story have been applied; see Notes 9.2 and 9.3.

A new set of data was obtained by Laponche et al. [E10] using global and local oscillators in the CESAR graphite moderated reactor. Of the results reported we use only the ratio data, since the absolute values reported by the authors cannot be regarded as independent measurements.

6. NEUTRON YIELD PER FISSION

6.1 DELAYED NEUTRON YIELDS

There are several recent reviews of delayed neutron yield data by Tomlinson [N47, table 2 page 6], by Manero and Konshin [N33, table 17], by Cox [N18], and by Tuttle [N52].

The delayed neutron yields change slightly but significantly with increasing incident neutron energy, and we use therefore only the thermal values as input to the least squares fit (see table 10). Less accurate data such as those by Notea [N39] were omitted. Some experimental values of delayed neutron yields had to be adjusted slightly for weak additional neutron groups; however such uncertainties affect the present fit only very little.

6.2 MEAN FISSION-NEUTRON SPECTRUM ENERGIES

The mean fission-spectrum energies $\overline{E}$ adopted in 1971 by A.B. Smith [M8] were systematically lower than the values assumed in Paper 2 (see table 11). The difference $\overline{E}$(Cf-252) - $\overline{E}$(U-235), which determines the correction required for $\bar{\nu}$ ratio data, was 0.25 MeV in Paper 2 and 0.21 MeV in Smith's review.

Whereas Smith's values represent weighted means of the existing data, which are partly rather discrepant, more recent careful experiments tend to support a rather high value for U-235, close to the value adopted in Paper 2, but a rather low value for Cf-252, in contrast to the value adopted in Paper 2. It seems now that both mean fission-spectrum energies for U-235 and Cf-252 are closer together than assumed earlier. This increases some of the experimental data of the ratio $\bar{\nu}$(U-235)/ $\bar{\nu}$(Cf-252) by up to a few tenth of a percent, compared to Paper 2.

For the values adopted see table 11. The errors were assumed rather large in order to take care of the fact that the single parameter $\overline{E}$ is a poor representation of the fission spectrum. Rose [M7] obtained a spread of $\pm$ 0.13 MeV in $\overline{E}$ depending on the type of fit he used.

For the treatment of the $\overline{E}$ values in the fit see section 2.5.

6.3 INPUT DATA

At the time of our 1969 review, a serious discrepancy existed between $\bar{\nu}$ values of Cf-252 measured by different techniques. The existing values formed two distinct groups with a discrepancy of 2.5%. The two liquid-scintillator measurements and one of the manganese-bath data formed the one group close to $\bar{\nu}_p = 3.8$, all the

other manganese bath data and the boron pile data formed the other group close to $\bar{\nu}_p = 3.7$.

This discrepancy among the Cf-252 $\bar{\nu}$ data does no longer exist, partially because after careful studies some of the previously extreme data had to be revised, and partially because a new liquid-scintillator measurement by Boldeman [N9] with a relatively low result, reconciled the previously existing systematic discrepancy between the liquid-scintillator method and the other methods. The revisions applied to earlier values are the following:

For the liquid-scintillator experiment by Asplund-Nilsson et al. [N2] improved Monte-Carlo calculations of the leakage correction were done by Condé et al. [N15] and by Axton [N4], yielding a significant reduction of the original disturbingly high result of this experiment.

Also the other rather high liquid-scintillator result by Hopkins and Diven was reduced. A recent paper by Poitou and Signarbieux [N41] added to previous Monte-Carlo calculations a new element, which is the emission of gamma cascades and their interactions with the scintillator. This effect and a correction for delayed gammas reduced the original result by 0.4%.

The manganese bath measurement by Axton et al. [N3] of which an extremely low preliminary result was available in Paper 2, was meanwhile finalized obtaining a value in good agreement with other recent results.

The Harwell boron pile experiment requires further investigations and accurate efficiency calculations. It seems that the removal of neutrons in copper and carbon has been neglected and that certain assumptions on the prompt gate length and the efficiency curve may have to be reviewed again. Although quantitive re-assessments have not been done, it seems justified to correct the boron pile data by + 0.2 ± 0.2%, and in addition the photoneutron calibrated value by + 0.25 ± 0.25%.

The situation is now such that five of the nine values for $\bar{\nu}_p$(Cf-252) are in excellent agreement in the range of about 3.715 to 3.735. These include the three most recent and most accurate determinations by De Volpi, Axton and Boldeman. However, their fitted mean value may still be shifted a bit depending on the mean fission spectrum energy $\bar{E}$ assumed for Cf-252. Only two of the nine values namely the 1967 manganese bath result by White and Axton, and the revised result of the 1963 liquid scintillator experiment by Asplund-Nilsson et al. still support a high value near 3.79. Although it would be interesting to know why these two results are 1.5% higher than the others, it appears that $\bar{\nu}_p$(Cf-252) is now well established at a value close to 3.735.

J.R. Smith at ANC is continuing experiments [E17] testing the accuracy of the manganese bath method. He points out that Axton and De Volpi agree in their Cf-252 $\bar{\nu}$ values, for which they claim accuracies better than 0.5%, but that their values for the hydrogen-to-manganese cross-section ratio differ by 1.4%. One may therefore still expect some small adjustments of $\bar{\nu}$(Cf-252) values, but the main discrepancy encountered earlier appears to be resolved.

Also the University of Michigan is studying the feasibility of using their manganese bath facility for another measurement of $\bar{\nu}$(Cf-252) [N48].

A further experiment was recently performed in the USSR. B.M. Aleksandrov at the Radievyj Institut Leningrad [N1] obtained a preliminary result of $\bar{\nu}_t$(Cf-252) = 3.770 ± 0.045. Since this experiment was not yet mentioned in the literature, it was not used for the present evaluation, and the final value and error analysis must be awaited. The neutron-yield was measured by three methods: 1. in a graphite sphere calibrated with t-d neutrons, 2. by activation of gold foils, 3. in a cylindrical manganese bath with 85 cm diameter and 95 cm height. The fissions were counted in a chamber with a small solid angle.

The input data for $\bar{\nu}$(Cf-252) are listed in table 12a. They were recently reviewed in detail by Axton [N4], but a few further revisions became necessary since then (see notes 12.01 to 12.06).

The $\bar{\nu}$ data for the U and Pu isotopes, mostly relative measurements, are listed in table 12b. The data are essentially the same as in Paper 2, but the corrections for fission-neutron spectra differences were treated differently, as discussed above, and the uncertainties for the shape of the detector efficiency were increased where appropriate.

If some numerical values look slightly different from Axton's paper respectively Paper 2, this is due to the following changes of the formulation of the input:

The values entered in the fit are prompt $\bar{\nu}$ data, as measured in all experiments, except the two by White and Axton, and by Axton, where $\bar{\nu}_t$ was measured and entered as such in the fit. This careful distinction between $\bar{\nu}_p$ and $\bar{\nu}_t$ in the fit would only then become significant, if the delayed-neutron yields were noticeably shifted in the fit. This was however not the case.

To take care of error correlations between different experiments, some variables were introduced: x_{NPL} for the common error sources of all experiments dependent on the NPL manganese bath; x_{BP} for the common error of the two experiments made at the

Harwell boron pile; x_{Bold} for the common error of the Boldeman measurements on the five nuclides considered.

The correction for the different fission-neutron energies includes a double uncertainty: First the uncertainty due to the mean spectrum energies; this is taken care of by entering the mean spectrum energies as variables to be fitted. Second the uncertainty due to the shape of the detector efficiency curve; if the shape of the efficiency curve is not well known, rather large uncertainties can result if the spectrum energy differences are in the order of magnitude of 0.1 MeV. For this reason, the errors of the data by Kalashnikova et al., Sanders, De Saussure and Silver, Moat et al., Jaffey and Lerner, were significantly increased.

7. g-FACTORS

For the temperature correction $g/g(T)$ which reduces the measured effective cross-section from the experimental spectrum temperature T to 20°C, the following sources were used:

U-233: Steen 1972 [G7] page 51.
U-235 and Pu-239: Westcott 1969 [G11] page A.V. 16.
Pu-241: Lemmel and Westcott 1967 [G3].

In Paper 2 the 20°C g-factors taken for input were those evaluated by Westcott [G11]. Since then, some new measurements and considerations suggested some changes. There is a slight inconsistency, if the 20°C g-factors assumed do not quite agree with the above-mentioned g-factor calculations used for the $g/g(T)$ corrections are supposed to cover this inconsistency.

7.1 EXTRAPOLATION OF CROSS-SECTION CURVES TO ZERO ENERGY

The crux of all g-factor calculations is the uncertainty of the curve shapes below 0.0253 eV, as already pointed out by Westcott [G11]. A large portion of the Maxwellian spectrum is situated below this energy, and measured cross-sections in this energy range, if existing at all, have usually insufficient accuracy. Thus, the extrapolation of the cross-section curves to zero energy must be based on somewhat arbitrary decisions. It seems therefore possible in some cases, that the lowest-energy curve shapes deviate from those assumed by Westcott. This may in particular be the case for the uranium isotopes, where the lowest-energy curve shapes are influenced by negative-energy resonances.

One can estimate the contribution of the lowest energy curve shape to the g-factor by studying the Maxwellian density distribution M(E). This is illustrated by figure 1. The g-factor is calculated from the cross-section curve $\sigma(E)$

according to

$$g\sigma_o \sqrt{E_o} = \int_0^\infty \sigma(E) \sqrt{E}\, M(E)\, dE$$

with $\int_0^\infty M(E)\, dE = 1$, resp. $M(E) = 2 \sqrt{E/\pi}\, (kT)^{-\frac{3}{2}}\, e^{-E/kT}$.

Knowing that in the integral the expression $\sigma(E) \sqrt{E}$ is nearly constant, it is essential to look at the density distribution $M(E)$. This has its maximum at $\frac{1}{2} kT$ that is 0.0125 eV. Therefore the g-factor is much determined by the cross-section values around 0.01 eV and, in fact, almost half of the integral determining the g-factor lies below the energy of 0.0253 eV.

For $kT = 0.0253$ eV it can be found that of the integral $\int_0^\infty M(E)dE$ approximately

4%	is in the energy-range	0. - 0.004 eV
5%	" " " " "	0.004 - 0.007 eV
5.5%	" " " " "	0.007 - 0.01 eV
9.5%	" " " " "	0.01 - 0.015 eV
9.5%	" " " " "	0.015 - 0.02 eV
9%	" " " " "	0.02 - 0.0253 eV
42.5%		0. - 0.0253 eV

If one changes the extrapolation of a cross-section curve to zero energy by

3%	in the range	0. - 0.004 eV
2.5%	" " "	0.004 - 0.007 eV
2%	" " "	0.007 - 0.01 eV
1.2%	" " "	0.01 - 0.015 eV
0.5%	" " "	0.015 - 0.02 eV
0%	" " "	0.02 - 0.0253 eV,

thus leaving the 0.0253 eV value unchanged, one obtains a change of 0.5% in g. For the uranium isotopes, where the extrapolation to zero energy is rather uncertain due to the negative-energy resonances, the uncertainty may even be much larger than 0.5%. It appears therefore that the g-factor errors assumed by Westcott in the order of magnitude of 0.2%, are too small.

The fact, that the lowest-energy cross-section curve-shapes for the uranium isotopes seem to depend much on the negative-energy resonance, the parameters of which are not well known, makes the treatment of the g-factors in a least-squares fit rather difficult, for two reasons. Firstly: within certain limites a number of different cross-section curves seem equally possible, and the error which one may assign to a g-factor, has hardly a Gaussian distribution and does therefore not fulfil the requirements of the least-squares fit. Secondly, the lowest-energy curve-shapes of the capture cross-section and of the fission cross-section are not

independent since both depend on the resonance-parameters chosen. Consequently, the g-factors g_γ and g_f (respectively g_a and g_f) are not independent, but their inter-dependence cannot be expressed in a way which is suitable for input in the least-squares fit. The significance of the g-factors of the uranium isotopes resulting from the least-squares fit is therefore limited, as long as the lowest-energy cross-section curves of the uranium isotopes are not better known than at present.

7.2 CORRELATIONS BETWEEN g_a AND σ_s

The absorption g-factor g_a is usually calculated from an absorption cross-section curve $\sigma_a(E)$, which has been deduced from an experimental curve of the total cross-section $\sigma_t(E)$ by assuming a certain value for the scattering cross-section σ_s, which is assumed as constant. If σ_s is changed, g_a will change, too, and this interdependence must be considered in a least-squares fit.

The g-factor g_a is related to the total cross-section σ_t by

$$\begin{aligned} g_a\,\sigma_a\sqrt{E_o} &= \int \sigma_a(E)\sqrt{E}\,M(E)\,dE \\ &= \int [\sigma_t(E) - \sigma_s]\sqrt{E}\,M(E)\,dE \\ &= \int \sigma_T(E)\sqrt{E}\,M(E)\,dE - \frac{2}{\sqrt{\pi}}\,\sigma_s\sqrt{E_o} \end{aligned}$$

since $\int \sqrt{E}\,M(E)\,dE = 2\sqrt{E_o/\pi}$.

From this one can deduce the change δg_a in the g-factor, caused by a change $\delta\sigma_s = \delta\sigma_a$ in the scattering cross-section:

$$\delta g_a = -\frac{\delta\sigma_s}{\sigma_a}\left(\frac{2}{\sqrt{\pi}} - g_a\right) .$$

For the uranium isotopes (resp. plutonium isotopes) a change of +1 barn in the scattering cross-section will cause a change of about -0.0002 (resp. -0.0001) in g_a.

Within the least-squares fit, as it will be seen later, the scattering cross-sections are shifted much less than 1 barn, and therefore the correlation with g_a is negligible in the given fit.

However, if one compares earlier g-factor calculations, where different scattering cross-sections have been assumed, with the present results, one may have to adjust g_a on account of σ_s.

Westcott [G11] resp. Lemmel and Westcott [G3] assumed 13, 15, 11, 11 barns for U-233, U-235, Pu-239, Pu-241 respectively, whereas our present values for

metal samples are 12.3, 14.8, 7.2, 10.8 barns respectively. Hence, Westcott's g_a values must be increased by +0.0002 for U-233 and +0.0004 for Pu-239.

7.3 CORRELATIONS BETWEEN g_a AND σ_a

There is a further peculiarity to be considered with the absorption g-factors. If the fission cross-section σ_f is adjusted in the least-squares fit, the normalization point of the $\sigma_f(E)$ curve is changed, but curve shape and g-factor remain unaffected. If, however, the absorption cross-section σ_a is adjusted in the fit, this may result in a different curve shape which will affect the g-factor g_a. As distinct from the fission cross-section curve, the total cross-section is measured absolutely at each energy. A small change of σ_a around 0.0253 eV will therefore not affect σ_a at other energies and will therefore result in a slightly different curve-shape and hence in a different g-factor.

It is however difficult to quantify the dependence of g_a on σ_a. If one keeps the extrapolation to zero energy unchanged, a rough assessment suggests that the parameter $(g_a\sigma_a - 0.3\,\sigma_a)$ will be approximately independent of σ_a for small changes in σ_a. An expression which would furthermore be independent of σ_s (compare the previous section) would be $(g_a\sigma_a - 0.3\,\sigma_a) + (2/\sqrt{\pi} - 0.3)\,\sigma_s$, and this is used as input for the two more important nuclides U-235 and Pu-239.

7.4 g-FACTORS FOR α, η, $\bar{\nu}$

For certain experimental quantities it is essential to consider carefully which g-factors apply. Measurements of the capture-to-fission cross-section ratio $\hat{\alpha}$ are usually made such that the absorption (resp. capture) in a Maxwellian spectrum and the fission in a Maxwellian spectrum are determined. Therefore, the g-factor to be applied for α is

$$g_{1+\alpha} = \frac{\hat{\sigma}_a}{\hat{\sigma}_f} \quad \frac{\sigma_a}{\sigma_f} = \frac{g_a}{g_f}$$

Similarly, the measurements of $\hat{\ }$ are such that the g-factor to be applied is

$$g = \frac{\bar{\nu}_t\,\hat{\sigma}_f}{\hat{\sigma}_a} \quad \frac{\bar{\nu}_t\,\sigma_f}{\sigma_a} = \frac{g_f}{g_a} \ .$$

This is however subject to the condition that $\bar{\nu}_t$ = constant in the thermal energy range. If this condition were not fulfilled, one had to compute a separate g-factor for the product $\bar{\nu}_t\,\sigma_f$, from which the g-factor for η could be deduced.

It must be considered whether the fission-neutron yield is sufficiently constant in the thermal energy range.

The recent work by Reed et al. [N43] shows that $\bar{\nu}$ for U-233 and U-235 is constant in the energy range from 0 to 1.5 eV, but drops by more than 1% at 2 eV and higher energies. This small structure at 2 eV is at a too high energy as to produce a g-factor for $\bar{\nu}_t \sigma_f$ deviating from g_f.

Reed's data look however discrepant from earlier data by Weinstein [N49] who found a slope in $\bar{\nu}(E)$ in the thermal region. However, the deviations from $\bar{\nu}$ = constant are such that they do not produce a g-factor for $\bar{\nu}_t \sigma_f$ which is significantly different from g_f.

Although it would be possible to introduce in the least-squares fit a g-factor for $\bar{\nu}_t \sigma_f$ which is close to but not identical with g_f, we prefer to retain the assumption $\bar{\nu}$ = constant and hence to retain $g_\eta = g_f / g_a$.

7.5 g-FACTORS FOR U-233

Since Paper 2, cross-section curve-shapes for U-233 were measured by Weston et al. [G12] for fission and capture, and by Deruytter and Wagemans [G1] for fission. See table 13a.

There is good agreement in g_f but some discrepancy in g_γ respectively g_a. This is not surprising considering the large scatter of lowest-energy absorption cross-sections shown by Westcott on page 46 of reference [G11]. Unfortunately, the new capture curve by Weston et al., being a very important measurement above about 0.03 eV, shows a rapid increase in possible systematic errors below this energy [G13]. In fact, the sum of Weston's lowest-energy capture and fission cross-sections gives an absorption cross-section which is considerably lower than all other data. A slight decrease in Weston's fission cross-section below 0.03 eV was however repeatable [G13] and seems significant. A similar decrease can be observed in the 1960 MTR data [G5]. For Deruytter's measurement [G1] the lowest-energy data being measured on the BR2 reactor, are not yet available.

Whereas in earlier g-factor calculations a linear extrpolation of the fission, capture and absorption cross-section curve shapes towards zero energy was assumed, a resonance structure as shown in Fig. 21 appears to be possible as well. In this figure possible curves are presented which were computed by Moore [G4], based on Weston's data assuming the resonance at 0.165 eV with a width of about 90 eV (case A in Fig. 21), plus an additional resonance at -0.01 eV with a width of 40 eV (case B). Case C shows a less likely case assuming the negative resonance with a width of 20 eV with zero fission width. Corresponding g-factors are given in table 13a. These indicate that it seems advisable to assume the uncertainties of g_γ respectively g_a considerably larger than in Paper 2.

Consequently, the temperature dependence of the capture g-factors $g_\gamma(T)$ is quite uncertain. For curve B g_γ is practically constant between 20°C and 100°C, whereas Steen [G7] obtains $g(20°C)\ g\ (100°C) = 0.977$. This means, when correcting an integral measurement from a spectrum temperature of 100°C to 20°C, there is an uncertainty of 2.3% in $\hat{\delta}_\gamma$ respectively 2. Corresponding uncertainties were therefore added in quadrature to the $\hat{\alpha}$ and $\hat{\delta}_\gamma$ data for U-233 and U-235. Compare Note 8.0.

7.6 g-FACTORS FOR U-235

The fission g-factor for U-235 appears to be rather well established. The value evaluated by Westcott [G11], which was 0.9772 ± 0.0015, was meanwhile confirmed by the fission-curve measurement by Deruytter et al. [F9] yielding 0.9780 ± 0.0010. Considering that Westcott's value and error reflects several independent measurements and their spread, a value of 0.9775 ± 0.0025 was adopted as input.

For the U-235 absorption g-factor Westcott [G11] obtained a value of $g_a = 0.979 \pm 0.001$ which was apparently based on an approximately constant extrapolation of α to zero energy, although some trial curves show also an increase of α towards zero energy.

The fission cross-section curve indicates the existence of a negative resonance, and it can be expected that this would give an increased value of α near zero energy, similar to the increased α near the 0.3 eV resonance. Compare BNL-325 [G8]. The scatter of experimental points is such that a variety of α curve shapes can be assumed near zero energy.

Several such α curve shapes are shown, for example, by Chawla [E4, fig. 2]. Chawla assumed the σ_a curve as well-known and thus adjusted the σ_f curve. After having the σ_f curve by Deruytter et al. [F9], it seems now that σ_f is better known and that the σ_a curve shape should be adjusted if the α curve is varied. If this is done, one obtains absorption g-factors g_a between about 0.976 and 0.990. Admitting that some extreme values may be rather unlikely, one will have to assume an uncertainty of at least ± 0.003 in g_a. According to section 7.4, the input was formulated in the form $(g_a\sigma_a - 0.3\ \sigma_a) + 0.8284\ \sigma_s$; see Note 13.

For the temperature corrections $g(20°C)/g(T)$ the same uncertainty was assumed as for U-233.

7.7 g-FACTORS FOR PU-239

The Pu-239 fission g-factor by Westcott [G11] was 1.0522 ± 0.0030, although many values resulting from his extensive fitting study were around 1.055. The

recent fission cross-section curves measured by Deruytter and Becker [F10] on the Mol BR2 reactor and by Deruytter and Wagemans [F8] on the CBNM Linac yield g-factors of 1.0522 and 1.0534 respectively([G2], superseding the considerably higher values of 1.054 and 1.0566 reported earlier by the same authors). A combined value of the two new results, which are not quite uncorrelated, gave $g_f = 1.053 \pm 0.003$. The quoted error is, to a large extent, due to the extrapolation to zero energy for which Wagemans and Deruytter [G2] "adopted very conservative errors". This appears to be an acceptable input considering that earlier reported g-factors range between 1.049 and 1.057 [G11].

Westcott's g-factor for absorption was $g_a = 1.0762 \pm 0.0031$, which must be increased, due to the revised scattering cross-section, to 1.0766. This value was assumed as input, but the input was formulated like that for U-235; see Note 13.

7.8 g-FACTORS FOR PU-241

The Pu-241 absorption g-factor by Lemmel [G3] must be revised to $g_a = 1.0395 \pm 0.002$ for a correction in the scattering cross-section to be subtracted from the measured total cross-sections. This revised value is in good agreement with Westcott's $g_a = 1.038 \pm 0.001$ [G11]. Increasing the error for extrapolation uncertainties, we use for input $g_a = 1.039 \pm 0.003$.

For fission, there remains an unexplained discrepancy between $g_f = 1.044 \pm 0.004$ by Lemmel [G3] and $g_f = 1.051 \pm 0.008$ by Westcott [G11], however the latter value was considered by the author as tentative only. The fission cross-section curve has recently been remeasued by Wagemans and Deruytter [G9] in an energy range going down to 0.01 eV. The resulting g-factor is $g_f = 1.046 \pm 0.006$ in good agreement with the value by Lemmel. We assume for input $g_f = 1.045 \pm 0.006$.

8. RESULTS OF THE LEAST-SQUARES FITTING

When fitting all data in a least-squares fit, some important input data are shifted in a disturbing way, due to discrepancies between some of the input data. In order to analyze, where the discrepancies are, some trial fits were made for subsets of the input data.

8.1 $\bar{\nu}$ DATA

Fit (2) in table 14 shows the results when fitting the data and their ratios alone. The agreement between the experimental data is sufficient. For $\bar{\nu}$(Cf-252), two of the nine experimental input data deviate from the fitted value by more than their input error. Axton pointed out earlier [N5], that the external

standard error ($\pm$ 0.0088) is not significantly greater than the internal error ($\pm$ 0.0082) of the weighted mean. In the present fit the consistency of the $\bar{\nu}$(Cf-252) data appears even better due to the additional revisions applied to some input data and due to the mean fission spectrum energies being treated as variables.

The ratios are consistent, in particular for U-235, where only one of 10 input data is discrepant from the weighted mean. For U-233 (resp. Pu-239, Pu-241) two out of eight input data (resp. three out of six, resp. one out of seven input data) deviate from the fitted value by more than the respective input errors.

Thus, $\bar{\nu}$(U-235) appears to be rather well established; however, this value maintains some flexibility in the fit due to the rather large uncertainties adopted for the mean fission spectra energies, through which the U-235/Cf-252 $\bar{\nu}$ ratio may be somewhat adjusted in the fit.

Table 14 shows on the bottom the mean fission-spectra energies resulting from the fit. Values and errors are determined little by the values chosen for input, but mainly from the comparisons of $\bar{E}$ dependent and $\bar{E}$ independent data. Thus, the resulting values can be regarded as an independent determination of the mean fission spectra energies, within the limitations inherent in the representation of the spectra by only one parameter.

8.2 2200 m/s DATA AND $\bar{\nu}$ DATA

The group of 2200 m/s data includes total cross-sections (absorption plus scattering), fission cross-sections, and the eta data by Smith. The eta data by Macklin, which are formally coded as 2200 m/s data, although they were measured in a Maxwellian spectrum, were excluded from this group.

Fit (1) in table 14 shows the results when fitting the 2200 m/s data alone, without $\bar{\nu}$ data. There are not many interrelations between the input data of this group, and the excellent agreement between the input data and the fitted data is therefore not significant.

Quite significant however is the outcome of fit (3) in table 14, where the 2200 m/s data were fitted simultaneously with the $\bar{\nu}$ data. As distinct from fit (1), the 2200 m/s data of σ_f, σ_a and η are, in fit (3), strongly coupled (except for U-233, see below) through the $\bar{\nu}$ data entered in the same fit. The fitted results of the fits (1) and (3) are in excellent agreement, and also the $\bar{\nu}$ data resulting from fits (2) and (3) are nearly identical. The agreement between the $\bar{\nu}$ data and the 2200 m/s data is indead extraordinary. If one compares the separate fits (1) for the 2200 m/s data and (2) for the data on the one

side with the combined fit (3) on the other side, one finds that in the worst cases the inaccurately known values of σ_f(U-233) and $T_{1/2}$(Pu-239) differ by as little as one half of their output errors. Almost all other data differ by only less than one tenth of their respective errors.

Among the 43 experimental 2200 m/s cross-section and eta data, only one total cross-section value and one fission cross-section value deviate from the fitted value by more than their experimental error. Both of these values are anyway rather inaccurate and have no significance in the fit.

The χ^2 value of fit (3) is about one third of its expectation value.

The important conclusion is, that the 2200 m/s data and the $\bar{\nu}$ data are absolutely consistent. This is essential, because the $\bar{\nu}$ data and the 2200 m/s fission cross-sections are those data out of all the fitted parameters which had the most drastic changes since Paper 2. One may conclude that the 2200 m/s data and $\bar{\nu}$ data obtained in fit (3) must be considered as reliable, and that a fit which does not sufficiently well reproduce this set of data, can hardly be accepted.

For U-233 the situation is different. The 2200 m/s fission cross-section of U-233 is poorly known (see fit (1)) from only a single direct measurement which is inaccurate. The accuracy of this quantity resulting in fit (3) comes exclusively from the indirect determination $\sigma_f = \frac{\eta}{\bar{\nu}_t}\,\sigma_a$. The result of an absolute precision measurement of σ_f(U-233) being planned at Geel [F26] is therefore eagerly awaited, in order to verify whether the agreement between monoenergetic experimental data of σ_f, σ_a, $\bar{\nu}$, η is as good for U-233 as for the other three nuclides.

8.3 HALF-LIVES

To check whether the half-life values entered in the fit cause discrepancies, several fits were made without any input for half-lives. The results are shown in table 15. Three fits were performed: In fit (4), where all fission cross-section data are fitted, half-lives are obtained from the comparison of half-life dependent and half-life independent measurements. In fit (5), where 2200 m/s data and data are fitted, half-lives are obtained mainly from Deruytter's $(\sigma_f T_{1/2})$, Smith's η, σ_a as obtained from the total cross-section measurements, and $\bar{\nu}_t$ from the fit of $\bar{\nu}$ data alone:

$$T_{1/2} = \frac{(\sigma_f T_{1/2})\,\bar{\nu}_t}{\eta\,\sigma_a}$$

In fit (6), all input data together are fitted without input for half-lives.

For U-234 the indirect half-life is consistent, in all three test-fits with the mean of the direct values used for input.

For Pu-239 the indirect values are in good agreement with the adopted input. However, if one prepares a fit of 2200 m/s data and data with using only the Pu-239 data by Smith and Deruytter (fit 5a) and ignoring ratio data to other nuclides, the resulting indirect Pu-239 half-life value is 0.5% lower and agrees with the results of the recent determinations described in section 3.2. This indicates, that some disturbances may be introduced in the Pu-239 data from the ratio data with other nuclides, especially with U-233.

The Pu-239 half-life value around $(2.440 \pm 0.005)\ 10^4$y which is obtained in most determinations by alpha counting, is not supported by any of the indirect values.

For U-233 the indirect half-life values are lower than the direct ones. However, this discrepancy is little significant in view of the internal discrepancies of U-233 data which are found in other test fits (see further below).

It is rather unfortunate that the experimental reason for the discrepancies of the experimental half-life values is not yet known. It is possible that there is an unknown systematic error in the α-counting technique of the half-life experiments. If this is so, the same unknown error may have affected those fission cross-section measurements in which the sample assay is done by α-counting. Such vague suspicion did however not justify to increase the errors of these fission cross-section measurements.

Fortunately, the 2200 m/s fission cross-section of U-235 is mainly based on measurements of σ_f(U-235)*$T_{1/2}$(U-234) and of $T_{1/2}$(U-234) both done very accurately at the same lab, such that any systematic error in the α-counting would cancel for σ_f(U-235). The result appears therefore to be reliable. This is confirmed by the good agreement between the direct and indirect half-life values of U-234. For U-233 and Pu-239 the situation is not so good, and one must wait for accurate measurements of σ_f*$T_{1/2}$(U-233) and of $T_{1/2}$(Pu-239) presently being done at Geel and elsewhere to obtain reliable fission cross-sections for U-233 and Pu-239.

8.4 20°C MAXWELLIAN DATA

In the group of Maxwellian input data there are fission cross-sections, alpha data, capture and absorption cross-sections, and eta data partially in the

form of $\hat{\eta}\hat{\sigma}_a = \bar{\nu}_t\hat{\sigma}_f$ and $(\hat{\eta} - 1)\,\hat{\sigma}_a$.

The eta data by Macklin and the $(\hat{\eta} - 1)\,\hat{\sigma}_a$ data by Muehlhause, Alikhanov and Cabell were omitted from all test fits, because these input data were reduced either without using g-factors or by using g-factors only in an approximative formalism. (For the total fit of all input data, these data were however included.)

Fit (7) in table 16 shows the results when fitting the Maxwellian input data alone. These input data are somewhat more interdependent with each other than the 2200 m/s data, and it is therefore not surprising that the Maxwellian input data are less consistent. However, there are some inconsistencies which are disturbing. These are shown in table 17.

The various measurements of $\hat{\alpha}$ for U-233 and U-235 are not quite consistent with each other. The spread of data suggests uncertainties of the mean value in the order of $\pm$ 0.003 and $\pm$ 0.002 for U-233 and U-235 respectively, instead of the resulting errors of $\pm$ 0.0005 resp. $\pm$ 0.0007 which are mainly determined by the Lounsbury experiment.

However, if one repeats the various fits with such increased errors of $\hat{\alpha}$, this does not make any differences because the quantity $(1 + \hat{\alpha})$ has still a dominating weight in the fit.

The first two lines in table 17 show two discrepant input data for the U-233 fission cross-section. The one of them (Keith) suggests a value considerably larger, the other (Bigham) considerably smaller than the fitted value of $\hat{\sigma}_f$(U-233). The error of $\hat{\sigma}_f$(U-233) resulting from fit (7) (see table 16) appears therefore as too small.

There are two input data which are particularly discrepant with the results of fit (7). These are the Pu-239/U-235 fission cross-section ratio by Sweet and the U-233/U-235 eta ratio by DeBoisblanc (see table 17). It is however just these two data which are in excellent agreement with fit (3), where the same Maxwellian ratios are obtained indirectly from a fit of 2200 m/s data and data, combined with the input g-factors. Many of the other Maxwellian data are discrepant with the data deduced from the 2200 m/s data from fit (3) and the g-factors. One may conclude that the input data by Sweet and DeBoisblanc are correct, although they are in disagreement with the other Maxwellian input data.

8.5 MAXWELLIAN DATA AND $\bar{\nu}$ DATA

If one deduces $\bar{\nu}$ data from the Maxwellian data through the equation $\bar{\nu}_t = \hat{\eta}\,(1 + \hat{\alpha})$, it becomes evident that Maxwellian data and $\bar{\nu}$ data are not consistent. From fit (7) of Maxwellian data alone, one obtains $\bar{\nu}_p = 2.49 \pm 0.02$; 2.428 ± 0.018; 2.85 ± 0.03; 2.95 ± 0.05 for U-233, U-235, Pu-239, Pu-241

respectively. For the plutonium isotopes these indirect values are in sufficient agreement with the direct values of $\bar{\nu}_p$ but for U-233 and U-235 the indirect results are more than 1% resp. 1.5% too high.

Consequently, if one fits the Maxwellian data and $\bar{\nu}$ data together in fit (8), serious discrepancies show up between input and output of Maxwellian fission cross-sections and the criticality data $y = (\hat{\eta} - 1)\,\hat{\sigma}_a$. (See tables 16 and 17.) The discrepancies can be illustrated by the relation $\bar{\nu}_t = 1 + \hat{\alpha} + y/\hat{\sigma}_f$. Due to their heavy weight, the $\hat{\alpha}$ data remain unaffected and y and $\hat{\sigma}_f$ are shifted instead.

The equation

$$\hat{\alpha} = \bar{\nu}_p + \bar{\nu}_d - y/\hat{\sigma}_f - 1$$

supplies a useful consistency test. Taking the values for U-235

$\bar{\nu}_p = 2.386 \pm 6$ from fit (3)
$\bar{\nu}_d = 0.016$
$y = 724.1 \pm 9.0$ from Gwin with author's error
$\hat{\sigma}_f = 569 \pm 3.8$ from fit (7)

one obtains $\hat{\alpha} = 0.129 \pm 0.028$. Of this result, at the best, the upper limit $\hat{\alpha} = 0.160$ can be correct, corresponding to $\bar{\nu}_p = 2.392$, $y = 715$, $\hat{\sigma}_f = 572.7$.

If one deduces $\hat{\alpha}$ from 2200 m/s data and g-factors (fit (3)), one obtains $\hat{\alpha} = 0.165 \pm 0.008$.

These two independent indirect determinations support a value of $\hat{\alpha}$ which is smaller than the value obtained directly; see table 19. For U-233 the situation is similar.

One may conclude that the high experimental values of $\hat{\alpha}$ appear seriously doubtful, but that in addition $\hat{\sigma}_f$ from fit (2) and $\bar{\nu}_p$ appear too low and Gwin's too high. Since Gwin's y has the lowest weight among these data, the discrepancy will be solved in the fit mainly by reducing Gwin's y(U-235) from 724 ± 11 to a value around 707 barns. This is not too bad, if one considers that Gwin's original result is 715 ± 9 barns (see Note 9.3). But the other data involved are shifted also by the fit.

8.6 MAXWELLIAN DATA AND 2200 m/s DATA

If one compares in table 16 the fit (7) of Maxwellian data alone with the same quantities obtained indirectly in fit (3) from 2200 m/s data, $\bar{\nu}$ data and g-factors, one sees that there are bad discrepancies for the uranium isotopes, whereas the data for the plutonium isotopes agree within the error limits.

In table FIT 5 all those Maxwellian input data are listed which are discrepant with the 2200 m/s deduced data of fit (3). The most disturbing discrepancies are marked with a star.

In the upper half of table FIT 5, most of the discrepant data are related to the U-233 fission cross-section. The fission cross-section ratios by Lounsbury and Bigham and one of the ratios by Keith, σ_γ(U-233) by Halperin, and the mean value of the $\hat{\alpha}$(U-233) data, all suggest consistently that $\hat{\sigma}_f$(U-233) should be 1% to 1.5% lower than the output of fit (3), that is about 525 to 530 b instead of 534 b. This reduction would in particular solve the most disturbing discrepancy with $\hat{\alpha}$(U-233).

Since σ_f(U-233) is known mainly indirectly from $\sigma_f = \frac{\eta}{\bar{\nu}_t}\,\sigma_a$, a reduction in σ_f would mean, that η(U-233) by Smith is too high, or that σ_a(U-233) is too high, or that $\bar{\nu}_t$(U-233) of Boldeman is too low. A lower value of η(U-233) is supported by Macklin whose result is 0.44% lower than that of Smith (whereas both agree within 0.15% for U-235 and Pu-239).

However, the four consistent U-233/U-235 fission cross-section ratios by Bigham, Keith, Lounsbury and Vidal suggest that $\hat{\sigma}_f$(U-233) should be increased by 1/2%, rather than decreased.

We do not suggest a solution to this dilemma, and can only let the data be adjusted by the least-squares fit according to their weight. The result is, that σ_f, η, $\bar{\nu}$ of U-233 and $\hat{\sigma}_f$(U-233/U-235) will be adjusted by more than their input ~~omit~~ error. The new measurement of σ_a(U-233) at Geel will most likely clarify the situation.

The lower half of table 18 shows that there are systematic discrepancies between the experimental criticality data $(\hat{\eta} - 1)\hat{\sigma}_a$ and the same expressions derived from the 2200 m/s data. The experimental criticality data for Pu-239 appear consistently as too low. The two experiments by Gwin and Magnuson appear to be somewhat inconsistent: whereas the $\hat{\eta}\hat{\sigma}_a$ ratios agree with the values deduced from the 2200 m/s data, the $(\hat{\eta} - 1)\,\hat{\sigma}_a$ data as reassessed in Note 9.3, do not.

A number of fits were made to test the experimental data of Maxwellian $\hat{\alpha}$ for the uranium isotopes, and these are shown in table 19. As discussed already in the previous section, one obtains too low values of $\hat{\alpha}$ if this is deduced either from fit (3) of 2200 m/s data and data with input g-factors, or from and the Maxwellian values of $y = (\hat{\eta} - 1)\,\hat{\sigma}_a$ and $\hat{\sigma}_f$. From this one may conclude that either the values are too low but this we excluded because of their agreement with the 2200 m/s data; or that the experimental $\hat{\alpha}$ values are too high.

However, the experimental $\hat{\alpha}$ values are consistent with most of the other Maxwellian data: if one fits (Fit 12) in table 19 the Maxwellian input data without input for $\hat{\alpha}$(U-233) and $\hat{\alpha}$(U-235), one obtains indirect $\hat{\alpha}$ values which are in good agreement with the direct values. Therefore, if the experimental $\hat{\alpha}$ values are too high, then other experimental Maxwellian data must be affected by the same systematic error. One will have to investigate, whether not part of this error in Maxwellian data of U-233 and U-235 may be due to a resonance structure in the capture cross-section close to zero energy.

8.7 g-FACTORS

It must be investigated whether the g-factors may be responsible for the encountered discrepancies. In fact, the g-factors do not only connect Maxwellian and monoenergetic cross-sections by the relation $g = \hat{\sigma}/\sigma$, but are also essential in a relation between neutron-yield and $\hat{\alpha}$ data: $\eta_o(1 + \hat{\alpha})\, g_f/g_a = \bar{\nu}_t$. If one enters in this formula η_o from Smith, $\hat{\alpha}$ from Lounsbury, and $\bar{\nu}_t$ from fit (2), one obtains $\frac{g_f}{g_a} = 0.985 \pm 0.005$; 0.985 ± 0.006; 0.970 ± 0.006 for U-233, U-235, Pu-239 respectively. These values are about 1% lower than those of Paper 2, and such low values seem possible having in mind the uncertainty of the lowest-energy curve shapes. It seems however, that the reduction in the values of g_f/g_a is at least partially from the existing discrepancy between neutron-yield data $\bar{\nu}_t/\hat{\eta}$ and Maxwellian $(1 + \hat{\alpha})$data, as stated in section 8.5 above.

In table 20 three further sets of indirect g-factors are shon: Fit (9) by fitting Maxwellian data together with 2200 m/s data, Fit (10) by including also the $\bar{\nu}$-data in the fit, and Fit (11) by fitting all data but omitting input for g-factors and for $\hat{\alpha}$(U-233) and $\hat{\alpha}$(U-235). It can be seen that some of the indirect g-factors, especially those for capture and absorption, appear to be impossible. One must conclude that there are systematic errors of unknown origin, probably within the Maxwellian data.

In the case of U-235 one obtains a too large value for the capture g-factor when $\bar{\nu}$ and $\hat{\alpha}$ are included in the fit (Fit 10), but acceptable values when either $\bar{\nu}$ or $\hat{\alpha}$ are omitted from the fit (Fits 9 and 11). For U-233 and Pu-239 practically all indirect g-factors except the values for fission, do not agree with the input g-factors. Since the Pu-239 data, as shown in the previous sections, are otherwise rather consistent, it seems possible that the discrepant indirect g-factors for Pu-239 originate, through Pu-239/U-233 ratio data, from discrepancies within the U-233 data.

The input g-factors used in the present paper are better in agreement with the indirect values than the input g-factors used in Paper 2. However, any further changes suggested by the indirect g-factors seem to be unrelistic and apparently result from discrepant Maxwellian cross-section measurements. Since direct and indirect fission g-factors are quite consistent, systematic errors, if any, are likely with the Maxwellian capture, absorption and $\hat{\alpha}$ measurements.

9. CONCLUSIONS

9.1 CONSISTENT SET OF RECOMMENDED VALUES

One may prefer to base a set of recommended values heavily on the consistent set of the 2200 m/s data and data, and to downweight all data which are discrepant from this set. However, as long as one does not know the reasons for the existing discrepancies, it does not seem justified to ignore or downweight any of the input data, even if they are discrepant with other data. If it were possible to locate the source of the discrepancy with a single experiment, then one had sufficient reason to reject or downweight this particular experiment. But this is not possible, since not a single experiment but a number of different experiments is responsible for the discrepancies. It seems that mainly the thermal-spectrum measurements of $\hat{\alpha}$ and $\hat{\sigma}_f$ for U-233, and to lesser extent for U-235, are the origin of the discrepancies; but due to the complex correlations within the fit, the origin may be found as well somewhere else. The fit does not provide sufficient evidence to decide which of the experiments are wrong.

It seems therefore best, to obtain a compromise by fitting all data together in a least-squares fit. Since the errors, and that means: the weights of the input data have been carefully assessed, the result of the least-squares fit will be the best compromise, and this is shown in table 21.

It appears however, that the errors of this set are too small, since the fitting program considers only the internal errors of each input value, and not the external errors defined by the difference between input value and fitted value. The errors of table 21 were therefore increased to reflect the existing discrepancies. The result is shown in table 22, and this is the table of recommended best values.

The increased errors were obtained by computing for each input value the quadratical sum of internal and external error. This is however not sufficient: input data for which a dominating accuracy is claimed, determine the fit and their external error will not be significant, even if they are discrepant from other data. Therefore, excess uncertainties were arbitrarily introduced for some of the

more controversial quantities when computing the increased errors for the recommended values. Such excess uncertainties were applied for $\hat{\alpha}$(U-233), $\hat{\alpha}$(U-235), and all forms of input for σ_f(U-233).

9.2 LOW-ENERGY CROSS-SECTION CURVES CONSISTENT WITH THE RECOMMENDED VALUES

In figures ... low-energy cross-section curves are given which are consistent with recommended values of the 2200 m/s cross-sections and g-factors. It should be noted however, that a given pair of values for σ_o and g is consistent with a variety of curve shapes, of which only a single one has been selected.

In tables ... g-factor ratios $g(T)/g(20^oC)$ are listed, which were drived from the given curves. With the help of these ratios one can calculate, from the recommended 20^oC Maxwellian data, values for any other spectrum temperature.

Note for the present draft: This work will be done only after we have agreed on a final set of recommended values.

9.3 SUMMARY OF UNCERTAINTIES

The discrepancies mentioned in the following are all in the order of magnitude of one percent.

1. The $\bar{\nu}$-η discrepancy does, most likely, not exist. The low $\bar{\nu}$ values and the relatively high η values are consistent, if they are compared by means of the 2200 m/s fission and absorption cross-sections: $\bar{\nu}_t \sigma_f = \eta \sigma_a$. The fact that the ratio $\bar{\nu}_t/\eta$ given by the input data, is increased in the least-squares fit, is likely due to uncertainties of unknown origin in the Maxwellian data.

2. Several Maxwellian data appear to be less reliable than the authors believe. It is likely that the thermal neutron spectra are less accurately known than assumed so far.

3. The Maxwellian $\hat{\alpha}$ data for U-233 and U-235 appear to be uncertain. They are inconsistent with many other input data through the relations

$$1 + \hat{\alpha} = g_a \sigma_a / g_f \sigma_f$$

$$1 + \hat{\alpha} = g_a \bar{\nu}_t / g_f$$

$$1 + \hat{\alpha} = \bar{\nu}_t - y / \delta_f \qquad \text{where } y = (\hat{\eta} - 1)\delta_a .$$

The present fit is highly determined by the existing measurements of $\hat{\alpha}$, and any revision in the $\hat{\alpha}$ data would significantly change the set of recommended values. Should there be something wrong with the $\hat{\alpha}$ data, then there must be a systematic error common to all $\hat{\alpha}$ and some other Maxwellian experiments. Other input data suggest that $\hat{\alpha}$ of the uranium isotopes should be between 0.5 and 1 percent lower than the present recommended values. As long as the source of the uncertainty is not known, the experimental values were left in the fit unchanged, although many of the input data are significantly shifted in the fit to obtain consistency with the $\hat{\alpha}$ data.

4. The U-233 fission cross-section, for which only one inaccurate monoenergetic measurement and discrepant Maxwellian measurements exist, requires further investigation. The uncertainty of this quantity may be related to the uncertainty in $\hat{\alpha}$(U-233). The new absolute monoenergetic measurement at Geel will hopefully bring some clarification. If the Geel value turns out to be significantly different from the presently recommended 530.5 ± 2 barns, this will entail noticeable revisions to the present set of recommended values.

5. The α-counting techniques appear to suffer from unknown systematic errors, due to which a large number of half-life measurements must be regarded as superseded. It seems essential to find the origin of this systematic uncertainty, and to investigate whether the same systematic error has affected also those fission cross-section measurements, where the sample was assayed by α-counting.

6. The Pu-239 half-life requires confirmation. Several new measurements are presently being performed. Should their result deviate significantly from the presently adopted input value of 24 100 ± 50 y, the Pu-239 fission cross-section will change. This would entail changes in the other related data.

7. The g-factors, in particular those of the uranium isotopes, are less accurately known than assumed so far. The increased capture and absorption g-factors can be explained by increased cross-sections between 0 and 0.02 eV. It must be verified however, whether the changed g-factors suggested in the present work are realistic, or whether they are simulated by systematic errors of measurements made in thermal neutron spectra. The results of the lowest-energy measurements of σ_f(U-233) by Deruytter at the BOR 2 reactor will contribute to clarify the question about the lowest-energy curve-shapes of U-233.

8. Different cross-section curve-shapes with extreme variations in the lowest energy range should be tested in integral experiments. As far as possible, precise cross-section measurements at very low energies would be desirable.

9.4 COMPARISON WITH OTHER EVALUATIONS

See table COMP. (To be completed later)

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Table 1: STANDARD CROSS-SECTIONS USED

Reaction		value assumed (barns)
H-1	(n,γ)	331 ± 4 mb
B-10	(n,absorption)	3838.8 ± 6.4b
Na-23	(n,activation)	529.9 ± 2.65 mb
Co-59	(n,activation)	37.20 ± 0.057b
Au-197	(n,γ)	98.7 ± 0.12b

Table 2: HALF-LIFE VALUES USED FOR INPUT (see text)

Author	Lab	Year	Ref.	Value
U-233				$T_{1/2}$(U-233) [10^5y]
Durham	CRC	1969	[H2]	1.583 ± 0.010
Vaninbroukx et al.	GEL	1974	[H18]	1.5925 ± 0.003
Jaffey et al.	ANL	1974	[H5]	1.591 ± 0.003
U-234				$T_{1/2}$(U-234) [10^5y]
Meadows	ANL	1969	[H11]	2.439 ± 0.014
Lounsbury + Durham	CRC	1971	[H9]	2.444 ± 0.012
de Bievre et al.	GEL	1971	[H1]	2.446 ± 0.0024
Pu-239				$T_{1/2}$(Pu-239) [10^4y]
adopted input			(see text)	2.424 ± 0.014
Pu-241				$T_{1/2}$(Pu-241) [y]
used, as in Paper 2, for correcting Pu-241 data			(see text)	14.5 ± 0.4

Table 3: SCATTERING CROSS-SECTIONS (barns)

Explanation: σ_{sb} = bound-atom scattering cross-section used for liquid and powdered-metal samples

σ_{sm} = scattering cross-section for rolled-metal or unspecified-metal samples

σ_{sox} = scattering cross-section for oxide samples

$\sigma_{s?}$ = scattering cross-section for unknown but not liquid samples

	U-233	U-235	Pu-239	Pu-241
used for input to the least-squares fit	$\sigma_{sm} = 12.2 \pm 0.7$ $\sigma_{sb} - \sigma_{sm} = 1.2 \pm 0.6$	$\sigma_{sb} = 16.5 \pm 1.3$ $\sigma_{sb} - \sigma_{sm} = 1.7 \pm 0.75$	$\sigma_{sb} = 8 \pm 1$ $\sigma_{sb} - \sigma_{sm} = 0.8 - 1.1$	$\sigma_{sb} = 12 \pm 2.6$ $\sigma_{sb} - \sigma_{sm} = 1.2 \pm 3$
used for corrections of total cross-sections measured on other samples	$\sigma_{sox} - \sigma_{sm} = 4.0 \pm 5.0$ $\sigma_{s?} - \sigma_{s,} = 3.0 \pm 6.3$	no experiment using oxide sample $\sigma_{s?} - \sigma_{sb} = 0 \pm 7$	$\sigma_{sox} - \sigma_{sm} = 3 \pm 5$ $\sigma_{s?} - \sigma_{sb} = 0 \pm 8$	$\sigma_{sox} - \sigma_{sb} = 3 \pm 5$
Comments	Note 3.1	Note 3.2	Note 3.3	[as Paper 2]

Notes to table 3: Scattering cross-sections

Note 3.1: For U-233 GREEN and MITCHELL [52] recently obtained a value of $\sigma_{sm} = 12.3 \pm 0.7$ for a metal sample, and this was used for input; the corrections for other sample types were left as in Paper 2.

Note 3.2: For U-235 CEULEMANS and POORTMANS [S1] reported a value of the average effective scattering cross-section of U-235 from a rolled-metal sample of 14.3 ± 0.5 b near 2200 m/s. This result was re-evaluated by LEONARD [S3] to give a value of $\sigma_{sm} = 14.8 \pm 0.6$ b based on a more precise determination of the reference vanadium scattering and an estimated correction for chemical binding. Note that the ± 0.6 b is an estimate of the uncertainty of the average value. The observed fluctuations of σ_{sm} were abpit ± 1 b.

According to the assumptions of Paper 2 the revised CEULEMANS result would correspond to a bound atom scattering of $\sigma_{sb} = \sigma_{sm}/0.9 = 16.44$ b.

In Paper 2 the estimated value of σ_{sb} was 17.0 b based on a potential scattering cross-section of $\sigma_p = 11.5$ b and the average value of several different resonance parameter analyses for U-235. LEONARD [S3] has since estimated that the σ_{sb} value should be reduced by about 0.4 b based on a reduction of the strength of the assigned dominant negative-energy level because of the neglect of distant negative-energy levels in the resonance analyses. Reduction of the Paper 2 value of σ_{sb} by 0.4 b gives 16.6 b, in agreement with the revised CEULEMANS' result.

In view of these considerations it appears that the reduction of the U-235 scattering cross-sections used in Paper 2 of 10% is valid and that the uncertainty in the estimated reduction and in the fluctuations is less than that assumed in 1969. We therefore adopted the values as given in table 3.

Note 3.3: For Pu-239 $\sigma_p = 10.2 \pm 1.1$ b was assumed in Paper 2 for the potential scattering cross-section, and $\sigma_{sb} = 8.6 \pm 2.1$ b for the bound-atom scattering cross-section.

Using UTTLEY'S value of $\sigma_p = 10.3 \pm 0.15$ b [S5], ENDF/B parameters for the first negative and positive energy levels and the uncertainty estimate due to distant levels gives $\sigma_{sb} = 8.56 \pm 1.2$ b. Reduction of the strength of the negative-energy level by 10%, as the indicated effect of distant negative levels, reduces this result by about 0.03 b only.

LEONARD'S [S3] evaluation of ROOF'S [S4] coherent-scattering measurement led to a value of $\sigma_{sb} = 7.46 \pm 0.8$ b.

The calculated scattering cross-section is dominated by the 0.3 eV resonance whose parameters lead to little uncertainty in the calculated value. Thus the ± 1.2 b error assignment which is a general result due to distant levels [S4] might well be reduced to ± 0.6 b. The small error assignment of UTTLEY [S5], however, for σ_p of ± 0.15 b is unconfirmed by other precision measurements. We give therefore the revised value of ROOF and the calculated value approximately equal weight and use the input values as given in table 3.

Table 4: TOTAL AND ABSORPTION CROSS-SECTIONS

Authors	Lab	Year	Ref.	Author's σ_T	Reassessed σ_T	Sample	Input
U-233							
Muether et al.	BNL	1954	[A8]	unpublished	597 ± 14	metal	$\sigma_a + \sigma_{sm} = 597 \pm 14$
Nikitin et al.	ITE	1955	[A9]	580 ± 20	accepted	unknown, not liquid	$\sigma_a + \sigma_{sm} = 577 \pm 21$
Pattenden	HAR	1956	[A11]	590 ± 15	600 ± 17	oxide	$\sigma_a + \sigma_{sm} = 596 \pm 18$
Green et al.	HAR	1956	[A6]	σ_a=578 ± 17	σ_a=574 ± 20	-	$\sigma_a = 574 \pm 20$
Simpson et al.	MTR	1959	[A18]	587 ± 6	587.0 ± 4.7	metal	$\sigma_a + \sigma_{sm} = 587.0 \pm 4.7$
Safford et al.	COL	1959	[A14]	587 ± 5	585.5 ± 5.8	liquid	$\sigma_a + \sigma_{sb} = 585.5 \pm 5.8$
				586 ± 2	585.4 ± 2.4	rolled metal	$\sigma_a + \sigma_{sm} = 585.4 \pm 2.4$
Block et al.	ORL	1960	[A1]	587 ± 3	accepted	metal	$\sigma_a + \sigma_{sm} = 587 \pm 3$
U-235							
Egelstaff	HAR	1951	[A4]	724 ± 15	724 ± 26	metal	$\sigma_a + \sigma_{sm} = 724 \pm 26$
Melkonian et al.	COL	1953	[A7]	691 ± 5	694 ± 14	rolled metal	$\sigma_a + \sigma_{sm} = 694 \pm 14$
Palevsky et al.	BNL	1954	[A10]	700 ± 5	700 ± 10	metal	$\sigma_a + \sigma_{sm} = 700 \pm 10$
Nikitin et al.	ITE	1955	[A9]	710 ± 20	accepted	unknown, not liquid	$\sigma_a + \sigma_{sb} = 710 \pm 21$
Simpson et al.	MTR	1959	[A18]	690 ± 10	690 ± 9.6	metal	$\sigma_a + \sigma_{sm} = 690 \pm 9.6$
Safford et al.	COL	1959	[A15]	694.97± 1.81	696 ± 2.5	liquid	$\sigma_a + \sigma_{sb} = 696 \pm 2.5$
				698.68± 4.81	698.68± 5.1	rolled metal	$\sigma_a + \sigma_{sm} = 698 \pm 5.1$
Block et al.	ORL	1960	[A1]	693 ± 5	accepted	rolled metal	$\sigma_a + \sigma_{sm} = 693 \pm 5$
Saplakoglu	ANL	1961	[A16]	694.2± 1.5	696 ± 2.5	rolled metal	$\sigma_a + \sigma_{sm} = 696 \pm 2.5$
Gerasimov	KUR	1962	[A5]	σ_a= 670± 8	σ_a= 670 ± 14	-	$\sigma_a = 670 \pm 14$
Pu-239							
Zimmerman et al.	BNL	1955	[A20]	unpublished	1022 ± 13	metal	$\sigma_a + \sigma_{sm} = 1022 \pm 13$
Nikitin et al.	ITE	1955	[A9]	1040 ± 30	accepted	unknown, not liquid	$\sigma_a + \sigma_{sb} = 1040 \pm 31$
Pattenden	HAR	1955	[A12]	1015 ± 30	accepted	oxide	$\sigma_a + \sigma_{sm} = 1012 \pm 30.4$
Bollinger et al.	ANL	1958	[A2]	1015 ± 10	1022 ± 14	rolled metal	$\sigma_a + \sigma_{sm} = 1022 \pm 14$
Safford + Havens	COL	1961	[A13]	1018 ± 7.4	accepted	rolled metal	$\sigma_a + \sigma_{sm} = 1018 \pm 7.4$
Pu-241							
Simpson et al.	MTR	1961	[A17]	Curve only	1389 ± 50	Oxide	$\sigma_a + \sigma_{sb} = 1386 \pm 50$
Craig + Westcott	CRC	1964	[A3]	1383 ± 30	1383 ± 40	Oxide	$\sigma_a + \sigma_{sb} = 1380 \pm 40$
Smith	MTR	1968	[A19]	1389 ± 15	accepted	rolled metal	$\sigma_a + \sigma_{sm} = 1389 \pm 15$

Table 5a: 2200 m/s FISSION CROSS-SECTIONS, HALF-LIFE INDEPENDENT

Authors	Lab	Year	Ref.	U-235 (barns)	Pu-239/U-235	Pu-241 (barns)	Pu-241/U-235	Pu-241/Pu-	Comments
Raffle	HAR	1955	[F20]	582 + 18					Note 5.1
Raffle + Price	HAR	1955	[F21]					1.332±0.080	Note 5.1
Saplakoglu	ANL	1958	[F22]	590 ± 16					Note 5.2
Deruytter	MOL	1961	[F4]	590 ± 8					as Paper 2
Watanabe +Simpson	MTR	1964	[F25]			985 ± 45			as Paper 2
Maslin et al.	ALD	1965	[F16]	583.5 ± 9					Note 5.2
White et al.	ALD	1966	[F27]		1.253±0.012		1.763±0.022		Note 5.4

Table 5b: 2200 m/s FISSION CROSS-SECTIONS, HALF-LIFE DEPENDENT

The superscripts 3, 4, 5, 9 denote the nuclides U-233, U-234, U-235, Pu-239 respectively.

Authors	Lab	Year	Ref.	$\sigma_f^3 * T_{1/2}^3$ (10^5 b y)	$\sigma_f^5 * T_{1/2}^4$ (10^5 b y)	$\sigma_f^9 * T_{1/2}^9$ (10^4 b y)	$\sigma_f^9 * T_{1/2}^9 / (\sigma_f^5 * T_{1/2}^4)$ (10^{-1})	Comments
Raffle	HAR	1955	[F20]	834.3±27.5		1716.4±48.7		Note 5.1
Fraysse+Prosdocimi	SAC	1965	[F11]				1.2425 ± 0.0210	Note 5.3
Deruytter et al.	GEL	1969/74	[F9,F10]		1438.7± 7.5	1811.7±9.7	1.2592 ± 0.0076	Note 5.5
Petrascu et al.	BUC	1970/73	[F2,F3,F17]		1434.2±23.6	1804.0±20.7	1.2578 ± 0.0108	Note 5.6

Notes to tables 5a and 5b: Fission cross-sections

Note 5.1 RAFFLE: The cross-section values were taken as published but the errors increased as assessed by Sjöstrand and Story [4]. The values are relative to Au(n,γ) for which the author assumed the same value as we do. For U-233 and Pu-239 the author's results depend on the half-life and input was therefore formulated as $\sigma_f * T_{1/2}$, although the samples were also assayed by other methods. For the Pu-241/Pu-239 ratio the dependence on half-lives is complex and was not considered. For this reason and for the rather brief documentation the error was increased by a factor of 1.4. As in Paper 2 the measurements with reactor and thermal-column neutrons were ignored. The errors are so large that error correlations were not considered.

Note 5.2 SAPLAKOGLU, MASLIN: The value of Saplakoglu was reduced by $2 \pm 2\%$, that of Maslin increased by $2 \pm 1\%$ for extrapolation to zero sample thickness as discussed in the survey by Deruytter [F7].

Note 5.3 FRAYSSE: As Paper 2 but reformulated with half-lives as variables to be fitted.

Note 5.4 WHITE: The 2200 m/s input data from this work are shown in table 5a, the thermal Maxwellian data in table 7. The treatment of these data is similar to that in Paper 2. The temperature corrections of the Maxwellian data were adjusted to our presently preferred g(T) tables. The error correlation was treated by introducing three error contributions x^5, x^9, x^1 as independent variables to be fitted: x^5 includes the error contributions due to the U-235 sample common to all input data; x^9 (and x^1) include the error contributions due to the Pu-239 (resp. Pu-241) sample common to the monoenergetic and Maxwellian input ratios of σ_f (Pu-239/U-235) resp. σ_f(Pu-241/U-235). The following expressions and values were entered in the fit:

$$(\sigma_f^9 / \sigma_f^5)\, x^5\, x^9 = 1.253 \pm 0.012$$

$$(\sigma_f^1 / \sigma_f^5)\, x^5\, x^1 = 1.763 \pm 0.022$$

$$((g_f^9\, \sigma_f^9)/(g_f^5\, \sigma_f^5))\, x^5\, x^9 = 1.358 \pm 0.020$$

$$((g_f^1\, \sigma_f^1)/(g_f^5\, \sigma_f^5))\, x^5\, x^1 = 1.882 \pm 0.025$$

$$x^5 = 1 \pm 0.012$$

$$x^9 = 1 \pm 0.009$$

$$x^1 = 1 \pm 0.021$$

The input data for the ratios exclude the error contribution x^5, x^9, x^1 which are entered separately.

The experimental data at 0.016 eV and 0.051 eV were not used. As in Paper 2, the Pu-241 ratios were corrected by $(-0.5 \pm 0.5)\%$ for Pu-241 decay. For the Pu-239 (resp. Pu-241) ratios, the 30°C thermal column data were given 80% (resp. 70%) of the weight when calculating the average with the data from the 90°C extracted thermal beam. Extra errors were added for temperature uncertainties (0.6%) and 1% for the unexplained spread between the 30°C and 90°C Pu-239 ratios after their conversion to 20°C.- Since the foils were assayed by several methods, no considerations of the alpha half-lives were made.

Note 5.5 DERUYTTER: The recent important measurements by Deruytter et al. of the fission cross-sections of U-235 [F9] and Pu-239 [F10] have been carefully studied. Subsequently a small adjustment of the Pu-239 value has been made by the authors for the curve-shape fitting around 0.0253 eV. The final author's results are σ_f(U-235) = 587.6 ± 2.6 b assuming $T_{1/2}$(U-234) = (2.446 ± 0.0024) * 10^5 y, and σ_f(Pu-239) = 742.9 ± 3.4 b assuming $T_{1/2}$(Pu-239) = (2.4395 ± 0.0029) * 10^4 y. For both nuclides, the half-life independent product of σ_f * $T_{1/2}$ was entered in the fit. The errors for these expressions exclude the half-life error contributions assumed by the authors.- The measurement was made relative to the B-10(n,α) cross-section assumed as 3835 ± 5 b [R4], which we revised to our preferred value. Both input data are therefore correlated, and their common uncertainties are 0.17% for the boron cross-section and 0.26% for the number of atoms in the boron sample. This correlation was treated with the procedure of Appendix B of Paper 2 and the input was formulated accordingly.

Note 5.6 PETRASCU: The authors' values are σ_f(U-235) = 582.7 ± 7.8 b assuming $T_{1/2}$(U-234) = 247 000 y from Lederer, 6th edition and σ_f(Pu-239) = 741.0 ± 7.0 b assuming $T_{1/2}$(Pu-239) = 24 390 y. For both nuclides, the half-life independent product of cross-section times half-life was entered in the fit, and for these expressions the errors were reduced by the half-life error contributions assumed by the authors.

After correspondence with Petrascu, both values were increased by (0.3 + 0.1)% for possible fission losses. In order to avoid the reference to a standard cross-section the authors developed a method which requires the knowledge of the B-10(n,α) branching ratio . We revised the value assumed by the authors (= 0.9348 ± 0.0009) to = 0.93692 ± 0.00006 according to Deruytter and Pelfer [R1]. The gammas from B-10(n,α) Li-7 were counted and the detector calibrated against activated gold. This requires a correction for the difference dE_γ between the gamma-lines from lithium and gold. We revised the value assumed by the authors (dE_γ = 65.4 keV) to dE_γ = 67.3 ± 1.5 keV according to Elliot and Bell [R3]. With the gamma-detector used, the uncertainty in dE_γ contributes considerably (0.56%) to the final results, and a repetition of the experiment with a Ge(Li) detector is planned by the authors.

The results for U-235 and Pu-239 are correlated, mainly due to the uncertainties in and dE_γ. This correlation was treated with the procedure of Appendix B of Paper 2 and the input was formulated accordingly.

Table 6: NEUTRON YIELD PER ABSORPTION, η, 2200 m/s INPUT VALUES (see Notes 6.1 and 6.2)

Authors	Lab	Year	Ref.	U-233	U-235	Pu-239	Pu-241
Macklin et al.	ORL	1960	[E11]	2.296 ± 0.010	2.077 ± 0.010		
		1962	[E12]			2.143 ± 0.015	
Revised corrections for cross-section curve shapes, as Paper 2:				- 0.06%	+ 0.26%	- 1.0%	
additional error for curve shapes:				± 0.2%	± 0.2%	± 0.2%	
Revised corrections due to manganese resonance absorption, fast-neutron capture in oxygen and fast neutron escape:				- 0.27%	- 0.30%	- 0.24%	
Increased errors for the fast-fission correction:				± 0.5%	± 0.3%	± 0.4%	
Result:				2.288 ± 0.016	2.076 ± 0.014	2.116 ± 0.018	
Input as $\eta * x_{Mac}$ with common error $x_{Mac} = 1 \pm 0.37\%$				2.288 ± 0.013	2.076 ± 0.011	2.116 ± 0.015	
For comparison: Re-analyzed by Steen			[G7]	2.298 ± 0.007			
Smith et al.	MTR	1963/64	[E18] [E16]	2.298 ± 0.009	2.079 ± 0.010	(2.108 ± 0.008) 2.119 ± 0.009	
Smith and Reeder	MTR	1967	[E19] [E16]	2.292 ± 0.010	(2.079 ± 0.06%)	2.120 ± 0.011	2.167 ± 0.011
Values chosen, see Note 6.2				2.298 ± 0.009	2.079 ± 0.010	2.119 ± 0.009	2.167 ± 0.013
values reduced by 0.25%			[E17]	2.292	2.074	2.114	2.162
Input as $\eta * x_{Smi}$ with common error $x_{Smi} = 1 \pm 0.32\%$				2.292 ± 0.006	2.074 ± 0.008	2.114 ± 0.0066	2.162 ± 0.0115
For comparison: re-analyzed by Steen			[G7]	2.296 ± 0.007			

changed 75-1-10

Note 6.1 MACKLIN: Although this measurement was made in a thermal neutron spectrum, the results are entered in the fit as 2200 m/s values, because the authors did not use Westcott g-factors for the reduction of their data. Table 6 shows the corrections which we applied. The corrections for cross-section curve shapes have been done as in Paper 2. Since the curve shapes adopted in Paper 2 may not quite agree with the present best ones, an additional error of 0.2% was introduced.

One of us (Axton) performed a detailed re-calculation of the corrections for manganese resonance absorption, fast-neutron capture in oxygen, fast-neutron escape, and fast fission. The resulting net corrections to be applied to the authors' results are shown in table E0. Incidentally, these corrections are almost identical with those introduced already in Paper 1 and re-used in Paper 2.

The correlation of the input data for the three nuclides was taken care of by introducing, for their common error, a variable x_{Mac} which is entered in the fit as separate input. As common error sources were considered the items 6 to 10 in table II.5 (resp. I) in reference [E11] respectively in table I in reference [E12], plus some fraction (assumed as 0.3%) of the multiplication errors. They sum up quadratically to 0.37%. Input was made in the form of $*x_{Mac}\pm$ where the errors exclude the common error, plus a separate input of $x_{Mac} = 1 \pm 0.0037$.

Note 6.2 SMITH: In 2963/64 σ_o was measured for U-233, U-235 and Pu-239 [E18]. The Pu-239 value was lateron revised [E16] due to scattering from the nickel cladding of one set of samples. In 1967 a measurement for Pu-241 was made [E19], and measurements for the other three nuclides were repeated [E16]. All results were entered in table 6. The 1967 U-235 data have not been fully reduced; the raw value obtained for the same sample configuration as in 1964, was 0.06% higher than the corresponding 1964 value. The other 1967 data were analyzed by hand-calculations based on the results of the least-squares analysis, which had been applied for the 2963/64 measurements. Of the 2967 data we use only the Pu-241 result, slightly downweighted for its preliminary hand-analysis. The other 2967 data would have to be downweighted because of their unpublished nature. Thus, they would have less weight than the 1963/64 data, and we omit them from the fit. The loss of information is not essential since the 1967 set of data is anyway much correlated with the 1963/64 data.

Recent Monte Carlo calculations at the Bettis Laboratory, made for the U-233 experiment, predicted 0.22% less loss of high-energy neutrons to oxygen and sulfur, and somewhat less absorption in the aluminum sample holder than found at MTR. Smith therefore suggests [E17] that the MTR values could be lowered by 0.2 or 0.3%. Consequently, we lowered them by 0.25%.

The correlation of the input data for the four nuclides was taken care of by introducing, for their common error, a variable x_{Smi} which is entered in the fit as separate input. As common error sources were considered the items B,E,F,G and part of A in table II of reference [E18] which sum up quadratically to 0.32%. Input was made in the form of $*x_{Smi}\pm$ where the errors exclude the common error, plus a separate input of $x_{Smi} = 1 \pm 0.0032$.

Table 7: 20°C MAXWELLIAN FISSION CROSS-SECTIONS

The superscripts 3,4,5,9,1 denote the nuclides U-233, 234, 235, Pu-239, 241 respectively.

Authors	Lab	Year	Ref.	Input				Comments
Popovic + Grimeland	KJL	1953	[F18]	$\hat{\sigma}_f^5$	=	571.9	± 13.5	Note 7.1
Popovic + Saeland	KJL	1955	[F19]	$\hat{\sigma}_f^3$	=	530.1	± 18.8	Note 7.1
Jaffey et al.	ANL	1955	[F13]	$\hat{\sigma}_f^1/\hat{\sigma}_f^9$	=	1.355	± 0.019	As Paper 2
Bigham et al.	CRC	1958	[F1]	$\hat{\sigma}_f^3/\hat{\sigma}_f^5$	=	0.9308	± 0.0037	Note 7.2
				$\hat{\sigma}_f^3\ T_{1/2}^3$	=	834.1	± 8.3	
				$(\hat{\sigma}_f^9\ T_{1/2}^9)/(\hat{\sigma}_f^3\ T_{1/2}^3)$	=	2.276	± 0.0091	
				$(\hat{\sigma}_f^9\ T_{1/2}^9)/(\hat{\sigma}_f^5\ T_{1/2}^3)$	=	2.116	± 0.0085	
				$\hat{\sigma}_f^1/(\hat{\sigma}_f^9\ T_{1/2}^9)$	=	0.5526	± 0.0055	
White et al.	ALD	1966	[F27]	$(\hat{\sigma}_f^9/\hat{\sigma}_f^5)\ x^5\ x^9$	=	1.358	± 0.020	Note 5.4 (see table 5)
				$(\hat{\sigma}_f^1/\hat{\sigma}_f^5)\ x^5\ x^1$	=	1.881	± 0.025	
Keith et al.	ALD	1968	[F14]	$\hat{\sigma}_f^3\ T_{1/2}^3$	=	834.6	± 13.2	Note 7.3
				$\hat{\sigma}_f^3/\hat{\sigma}_f^5$	=	0.9383	± 0.0077	
				$\hat{\sigma}_f^9\ T_{1/2}^9$	=	1904.3	± 27	
				$(\hat{\sigma}_f^9\ T_{1/2}^9)/(\hat{\sigma}_f^3\ T_{1/2}^3)$	=	2.282	± 0.035	
Lounsbury et al.	CRC	1970	[C11]	$\hat{\sigma}_f^3/\hat{\sigma}_f^5$	=	0.938	± 0.013	Note 7.4
				$\hat{\sigma}_f^9/\hat{\sigma}_f^3$	=	1.484	± 0.012	
				$\hat{\sigma}_f^9/\hat{\sigma}_f^5$	=	1.392	± 0.012	
Vidal et al.	FAR	1970	[F24]	$\hat{\sigma}_f^3/\hat{\sigma}_f^5$	=	0.932	± 0.008	Note 7.5
Sweet	WIN	1973	[F23]	$(\hat{\sigma}_f^9\ T_{1/2}^9)/(\hat{\sigma}_f^5\ T_{1/2}^4)$	=	1.354	± 0.019	Note 7.6

Notes to table 7: Maxwellian fission cross-sections

Note 7.1 POPOVIC: Same as Paper 2, but the sodium activation cross-section was revised to our preferred value; this led to a 0.8% reduction of the values compared to Paper 2.

Note 7.2 BIGHAM: This experiment comprised, as pointed out in Paper 2, statistically independent measurements of $\hat{\sigma}^3_f / \hat{\sigma}^5_f$,

$(\hat{\sigma}^9_f T^9_{1/2})/(\hat{\sigma}^3_f T^3_{1/2})$, $(\hat{\sigma}^9_f T^9_{1/2})/(\hat{\sigma}^5_f T^3_{1/2})$, $\hat{\sigma}^3_f T^3_{1/2}$, $\hat{\sigma}^1_f/(\hat{\sigma}^9_f T_{1/2})$ with percentage accuracies of $\pm$ 0.14, 0.17, 0.158, 0.583, 0.4, with about equal contributions from counting statistics and isotopic analysis. These expressions are entered in the least-squares fit. The following corrections were made to the authors' published values: the g-factors used for the correction from a 27°C Maxwellian to 20°C were updated, the Pu-241 half-life was updated as in Paper 2, and for the absolute U-233 cross-section the gold standard was changed to our preferred value.

The errors of the expressions entered in the fit, as listed above, are very small compared to other data. The recent measurement by Deruytter obtains for the ratio $(\sigma^9_f * T^9_{1/2})/(\sigma^5_f * T^4_{1/2})$ an accuracy of 0.47%, and the fission cross-section ratios measured in 1968/69 by Lounsbury and Keith have accuracies well above 0.6%. Bigham's good accuracies result from the fact that systematic errors mostly cancel in the measured ratios, and that reliable alpha and fission counting was possible since the thermal-Maxwellian rather than monokinetic flux allowed very thin samples to be used. Nevertheless, it seems doubtful that the mass spectrometry was really as accurate as claimed. Regrettably, the documentation of systematic errors is too brief, since at that time the half-life errors were predominant.

Adopting Bigham's accuracies as quoted above would have the consequence that the fission ratios were exclusively based on a single, namely Bigham's experiment due to its predominant weight in the fit. Since this seems unwise regarding the brief documentation of this experiment, it was decided to increase its percentage errors to $\pm$ 0.4, 0.4, 0.4, 1.0, 1.0, in order to bring its weight more in balance with other data. This is, admittedly, an arbitrary and unsatisfactory decision and does not quite agree with our general principles outlined in section 2.1.

Note 7.3 KEITH: The problems with the U-233 half-life in this experiment have been discussed in Paper 2 page 13. The original experiment measured the product $\hat{\sigma}^3_f T^3_{1/2}$. Subsequently, Keith measured also $T^3_{1/2}$ by determining the masses of the same sources that had been fission and alpha counted. Thus, Keith's experiment had been treated in Paper 2 as direct determination of $\hat{\sigma}^3_f$.

Meanwhile the recent U-233 half-life determinations with a weighted mean around $(1.591 \pm 0.002) * 10^5$ years indicate that Keith's value of $(1.553 \pm 0.010) * 10^5$ years must be wrong, the difference being about 2.4%. We therefore ignore Keith's half-life value and enter now the originally measured product $\hat{\sigma}^3_f * T^3_{1/2}$ in the fit. The Pu-239 cross-section and the Pu-239/U-233 ratio is entered accordingly, whereas the U-233/U-235 cross-section ratio does not depend on half-life data and is therefore entered as $\hat{\sigma}^3_f/\hat{\sigma}^5_f$. No separate input is made for $\hat{\sigma}^5_f$ since this was essentially determined through the U-233/U-235 ratio.

The temperature correction of the g-factors from 35°C to 20°C and the Co-59(n,γ) reference cross-section were revised using the presently preferred values.

As suggested earlier by Deruytter [F7] Keith's cross-sections were increased by (1 ± 1)% for absorption effects in the thin sample.

The error correlations of $\hat{\sigma}^3_f T^3_{1/2}$, $\hat{\sigma}^9_f T^9_{1/2}$ and their ratio were treated according to Appendix B of Paper 2.

Note 7.4 LOUNSBURY: The results published in [C11] are slightly different from and supersede the values used in Paper 2. The temperature corrections of the g-factors from 37°C to 20°C were revised using our preferred values. Some unpublished details on the error analysis, which were communicated by G.C. Hanna, are given in Appendix A. The mass-spectrometric errors were increased by a factor 1.5. The error-correlations of the three cross-section ratios were treated according to Appendix B of Paper 2.

Note 7.5 VIDAL: A special feature of this measurement was the method used for the relative assay of the two fissile samples. The U-233 and U-235 samples used in the thermal neutron measurements were assayed by fission counting in a fast neutron spectrum relative to mixed samples, U-233 + U-238 and U-235 + U-238. The result of this work is given as

$$\hat{\sigma}_f(\text{U-233})/\hat{\sigma}_f(\text{U-235}) = 0.932 \pm 0.007 = (0.75\%) \qquad (1)$$

Another value is derived directly from fission counting of the U-233 and U-235 samples in the fast and thermal neutron spectra

$$\hat{\sigma}_f(\text{U-233})/\hat{\sigma}_f(\text{U-235}) = 0.928 \pm 0.009 \qquad (2)$$

The weighted mean of these two results is given as

$$0.931 \pm 0.005 \qquad (3)$$

This value and its uncertainty seems to be based on the assumption that (1) and (2) are independent measurements. This could only be true if in deriving (2) assumptions were made about the fast neutron spectrum, and about the fast fission cross-sections: if this had been done the accuracy claimed for (2) would be grossly exaggerated. It is much more likely that (2) is derived by manipulating in a different way the same set of experimental data as was used in deriving (1). If this second interpretation is correct (as we believe) the results are not independent and (1) appears to be the "best" interpretation of the measurements; certainly the uncertainty should be downweighted to allow for possible deviations of the "thermal" neutron spectrum from the 20°C Maxwellian shape; for this purpose it was assumed that the thermal spectrum is Maxwellian with a temperature of (20 ± 20)°C.

Note 7.6 SWEET: A memorandum from D.W. Sweet summarizes the results of some quite careful work which has been going on for some time for calibration of fission foils for experimental use in fast reactor assemblies.

In the process of analyzing what was originally conceived as a small discrepancy between two different methods of sample assay - by alpha counting, and by fission counting in a large thermal column - the fast reactor physicists have in fact come up with what is effectively a new measurement of the Pu-239/U-235 thermal fission ratio. More specifically they obtain

$$\frac{\hat{\sigma}_f \, T_{1/2}(\text{Pu-239})}{\hat{\sigma}_f(\text{U-235}) * T_{1/2}(\text{U-234})} = (1.3544 \pm 0.0136) \times 10^{-1}$$

The error was multiplied by 1.4 for lack of a publication.

Table 8a: 20°C MAXWELLIAN CAPTURE-TO-FISSION CROSS-SECTION RATIOS ($\hat{\alpha}$)

Authors	Lab	Year	Ref.	U-233	U-235	Pu-239	Pu-241	Comments
Inghram et al.	ANL	1955	[C8]	0.0940±0.0033				Note 8.0
Cornish	HAR	1960	[C5]		0.1880±0.0140			Note 8.0
Okazaki et al.	CRC	1964	[C12] [C13]	0.0902±0.0015	0.1705±0.0020			Note 8.0
Lisman-Rider	GEV MTR	1965 1966	[C10]	0.0930±0.0027	0.1712±0.0030			Note 8.0
Cabell+Wilkins	HAR	1966	[C2]	0.0857±0.0070	0.1696±0.0080	0.3812±0.0350		Note 8.1
Durham et al.	CRC	1967	[C7]		0.1746±0.0020	0.3882±0.0059		Note 8.0
Cabell	HAR	1968	[C1]			0.4048±0.0184	0.3480±0.0170	as Paper 2
Conway	BET	1968	[C4]	0.0851±0.0050	0.1705±0.0075			Note 8.2
Lounsbury et al.	CRC	1970	[C11]	0.0895±0.00075	0.1720±0.0015	0.3907±0.0024		Note 8.3

Table 8b: 20°C MAXWELLIAN CAPTURE (AND ABSORPTION) CROSS-SECTIONS (barns)

Authors	Lab	Year	Ref.	Input Expression	Value	Comments
Cornish+Lounsbury	CRC	1956	[C6]	$\hat{\sigma}_\gamma$ (Pu-239)	312.3 ± 14	Note 8.4
Halperin et al.	ORL	1962	[C9]	$\hat{\sigma}_\gamma$ (U-233)	49.6 ± 3.2	Note 8.4
Cabell	HAR	1968	[C1]	$\hat{\sigma}_\gamma$ (Pu-239)	310.8 ± 11.5	Note 8.4
				$\hat{\sigma}_\gamma$ (Pu-241)	372.7 ± 9.6	
				$\hat{\sigma}_a$ (Pu-241	1443 ± 31	
Cabell + Wilkins	HAR	1971	[C3]	$\hat{\sigma}_\gamma$(U-233)/[$\hat{\sigma}_a$(U-233)-$\hat{\sigma}_\gamma$(U-234)] with $\hat{\sigma}_\gamma$ (U-234) = 95.9 ± 2	0.0983 ± 0.005	Note 8.5

Notes to tables 8a and 8b: $\hat{\alpha}$, $\hat{\sigma}_\gamma$ and $\hat{\sigma}_a$.

Note 8.0: For the uranium isotopes the temperature correction $g(20^\circ C)/g(T)$ is rather uncertain (see section 7.5). For this reason, the errors were increased: Inghram 0.003 to 0.0033, Cornish 0.014 unchanged, Okazaki U-233 0.0013 to 0.0015, Okazaki U-235 0.0015 to 0.0020, Lisman U-233 0.0020 to 0.0027, Lisman U-235 0.0015 to 0.0030, Cabell U-233 0.0058 to 0.007, Cabell U-235 0.0065 to 0.008, Durham 0.0017 to 0.002, Conway U-233 0.0042 to 0.005, Conway U-235 0.0072 to 0.0075, Lounsbury U-233 0.0006 to 0.00075, Lounsbury U-235 0.0011 to 0.0015, Cabell 1971 0.0033 to 0.005.

Note 8.1 CABELL 1968: Since Paper 2 the authors revised their result for U-233. Subsidiary data were updated and the error was increased due to contributions by epithermal neutrons. An uncertainty of 5% was introduced for U-233 resonance-integrals. We assumed that a similar error should be introduced also for the results on U-235 and Pu-239 and increased the errors accordingly.

Note 8.2 CONWAY: These data depend on the fission yield of Cs-137, and for this a new value was taken from Walker [R6].

Note 8.3 LOUNSBURY: For a more detailed error analysis see Appendix A. The mass-spectrometric errors were increased by a factor of 1.5.

Note 8.4 CORNISH, HALPERIN, CABELL: As Paper 2, but input formulated as 20°C Maxwellian and reduced by 0.8% due to the new lower value of the cobalt activation cross-section used as standard.

Note 8.5 CABELL 1971: Directly measured is the expression

$$\hat{\sigma}_\gamma(\text{U-233})/[\hat{\sigma}_a(\text{U-233}) - \hat{\sigma}_\gamma(\text{U-234})]$$

in a spectrum with $r = (7.5 \pm 1.0) * 10^{-4}$ and $T = (116 \pm 9)^\circ C$. This is converted to a 20°C Maxwellian spectrum by using our preferred g-factors. For $\hat{\sigma}_\gamma$(U-234) a value of 95.9 ± barns was assumed, being the mean of Cabell's assumed value of 96.2 ± 2.2 and the value by Lounsbury [C11] of 95.6 ± 2.1 barns.

Table 9: 20°C MAXWELLIAN RATIOS FOR $\hat{\eta}$, $\hat{\sigma}_a$, $\hat{\eta}\hat{\sigma}_a$ and $(\hat{\eta} - 1)\hat{\sigma}_a$

Abbreviations: $x = (\eta - 1)\sigma_a g_f$ (see note 9.1) $y = (\hat{\eta} - 1)\hat{\sigma}_a = \bar{\nu}_t \sigma_f g_f - \sigma_a g_a$

Authors	Lab	Year	Ref.	Input	
Muehlhause	ANL	1953	[E14]	x(U-233)/x(U-235) =1.001 ± 0.039 x(Pu-239)/x(U-235) =1.513 ± 0.103	Note 9.1
Alikhanov et al.	CCP	1955	[E1]	x(U-233)/x(U-235) =1.039 ± 0.037 x(Pu-239)/x(U-235) =1.565 ± 0.105	Note 9.1
Cabell et al.	HAR	1960	[E3]		Note 9.1
DIMPLE				x(U-233)/x(U-235) =1.046 ± 0.030 x(Pu-239)/x(U-233) =1.537 ± 0.044 x(Pu-239)/x(U-233) =1.608 ± 0.048	
GLEEP				x(U-233)/x(U-235) =1.031 ± 0.048 x(Pu-239)/x(U-233) =1.574 ± 0.079 x(Pu-239)/x(U-235) =1.622 ± 0.085	
Gwin + Magnuson	ORL	1961			
reactivity experiments			[E8]	$\eta\sigma_a g_f$ (U-233)/$\eta\sigma_a g_f$ (U-235) = 0.953±0.014	Note 9.2
			[E13]	$\eta\sigma_a g_f$ (Pu-239)/$\eta\sigma_a g_f$ (U-235) = 1.631±0.023	
liquid critical			[E9] [E13]	y (U-233) = 740.35 ± 16.3 b y (U-235) = 724.1 ± 11.0 b y (U-233)/y(U-235) = 1.025 ± 0.008	Note 9.3
DeBoisblanc + Fast	MTR	1961	[E5]	$\hat{\eta}$ (U-233)/$\hat{\eta}$ (U-235)= 1.1145 ± 0.012	as Paper 2
Fast + Aber	MTR	1967	[E6]	$\hat{\eta}$(Pu-241)/$\hat{\eta}$(U-235)= 1.049 ± 0.017	as Paper 2
Laponche	SAC	1971	[E10]	y(Pu-239)/y(U-235) = 1.606 ± 0.018 y(Pu-241)/y(Pu-239)= 1.469 ± 0.053 $\hat{\sigma}_a$(Pu-239)/$\hat{\sigma}_a$(U-235)= 1.649 ± 0.010	Note 9.4

Note 9.1 MUEHLHAUSE, ALIKHANOV, CABELL: In Papers 1 and 2 the input of these ratios was based on the review by Sjöstrand and Story [4, pages 37-45], where ratios of the 2200 m/s expression $(-1)\,\sigma_a$, which is identical to ${}_t\sigma_f - \sigma_a$, were calculated. For the present least-squares fit these should be entered as Maxwellian expressions $y = {}_t\sigma_f\, g_f - \sigma_a\, g$. This is tedious to calculate from the available parameters and not worth the effort considering the low weight of these data. Sjöstrand and Story show in equation (4.14) that for the expression $(-1)\sigma_a$ in first approximation the g-factors for fission apply, and therefore ratios of the expression $x = (-1)\sigma_a\, g_f$ were entered in the fit. These were calculated from the $(-1)\sigma_a$ ratios deduced by Sjöstrand and Story [4] and the 20°C fission g-factors from Westcott [G 10] which had been used in [4]. The errors of [4] were doubled.

Note 9.2 GWIN + MAGNUSON, reactivity experiments: The original values published in [E8] were revised by Magnuson [E13] to

$$\sigma_a g_f \text{ (U-233)} / \sigma_a g_f \text{ (U-235)} = 0.953 \pm 0.014$$

$$\sigma_a g_f \text{ (Pu-239)} / \sigma_a g_f \text{ (U-235)} = 1.631 \pm 0.023$$

for a 25°C Maxwellian spectrum. These data were revised to 20°C using our preferred g-factors. The errors were treated as in Paper 2.

Note 9.3 GWIN + MAGNUSON, large liquid critical experiments: In [E9] 20°C Maxwellian values for were published:

$$(U\text{-}233) = 2.292 \pm 0.015$$
$$(U\text{-}235) = 2.076 \pm 0.015$$
$$\text{Ratio U-233/U-235} = 1.104 \pm 0.009$$

Revised values were given by Magnuson [E13] based on more up-to-date input data in the analysis:

$$(U\text{-}233) = 2.283 \pm 0.015$$
$$(U\text{-}235) = 2.076 \pm 0.015$$

The associated ratio value is not reported: we must assume the uncertainty is unchanged.

The eta values derived from these measurements are not independent of the fissile material absorption cross-sections used in the analysis. It is therefore more appropriate to interpret the results as measurements of $y = (\quad - 1)\hat{\sigma}_a$ for U-233 and U-235 and their ratio. In this formalism the revised results may be written as

$$y(U\text{-}233) = 735.69 \pm 7.78 \text{ barns}$$
$$y(U\text{-}235) = 714.91 \pm 8.99 \text{ barns}$$
$$\text{Ratio U-233/U-235} = 1.029 \pm 0.0072$$

However, some further revision would be desirable using revised cross-sections for the other nuclides present, in particular 0.3320 barns for $g\sigma_a$(H) and 758.8 barns for $g\sigma_a$(B). Since the hydrogen is the dominant term the results would be reduced by about 0.15% to 734.58 and 713.84 barns, respectively. Some of the spherical critical assemblies have also been analyzed by Slaggie [E15] and by Chawla [E4] using multigroup methods. Using cross-sections generated from the ENDF/B 2 library Slaggie's calculations yield eigenvalues for the U-235 systems which are systematically low by about 1.2%; (the mean of 3 values is $k_{eff} = 0.988937$ Since the ENDF/B-2 data for U-235 were compiled in agreement with the Paper 2 recommended values in the thermal region, the best interpretation of these 3 criticals, according to Slaggie's analyses, is

$$y(U\text{-}235) = 725.5 \text{ barns at } 20.44^{\circ}C.$$

For U-235 and H, Chawla used cross-sections generated from DFN-48 and DFN-901 in the UK Nuclear Data Library, and his calculations yield eigenvalues which (like Slaggie's) are systematically low by about 1.35%; (the mean of 5 values is $k_{eff} = 0.9866$, after a small correction to 3 of the 5 results to allow for the coarse meshes used in the computations). The data in DFN-48 give $= 2.430$ in the thermal region. and $g_f\sigma_f = 565.70$ barns, $g_\gamma\sigma_\gamma = 98.04$ barns at 20.44°C. Thus, the best interpretation of these 5 criticals, according to Chawla's analyses, is

$$y(U\text{-}235) = [(\quad/0.9866) - 1]\, g_f\sigma_f - g_\gamma\sigma_\gamma = 729.58 \text{ barns.}$$

From DFN-901 one would calculate $g_a\sigma_a$(H) as 0.33292 barns, and revising this to 0.3320 barns increases the result to

729.8 barns at 20.44°C

Askew [E2] has examined the sources of the discrepancy between Gwin & Magnuson's (1960) analysis and that of Chawla. With some revision and selection the principal items are:

i Inclusion of O(n,α) fast neutron absorption, which reduces k_{eff} by (0.44 ± 0.11)%, with nominal uncertainty.

ii The more detailed model of the thermal events shows that the thermal neutron spectrum is distorted, reducing the thermal utilization factor by 0.185%. (It is of interest to note that this effect corresponds to a reduction in $g_a \sigma_a{}^{\circ}$(U-235) by 0.43%, or to an effective neutron temperature of about 38°C).

The first correction presumably applies equally to the U-233 criticals, but the second would have a much smaller effect on the U-233 effective cross-sections. Consequently, the results of Gwin & Magnuson may be revised to

$$y(\text{U-233}) = 740.35 \pm 7.83 \text{ barns}$$
$$y(\text{U-235}) = 722.50 \pm 9.09 \text{ barns}$$
$$\text{Ratio U-233/U-235} = 1.0247 \pm 0.0072$$

including the σ_a(H) revision mentioned above.

It should be noted that Slaggie and Chawla analyzed only 3 and 5 respectively of the 13 U-235 criticals reported by Gwin & Magnuson. A detailed consideration of all analyses suggests a weighted mean value of y(U-235) = 724.1 barns.

The accuracy, which is not easy to establish reliably, was estimated as follows. An uncertainty of + 0.5% in the uranium density was reported by Gwin & Magnuson, and we may suppose an uncertainty of ± 0.6% in the thermal neutron absorption cross-section of hydrogen; these estimates are common to all the estimates presented above, and so, too, is the uncertainty of ± 0.11% in k_{eff} proposed in (i) above. The general analytical uncertainties of the multigroup method may possibly be adequately represented by ± 0.35% in k_{eff} (which corresponds to - 0.67% in the parameter y). For the U-233 calculations the same uncertainty of ± 0.35% in k_{eff} is proposed as a measure of the uncertainty in the non-leakage probability (and corresponds to ± 0.62% in the parameter y). Hence the total uncertainty in y is ± 1.05% for U-235, and ± 1.02% for U-233. However, because the U-233 experiments have not been so extensively analyzed as the U-235 criticals, we increase the so-called leakage uncertainty proposed above by a factor 1.4. Thus, the results become

$$y(\text{U-233}) = 740.35 \pm 8.78 \text{ barns}$$
$$y(\text{U-235}) = 724.1 \pm 7.6 \text{ barns.}$$

Many of the uncertainties are common and disappear from the y(U 233)/y(U-235) ratio. This remark would be particularly valid if we were to re-calculate the ratio values for each experimental configuration separately. Lacking such re-calculation the uncertainties are ± 0.5% for the U-233 densities, ± 0.5% for the U-235 densities, and something around ± 0.15% for random fluctuations and correction terms in each of the two series. Thus the ratio becomes

$$y(\text{U-233})/y(\text{U-235}) = 1.0247 \pm 0.00756$$

Of course, this ratio value does not have exactly the value which would be obtained from the two input values for y; nor is that necessary if all three values are to form input data in the least-squares fit.

The correlation of errors was treated according to appendix B of Paper 2, and the input becomes

$$y(\text{U-233}) = 740.35 \pm 16.3$$
$$y(\text{U-235}) = 724.1 \pm 11.0$$
$$\text{Ratio U-233/U-235} = 1.0247 \pm 0.0079$$

Note 9.4 LAPONCHE: Measurements were made using global and local oscillators in the central channel of the CESAR graphite moderated reactor. The energy sensitivity of the local detector is not given explicitly, but is probably fairly flat. We might expect then that the measurements with the global oscillator would yield relative values for

$$(\hat{W} - 1)\,\hat{\sigma}_a/\hat{\sigma}_p$$

and the measurements with the local oscillator would yield relative values for $\hat{\sigma}_a$. ($\hat{\sigma}_p$ represents other absorbers.)

Cross-sections for spectrum calculations and effective cross-sections were derived from the UK Nuclear Data Library, however, the data were normalized to the recommended values of Paper 2. Consequently, for the g-factors needed in re-interpreting the results we need the g-factor values deduced from the specified data files. For 20.44°C these are:

Nuclide	DFN	g_a	g_f
U-235	30	0.97850	0.97812
Pu-239	329	1.07769	1.05453
Pu-240	201	1.02836	1.01942
Pu-241	40	1.03419	1.03068

The conclusions drawn from the measurements are presented in items 1b,c and 2b of section III E of reference [E10], and we may re-interpret them as follows:

$$\hat{\sigma}_a(\text{Pu-240}) = 288.1 \pm 10 \text{ barns} \tag{1}$$

$$_t\sigma_f(\text{Pu-241}) = 3122.24 \pm 60.9 \text{ barns} \tag{2}$$

$$\hat{\sigma}_a(\text{Pu-239})/\hat{\sigma}_a(\text{U-235}) = 1.6491 \pm 0.0082 \tag{3}$$

$$_t\hat{\sigma}_f(\text{Pu-239})/\ _t\hat{\sigma}_f(\text{U-235}) = 1.6266 \pm 0.0081 \tag{4}$$

with $_t\hat{\sigma}_f = \sigma_a g_f$. According to the remarks in the first paragraph above, this last result may be better represented by

$$y(\text{Pu-239})/y(\text{U-235}) = 1.6058 \pm 0.0171 \tag{5}$$

with $y = (\hat{\ } - 1)\,\hat{\sigma}_a = {}_t\hat{\sigma}_f - \hat{\sigma}_a$. The Pu-241 result (2) may be better presented by

$$y(\text{Pu-241})/y(\text{U-235}) = 1.4687 \pm 0.0525. \tag{6}$$

Thus, the final results for a 20°C Maxwellian are given by (3) (5) and (6). An additional error of 0.3% was added quadratically to allow for possible inaccuracies in deriving these results from measurements in a reactor spectrum at about the ± 0.3% level.

Absolute values quoted by Laponche et al. are derived from these expressions and can therefore not be used as input to the least-squares fit.

Table 10: DELAYED NEUTRON YIELDS, $\bar{\nu}_d$ [10^{-3}]

Authors	Lab	Year	Ref.	U-233	U-235	Pu-239	Pu-241	Cf-252	Comments
Keepin et al.	LAS	1957	[N31]	6.6±0.44	15.8 ± 0.74	6.1 ± 0.44			Note 10.1
Cox et al.	ANL	1958	[N16]					8.6 ± 4.0	Note 10.2
Cox	ANL	1961	[N17]				15.7 ± 1.5		Note 10.3
Conant+Palmedo	BNL	1970	[N13]	6.66±0.25	15.63± 0.72	6.58 ± 0.57			Note 10.4

Note 10.1 KEEPIN: The uncertainties were converted to standard deviations as done by Tomlinson [N47].

Note 10.2 COX et al.: The error was increased, following Axton [N4], on account of nanosecond groups observed by Nefedov et al. [N37].

Note 10.3 COX: Tomlinson [N47] suggested to increase value and error to 0.0159 ± 0.0016, to include a small sixth group indicated by Bohn [N6]. Cox himself revised his result, for the same reason, to 0.0157 ± 0.0015 [N18].

Note 10.4 CONANT: The authors' results, which are given as delayed neutron fractions, were converted to absolute values using approximately the values resulting from this work.

Table 11: MEAN FISSION-SPECTRUM ENERGIES (MeV)

Authors	Lab	Year	Ref.	U-233	U-235	Pu-239	Pu-241	Cf-252
Earlier adopted values :								
Paper 2	IAEA	1969	[2]	ratio vs U-235 1.02 ± 0.01 that is 2.14 ± 0.10	2.10 ± 0.10	ratio vs U-235 1.06 ± 0.02 2.24 ± 0.11	ratio vs Pu-239 1.00 ± 0.07	2.35 ± 0.18
A.B. Smith	ANL	1971	[M8]		1.979 ± 0.086	2.084 ± 0.050		2.189 ± 0.111
range of experimental values					1.80 to 2.11	2.01 to 2.14		2.08 to 2.35
More recent values:								
Pauw & Aten	AMS	1971	[M6]					2.085
Rose	HAR	1972	[M7]					
(incident neutron energy = 140 keV)								
depending on fit, ranging from					1.937 ± 0.050	2.007 ± 0.055		
to					2.201 ± 0.065	2.136 ± 0.075		
Steen	BAP	1972	[M9]	2.012 ± 0.010	2.018 ± 0.024			
Johansson et al.	FOA	1972	[M3]					
(incident neutron energy = 0.53 MeV								
Maxwellian fit					2.13 ± 0.015			
Watt fit					2.11			
Islam & Knitter	GEL	1973	[M2]					
(incident neutron energy = 0.4 MeV)								
Watt fit = Maxwellian fit =					2.06 ± 0.05			
Green et al.	BET	1973	[M1]					2.105 ± 0.014
Knitter et al.	GEL	1973	[M5]					2.13 ± 0.08
Johansson et al.	FOA	1975	[M4]			ratio vs U-235 1.052		
(incident neutron energies 0.1-2 MeV)								
Presently adopted as input:				2.11 ± 0.15	2.07 ± 0.13	2.08 ± 0.15	2.08 ± 0.15	2.12 ± 0.13
For comparison:								
Fitted values when fitting all $\bar{\nu}$ data in a least squares fit (compare table 14 Fit (2))				2.03 ± 0.07	2.01 ± 0.07	2.09 ± 0.07	2.05 ± 0.07	2.20 ± 0.08

Table 12a: NEUTRON YIELD PER FISSION, $\bar{\nu}$, FOR Cf-252

The input to the least squares fit is formulated as $\bar{\nu}/(1 + s\,(\bar{E}_2 - \bar{E}_a)) = \text{value}$ where $\bar{E}_2$ is the mean energy of the Cf-252 fission-neutron spectrum which is entered as a variable to be fitted, and $\bar{\nu}$, s, $\bar{E}_a$ and value are given in the table. Compare section 2.5.

Authors	Lab	Year	Ref.	$\bar{\nu}$ given in the form of:	s =slope of detector efficiency [MeV^{-1}]	$\bar{E}_a$ =$\bar{E}$ (Cf-252)assumed [MeV]	value if $\bar{E}$(Cf-252)=$\bar{E}_a$	Comments
Dependent on NPL manganese bath								
Moat et al	ALD	1961	[N36]	$\bar{\nu}_p * x_{NPL}$	0.0777	2.35	3.718 ± 0.062	Note 12.01
Colvin et al	HAR	1966	[N12]	$\bar{\nu}_p * x_{NPL} * x_{BP}$	-		3.691 ± 0.027	Note 12.04
White & Axton	ALD	1967	[N51]	$\bar{\nu}_t * x_{NPL}$	-		3.797 ± 0.039	as Axton[N4]
Axton et al	NPL	1972	[N3]	$\bar{\nu}_t * x_{NPL}$	0.0084	2.1	3.725 ± 0.021	as Axton[N4]
Other values								
Asplund-Nilsson et al	FOA	1963	[N2]	$\bar{\nu}_p$	0.0333	2.145	3.782 ± 0.038	Note 12.02
Hopkins & Diven	LAS	1963	[N27]	$\bar{\nu}_p$	0.013	2.1	3.754 ± 0.035	Note 12.03
Colvin & Sowerby	HAR	1965	[N11]	$\bar{\nu}_p * x_{BP}$	-		3.714 ± 0.015	Note 12.04
De Volpi & Porges	ANL	1969	[N21]	$\bar{\nu}_p$	-		3.720 ± 0.015	Note 12.05
Boldeman	AUA	1972	[N9]	$\bar{\nu}_p * x_{Bold}$	0.0245	2.15	3.735 ± 0.011	Note 12.06
				Common errors:	x_{NPL} = 1. ± 0.00325			as Axton [N11]
					x_{BP} = 0.998 ± 0.003			Note 12.04
					x_{Bold} = 1. ± 0.00209			Note 12.06

Table 12b: PROMPT NEUTRON YIELD PER FISSION ($\bar{\nu}$) FOR U AND PU ISOTOPES

Authors	Lab	Year	Ref.	$\bar{\nu}$ given in the form of	s = slope of detector efficiency [MeV^{-1}]	$\bar{E}_a$ or $\sigma\bar{E}_a$ assumed [MeV]	Value if $\bar{E} = \bar{E}_a$, or if $\sigma\bar{E} = \sigma\bar{E}_a$	Comments
Boldeman & Dalton	AUA	1966	[N7]	$\bar{\nu}_p$ (U-233)	0.0245	$\bar{E}_a$ = 1.974	2.455 ± 0.0084	Note 12.06
Sanders	HAR	1955	N44	$\bar{\nu}_p$ (U-233/U-235)	not known		1.010 ± 0.027	Note 12.07
De Saussure& Silver	ORL	1958	[N19]	"	0.3	$\sigma\bar{E}_a$ = 0	1.024 ± 0.022	Note 12.10
Colvin & Sowerby	HAR	1965	[N11]	"	-		1.0239± 0.0065	Note 12.04
Hopkins & Diven	LAS	1963	[N27]	$\bar{\nu}_p$(U-233/Cf-252)	0.013	$\sigma\bar{E}_a$ = 0	0.656 ± 0.009	Note 12.03
Mather et al.	ALD	1964	[N34]	"	0.025	$\sigma\bar{E}_a$ = 0	0.671 ± 0.008	Note 12.12
Fultz et al.	LRL	1966	[N25]	"	-		0.672 ± 0.011	as Paper 2
Nurpeisov et al.	FEI	1972	[N40]	"	0.043	$\sigma\bar{E}_a$ = 0.19	0.6615± 0.0027	Note 12.15
Kenward et al.	HAR	1957	[N32]	$\bar{\nu}_p$(U-235)*x_{NPL}	-		2.382 ± 0.023	Note 12.09
Boldeman & Dalton	AUA	1966	[N7]	$\bar{\nu}_p$(U-235)*x_{Bold}	0.0245	$\bar{E}_a$ = 1.935	2.379 ± 0.0085	Note 12.06
Meadows & Whalen	ANL	1961	[N35]	$\bar{\nu}_p$(U-235/Cf-252)	0.074	$\sigma\bar{E}_a$ = 0.2	0.644 ± 0.0105	Note 12.11
Hopkins & Diven	LAS	1963	[N27]	"	0.013	$\sigma\bar{E}_a$ = 0	0.643 ± 0.008	Note 12.03
Mather et al.	ALD	1964	[N34]	"	0.025	$\sigma\bar{E}_a$ = 0	0.639 ± 0.003	Note 12.12
Condé	FOA	1965	[N14]	"	0.0576	$\sigma\bar{E}_a$ = 0.25	0.639 ± 0.0056	Note 12.11
Colvin & Sowerby	HAR	1965	[N11]	"	-		0.6379± 0.0037	Note 12.04
Fultz et al.	LRL	1966	[N25]	"	-		0.643 ± 0.021	as Paper 2
De Volpi & Porges	ANL	1966	[N20]	"	-		0.642 ± 0.010	Note 12.13
Prokhorova et al.	FEI	1970	[N42]	"	0.043	$\sigma\bar{E}_a$ = 0.215	0.6379± 0.0037	Note 12.15
Boldeman & Dalton	AUA	1966	[N7]	$\bar{\nu}_p$(Pu-239)*x_{Bold}	0.0245	$\bar{E}_a$ = 2.084	2.862 ± 0.0102	Note 12.06
Sanders	HAR	1955	[N44]	$\bar{\nu}_p$(Pu-239/U-235)	not known		1.184 ± 0.045	Note 12.07
DeSaussure & Silver	ORL	1958	[N19]	"	0.3	$\sigma\bar{E}_a$ = 0	1.230 ± 0.027	Note 12.10
Colvin & Sowerby	HAR	1965	[N11]	"	-		1.1873± 0.0085	Note 12.04
Hopkins & Diven	LAS	1963	[N27]	$\bar{\nu}_p$(Pu-239/Cf-252)	0.013	$\sigma\bar{E}_a$ = 0	0.751 ± 0.009	Note 12.03
Mather et al	ALD	1964	[N34]	"	0.025	$\sigma\bar{E}_a$ = 0	0.776 ± 0.009	Note 12.12
Bolodin et al.	FEI	1972	[N10]	"	0.043	$\sigma\bar{E}_a$ = 0.15	0.7679± 0.0072	Note 12.15
Boldeman & Dalton	AUA	1966	[N7]	$\bar{\nu}_p$(Pu-241)*x_{Bold}	0.0245	$\bar{E}_a$ = 1.987	2.896 ± 0.009	Note 12.06
Jaffey & Lerner	ANL	1969	[N29]	$\bar{\nu}_p$(Pu-241/U-233)	0.3	$\sigma\bar{E}_a$ = 0	1.161 ± 0.023	Note 12.14
Sanders	HAR	1955	[N44]	$\bar{\nu}_p$(Pu-241/U-235)	not known		1.226 ± 0.082	Note 12.07
De Saussure & Silver	ORL	1958	[N19]	"	0.3	$\sigma\bar{E}_a$ = 0	1.295 ± 0.036	Note 12.10
Colvin & Sowerby	HAR	1965	[N11]	"	-		1.2119± 0.011	Note 12.04
Jaffey & Lerner	ANL	1969	[N29]	"	0.3	$\sigma\bar{E}_a$ = 0	1.224 ± 0.024	Note 12.14
Kalashnikova	CCP	1955	[N30]	$\bar{\nu}_p$(Pu-241/Pu-239)	not known		1.044 ± 0.032	Note 12.08
Jaffey & Lerner	ANL	1969	[N29]	"	0.3	$\sigma\bar{E}_a$=0	0.999 ± 0.020	Note 12.14

Notes to tables 12a and 12b: Neutron yield per fission

Note 12.01 MOAT: As Paper 2. The error was further increased for uncertainty in the slope of the efficiency curve of the neutron detector. No further evaluation of this experiment was done since it has only little weight in the fit.

Note 12.02 ASPLUND-NILSSON: The original result of the liquid-scintillator experiment by Asplund-Nilsson et al. [N2] has subsequently been revised by Conde et al. [N15] and recently by Axton [N5] with improved Monte-Carlo calculations of the leakage correction. Axton's result as reviewed and agreed by Conde [N5] is $\bar{\nu}_p$(Cf-252) = 3.782 ± 0.038 assuming $\bar{E}$ = 2.145 MeV and a slope of the detector efficiency of 3.33% MeV.

Note 12.03 HOPKINS: A new Monte-Carlo simulation of the capture and detection of neutrons with large liquid scintillators by Poitou and Signarbieux [N41] added to previous calculations, a new element which is the emission of gamma cascades and their interactions with the scintillator. On this basis Diven [N23] interpreted a correction to his nubar value from previously 3.771 ± 0.031 to 3.755 ± 0.031. There is however some uncertainty to this correction and we prefer to use a correction of - 0.01 ± 0.01 resulting in a value of 3.761 ± 0.035.

Diven suggests that his result should be corrected by - 0.3% for delayed gammas [N4], partially compensated by a net increase of + 0.1% resulting from some minor revisions. Thus we obtain $\bar{\nu}_p$ = 3.754 ± 0.035.

The slope of the detector-efficiency curve was deduced from the authors' statement that an increase in T from 1.4 to 1.59 MeV raises by 0.38%.

The ratio values were left unchanged assuming that the corrections mentioned cancel in the ratios. For the ratios, the authors did not assume any fission-neutron spectra differences, and the input was formulated accordingly.- The results for the four nuclides could have been formulated in the same way as the Boldeman data, but correlations between the four results were not considered.

Note 12.04 COLVIN: Leonard reviewed this boron pile experiment and came to the following conclusions:

There are a number of factors in these experiments that indicate that assigned errors should be increased and that values should be changed. The situation is quite complicated because of the two different methods used to calibrate the pile efficiency. In some cases detailed calculations need to be performed to quantitatively assess the factors and uncertainties. The different factors are discussed separately.

The Effect of Prompt Gate Length

Essentially all of the vital gated experiments used a 4 msec prompt gate. The typical correction required for the neutron events that took place after the gate was closed was 4.3% [N12, p. 315, table V]. The data presented in table V for the calibration by Na(γ) and D(γ,n) measurements give a 4 ms gate efficiency which is 0.23 ± 0.27 percent higher than the 8 ms gate efficiency. The corresponding effect for the best Pu-240 spontaneous fission source is +0.09 ± 0.38 percent. Thus, it would seem that on either basis any absolute nubar

measurement should contain a common error of about ± 0.50 percent. For ratio measurements some portion of this factor should be included since the neutron slowing down time depends on the neutron spectrum. The author [N12, p. 313] claimed for this effect an error of ± 0.10 percent, which is not verified experimentally.

Normalization of the Calculated Efficiency Curve

The procedure used to determine the Boron Pile efficiency as a function of initial neutron energy was to normalize an efficiency vs E_n curve calculated by the Sn method to measured photoneutron efficiencies for E_n = 265 keV and 2 MeV. Experimentally, the 2 MeV efficiency was 0.37 ± 0.33 percent lower than the 265 keV efficiency. Colvin assumed the efficiency linear from 0 to 2 MeV given by the experimental values. The theory shape is distinctly non-linear in this region and is normalized to the 2 MeV experimental value. The normalization chosen by Colvin appears to be arbitrary. Any other choice of normalization procedure would have resulted in an efficiency 0.25 to 0.5 percent lower with a corresponding increase in derived nubar values, the value depending on the fission spectrum. Colvin claimed an efficiency for the photoneutron calibration of 0.6428 ± 0.0020 (± 0.31%) for the Cf-252 spectrum [N12, p. 310] apparently independent of spectrum uncertainty. I propose that the absolute nubar values should be increased by +0.375% and this increase added in quadrature to the photo-neutron experiment error which I take to be ± 0.23% to give an error of ± 0.44 percent independent of the gate length error.

Shape of Calculated Efficiency Curve

It is well known that multigroup transport or Monte Carlo methods are not capable of handling in detail the calculation of deep penetration in graphite [N26, 50] and also that the results are sensitive to the descriptions given of the microscopic carbon cross-sections. The Boron Pile experiment needs to be recalculated with the best techniques and data to independently evaluate the efficiency shape and uncertainty, (similar as for manganese bath and liquid scintillator systems.)

There is another factor which is, however, independent of calculational and data problems. This factor is due to the apparent neglect of the removal of neutrons by (n,p) and (n,α) reactions in Cu and by (n,α) reactions in C in the Boron Pile efficiency calculations. These reactions were apparently not included. The effect of the neglect of these reactions could be very important and would apply (differently) to the photoneutron and standard source calibrations. The reaction threshold energies are above the 265 keV photoneutron energy and all but Cu(n,p) for the 2 MeV source. I calculated the first flight probabilities for these reactions for the Cf-252 spectrum. The results were 0.03% for the copper (n, particle) reactions and 0.08% for the C(n,α) reaction. Since a fast neutron undergoes many collisions in graphite before its energy drops below threshold, the probability of absorption in these reactions is expected to be many times the values calculated above. The effects of these reactions on fission spectrum efficiency could be readily estimated by simple transport calculations (e.g., ANISN). The results will be quite sensitive to assumed spectrum temperature, e.g., they are estimated to be over a factor of two less for the Pu-240 spontaneous fission spectrum. In this manner they effect the standard source calibration and nubar ratios.

Further details must still be investigated in contact with Harwell scientists, and more accurate re-calculations are still to be done. Meanwhile, it seems justified to make modest adjustments to the boron pile data, that is to correct the photoneutron calibrated value by +025 ± 0.25%, and to adjust both boron pile data by +0.2 ± 0.2%. The latter is equivalent to changing the common error of the boron pile from 1 ± 0.0023 to 0.998 ± 0.003.

Note 12.05 DE VOLPI: Axton [N4] has reviewed this important experiment carefully and suggested to increase the error from 0.4% to 0.8% to cover possible additional uncertainties in the correction factors and in aliquoting. Since De Volpi did not agree, his original value and error were entered in the fit.

Note 12.06 BOLDEMAN: The $_p$ measurements by Boldeman were reported as an absolute measurement for Cf-252 [N9], and measurements for U-233, U-235, Pu-239, Pu-241 relative to Cf-252 [N7]. These were re-formulated by the author [N8] as five absolute measurements correlated by a common error x_{Bold}, which was entered in the fit as a separate variable. As common error contributions were considered: 0,1% for the "french effect", 0.07% for the delayed gammas of Cf-252, and 0.17% for the shape of the efficiency curve of the neutron detector. These sum up quadratically to 0.209%. The slope of the efficiency curve was 0.0245/MeV, and the mean fission spectrum energies $\bar{E}$ assumed by the author for the five nuclides can be found in the tables 12a and 12b.

Note 12.07 SANDERS: As Paper 2. The error contribution due to fission spectra differences was increased from 1% to 2%. The Pu-241/Pu-239, which was measured as a sample with only 13.9% Pu-241 and 26.8% Pu-239, was revised using more up-to-date values for the fission cross-sections which enter in a correction factor.

Note 12.08 KALASHNIKOVA: Since nothing is known about the energy dependence of the neutron-detector the error was increased to 3%.

Note 12.09 KENWARD: The same value as in Paper 2 was used, based on the revision by Fieldhouse et al. [N24]. The error common to the (Cf-252) data, dependent on the NPL manganese bath, was taken care of by formulating the input as $_p * x_{NPL}$. The error of this expression must not include the error contribution from the NPL bath, but the error was increased (factor 1.4) because of the poor documentation of this experiment. The formulation using x_{NPL} makes it redundant to enter a $_p$ ratio U-235/Cf-252 as it was done in Paper 2.

Note 12.10 DE SAUSSURE: The authors assumed an error of 0.5% for possible fission-neutron spectra differences, but no correction was applied on this ground. The authors do not give any information about the efficiency curve of their detector.

The detector was a Hornyak button, Hornyak gives in [N28] an efficiency which increases at neutron-energies around 2 MeV by about 3% with 0.1 MeV increase in neutron-energy. We therefore assume an efficiency slope of (3 ± 1.5)% per 0.1 MeV. The errors of the ratios were increased for the uncertainty in this slope.

Note 12.11 MEADOWS - CONDE: As Paper 2. The measurement by Meadows (respectively Conde, see figures in parentheses) was performed with incident neutrons of 30 (60) keV. The correction to thermal energy was made in Paper 2 assuming a slope (E) of 0.11 ± 0.11 per MeV. This slope was about confirmed by Manero and Konshin [N33: fig. 10, page 687], so that the value of Paper 2 was left unchanged.- The slope of the detector efficiency curve was 0.074 (0.0576) per MeV, and the difference $\bar{E}$(Cf-252) - $\bar{E}$(U-235) was assumed as 0.2 (0.25) MeV.

Note 12.12 MATHER: The slope of the detector-efficiency curve was assumed as 0.025/MeV, whereas the authors had assumed 0.013/MeV. The ratio values used are those by the authors before they applied their spectra corrections. As in the case of Hopkins (note 12.03) corrections for delayed gammas are considered to cancel in the ratios.

Note 12.13 DE VOLPI: In Paper 2 a ratio of $_t$(U-235)/ $_t$(Cf-252) $= 0.6445 \pm 0.010$ was used, which had been obtained by private communication superseding the published value [N20], and where the error had been increased to cover a 3.3% difference

between the results from the two fission-chambers used. This revised value was apparently not published, but the revision was due to the revised manganese bath calibration published in [N17]. Thus we continue to use the value of Paper 2, which was also accepted by De Volpi in his review paper [5], assuming that the 1972 revision [N22] of the (Cf-252) value would not affect the ratio.

Note 12.14 JAFFEY: The published values were corrected for differences in the fission-neutron energy spectra of the different nuclei. The authors' percentage corrections were 0.9 ± 0.5, 2.5 ± 0.4, 2.0 ± 0.5 for the ratios of (Pu-241) versus U-233, U-235, Pu-239 respectively, based on assumed $\bar{E}$ ratios of 1.006, 1.042, 1.112 respectively. From these we calculated a slope of the detector efficiency curve of 7.7, 3.1, 0.92% per 0.1 MeV respectively. This appears to be rather inconsistent. We therefore go back to the authors' uncorrected $_p$ ratios, and assume a slope of the efficiency curve of (3 ± 2)% per 0.1 MeV, similar to the Oak Ridge experiment; compare note 12.10. Due to the uncertainty in the slope of the efficiency curve the errors of the $_p$ ratios were increased to 2%.

Note 12.15 OBNINSK GROUP: A new set of experiments was made, since Paper 2, by a group at Obninsk. Neutrons were detected by He-3 counters in paraffin, fission fragments by an ionization chamber with many layers. The main emphasis of the experiment was to determine the energy-dependence (E). For the thermal neutron source, 0.3 MeV neutrons were slowed down in a paraffin block resulting in a cadmium ratio of 16. The errors quoted by the authors claim a good accuracy, but the neutron detector has a rather steep dependence on the fission-neutron energy.

The results for prompt ratios versus Cf-252 are 0.6615 ± 0.0027, 0.6379 ± 0.0037, 0.7679 ± 0.0040, for U-233, U-235 and Pu-239 respectively, the latter value superseding the result presented in [N38]. The efficiency for detecting fission fragments from the different nuclides differed a bit and corresponding percentage correction factors were 0.71 ± 0.2, 1.11 ± 0.2, 3.8 ± 0.2, respectively. The error of the Pu-239 correction seems a bit under-estimated and we increased it to 20% of the correction, thus obtaining an error of ± 0.0072 for the Pu-239 ratio.

The authors state that they assumed mean fission-neutron spectrum energies according to Terrell's relationship as published in 1959 [N45] and not to Terrell's revision of 1965 [N46]. We conclude that the authors assumed values oe $\bar{E} = 1.96$, 1.35, 2.00, 2.15 MeV for U-233, U-235, Pu-239, Cf-252 respectively. For the U-235/Cf-252 ratio the authors quote a correction factor of 0.9907 ± 0.0020, from which we calculate a slope of the detector-efficiency curve of 0.043 ± 0.009 per MeV.

Table 13a: g-FACTORS

U-233	fission	capture	absorption
Westcott [G11] = input Paper 2	0.9961 ± 0.0020	(0.999)	0.9963 ± 0.0012
g-factors calculated by Steen [G7] from Weston's cross-sections [G12]	0.9966	1.0263	0.9990
Deruytter [G1], assuming σ E= const below 18 meV	1.000 ± 0.005		
assuming curve-shapes according to fig. 2	0.996 (B) to 0.997 (A)	1.027 (B) to 1.055 (A)	0.998 (B) to 1.002 (A)
adopted input:	0.9965 ± 0.002	1.027 ± 0.028	0.999 ± 0.003
U-235			
Westcott [G11] = input Paper 2	0.9772 ± 0.0015		0.979 ± 0.001
Deruytter et al. [F9]	0.9780 ± 0.0010		
assuming different curve shapes near E = 0			0.976 to 0.990
adopted input:	0.9775 ± 0.0015		see note 13
Pu-239			
Westcott [G11] = input Paper 2	1.0522 ± 0.0030		1.0762 ± 0.0031
same, revised σ_s			1.0766
Deruytter et al [G2]	1.0522 1.0534		
adopted input:	1.053 ± 0.003		see note 13
Pu-241			
Lemmel [G3] revised Westcott [G11] Wagemans + Deruytter [G9]	1.044 ± 0.004 1.051 ± 0.008 1.046 ± 0.006		1.0395 ± 0.002 1.038 ± 0.001
adopted input	1.045 ± 0.006		1.039 ± 0.003

Table 13b: U-235 VALUES OF σ_s, σ_a, g_a, $\bar{\sigma}_a$, and $(g_a - 0.3)\,\sigma_a$ at 20.44°C (barns)

		σ_{sb}	σ_{sm}	σ_a	$g_a\,\sigma_a$	$(g_a - 0.3)\,\sigma_a$
Westcott (1960) [G10]				683.0	668.0	463.1
UKNDL (DFN-159B)		16.0	14.4	679.9	664.3	460.10
IAEA (1965) [1]	Input	16.0	14.5	680.6 ± 2.7	665.0	460.81
	Output			679.9 ± 2.3	664.0	460.16
Smith (1966) [G14]				679.9	664.8	460.84
Westcott (1969) [G11]		15	15			
	Range			677.1 to 677.6	662.7 to 663.2	459.51 to 459.98
	Mean			677.3	662.9	459.730
IAEA (1969) [2]						
	Input	17.0	15.3	679.5 ± 2.5	665.0 ± 0.6	461.15
	Output	17.6		678.5 ± 1.7	664.05 ± 0.7	460.50
Present study		16.5	14.8	(679.9)	664.8 ± 1.0	460.439

Table 13c: Pu-239 VALUES OF σ_s, σ_a, g_a, σ_a and $(g_a - 0.3)\,\sigma_a$ at 20.44°C (barns)

		σ_{sb}	σ_{sm}	σ_a	$g_a\,\sigma_a$	$(g_a - 0.3)\,\sigma_a$
UKNDL (DFN-161A)		(11)	(11)	1008.1	1086.8	784.3
Westcott (1960)	[G10]			1029.1	1103.6	794.9
IAEA (1965)	[1]					
	Input	11	11	1006.6 ± 6.4	1079.3	777.4
	Output			1008.1 ± 4.3	1081.0	778.6
Smith (1966)	[G14]			1008.1	1090.9	788.5
Westcott (1969)	[G11]	11	11			
	Range			1008.5 to 1018.0	1086.1 to 1097.2	783.1 to 792.5
	Mean			1012.95	1090.1	786.2
IAEA (1969)	[2]					
	Input	8.6	7.7	1012.1 ± 6.2	1089.2	785.6
	Output	8.5		1012.9 ± 3.6	1089.1	785.2

Note 13: Absorption g-factors for U-235 and Pu-239.

According to section 7.3, the correlations between g_a, σ_a and σ_s are reflected by formulating an input into the fit for the expression $(g_a\sigma_a - 0.3\,\sigma_a) + (2/\quad - 0.3)\sigma_s$ If one considers, for U-235, that the scattering cross-section is entered partially as σ_{sb} and partially as σ_{sm}, a better input is made for the expression $X = (g_a - 0.3)\sigma_a + 0.8284\,(0.379\sigma_{sb} + 0.621\,\sigma_{sm})$. Table 13b shows values of the expression $(g_a - 0.3)\sigma_a$ by various authors. Looking at the 2969 evaluation by Westcott [G11] it seems strange that of the whole set of different fits presented, not one gives a value of σ_a(0.0253 eV) in the range 678.5 to 682.8 barns where the best value is supposed to be. Consequently, the value of $(g_a - 0.3)\sigma_a$ derived from his study appears to be too low. Instead we arrive at a value of 460.4 ± 1.0 barns corresponding to an input value of $X = 473.2 \pm 1.0$ barns. All the fits given in table 13b are based on rather conservative extrapolations of $\sigma_a(E)$ to zero energy. Assuming an uncertainty of 0.3% in g_a and 0.3% in σ_a one obtains $X = 473.2 \pm 2.5$ barns. Corresponding data for Pu-239 are shown in table 13c. We adopt the 1969 value by Westcott, which leads to $Y = (g_a - 0.3)\sigma_a + 0.8284\sigma_{sm}$ $= 795.2$ barns. Assuming an uncertainty of 0.3% in g_a and of 0.6% om σ_a. one obtains as input $Y = 795.2 \pm 5.7$ barns.

Table 14: FITS OF 2200 m/s DATA AND $\bar{\nu}$ DATA

Cross-sections in barns

		Fit (1) of 2200 m/s data alone	Fit (3) of 2200 m/s data and $\bar{\nu}$ data	Fit (7) of Maxwellian data alone with input g-factors
2200 m/s data				
U-233	σ_f	524 ± 17	533 ± 3	529 ± 4
	σ_a	574 ± 2	574 ± 2	575 ± 4
	η	2.292 ± 0.009	2.291 ± 0.009	2.30 ± 0.02
U-235	σ_f	588 ± 2	588 ± 2	579 ± 4 *
	σ_a	680 ± 2	681 ± 2	676 ± 18
	η	2.074 ± 0.010	2.075 ± 0.008	2.10 ± 0.05
Pu-239	σ_f	744 ± 5	746 ± 4	745 ± 6
	σ_a	1013 ± 6	1011 ± 5	1009 ± 28
	η	2.114 ± 0.009	2.112 ± 0.008	2.12 ± 0.06
Pu-241	σ_f	1022 ± 22	1021 ± 11	1013 ± 11
	σ_a	1377 ± 14	1377 ± 13	1378 ± 13
	η	2.162 ± 0.013	2.162 ± 0.013	2.18 ± 0.04
$\bar{\nu}$ data (prompt)		Fit (2) of $\bar{\nu}$ data alone		Fit (14) of all data but without input for $\bar{\nu}$ data
U-233		2.462 ± 0.008	2.462 ± 0.008	2.487 ± 0.009 *
U-235		2.387 ± 0.007	2.387 ± 0.006	2.422 ± 0.009 *
Pu-239		2.855 ± 0.010	2.856 ± 0.010	2.857 ± 0.014
Pu-241		2.899 ± 0.011	2.899 ± 0.010	2.928 ± 0.028
Cf-252		3.731 ± 0.008	3.731 ± 0.008	
$\bar{E}$	U-233	2.03 ± 0.07	2.04 ± 0.07	
	U-235	2.01 ± 0.07	2.01 ± 0.07	* = disturbing discrepancy
	Pu-239	2.09 ± 0.07	2.09 ± 0.07	
	Pu-241	2.05 ± 0.07	2.05 ± 0.07	
	Cf-252	2.20 ± 0.08	2.20 ± 0.08	

Table 15: INDIRECT HALF-LIFE DETERMINATIONS

Fit		$T_{1/2}$(U-233) 10^5y	$T_{1/2}$ (U-234) 10^5y	$T_{1/2}$ (Pu-239) 10^4y
(4)	Fit of all fission cross-section data without input for half-lives	1.576 ± 0.013	2.464 ± 0.020	2.419 ± 0.022
(5)	Fit of 2200 m/s and $\bar{\nu}$ data without input for half-lives	1.566 ± 0.052	2.448 ± 0.016	2.422 ± 0.020
(5a)	Same fit, but for Pu-239 data only			2.416 ± 0.024
(6)	Fit of all data without input for half-lives	1.584 ± 0.008	2.471 ± 0.011	2.429 ± 0.011
	Input values	1.591 ± 0.002	2.446 ± 0.002	2.424 ± 0.014

Table 16: FITS OF MAXWELLIAN DATA

Maxwellian data		Fit (7) of Maxwellian data alone	Fit (8) of Maxwellian data and $\bar{\nu}$ data	Maxwellian data deduced from fit (3) of 2200 m/s data, $\bar{\nu}$ data and g-factors	Difference with fit (7)
U-233	$\hat{\sigma}_f$	527 ± 3	530 ± 3	531 ± 3	4 *
	$\hat{\alpha}$	0.090 ± 0.0006	0.090 ± 0.0006	0.080 ± 0.006	0.010 *
	$\hat{\eta}$	2.296 ± 0.019	2.266 ± 0.007	2.286 ± 0.010	0.010
U-235	$\hat{\sigma}_f$	566 ± 4	570 ± 3	574 ± 2	8 *
	$\hat{\alpha}$	0.172 ± 0.001	0.172 ± 0.001	0.157 ± 0.006	0.015 *
	$\hat{\eta}$	2.091 ± 0.016	2.058 ± 0.006	2.077 ± 0.011	0.014
	$(\hat{\eta} - 1)\hat{\sigma}_a$	723 ± 9	706 ± 5	716 ± 6	
Pu-239	$\hat{\sigma}_f$	785 ± 6	788 ± 5	785 ± 5	0
	$\hat{\alpha}$	0.391 ± 0.002	0.392 ± 0.002	0.391 ± 0.009	0
	$\hat{\eta}$	2.064 ± 0.019	2.053 ± 0.007	2.058 ± 0.013	0.006
Pu-241	$\hat{\sigma}_f$	1059 ± 10	1064 ± 10	1067 ± 13	8
	$\hat{\alpha}$	0.352 ± 0.008	0.350 ± 0.008	0.341 ± 0.012	0.011
	$\hat{\eta}$	2.193 ± 0.032	2.162 ± 0.014	2.174 ± 0.019	0.019

*= disturbing discrepancy

Table 17: DISCREPANCIES AMONG MAXWELLIAN INPUT DATA

		Input	Fit (7) of Maxwellian data alone	Fit (8) Maxwellian data and $\bar{\nu}$ data	Fit(3) of 2200 m/s data $\bar{\nu}$ data and g-factors (see table 18)
Keith	$\hat{\sigma}_f$(U-233/U-235)	0.938 ± 0.008	0.931 ± 0.002	0.930 ± 0.002	0.924 ± 0.006
Bigham	$\hat{\sigma}_f T_{1/2}$ (U-233)	834 ± 8	838 ± 5	842 ± 5	844 ± 5
Sweet	$\hat{\sigma}_f T_{1/2}$ (Pu-239)/ $\hat{\sigma}_f$(U-235) $T_{1/2}$ (U-234)	1.354 ± 0.019	1.377 ± 0.004	1.374 ± 0.004	1.355 ± 0.007
$\hat{\alpha}$(U-233)	Inghram	0.094 ± 0.003			
	Lisman	0.093 ± 0.002	0.090 ± 0.006	0.090 ± 0.0006	0.080 ± 0.006
	Lounsbury	0.089 ± 0.0007			
	Conway	0.085 ± 0.005			
$\hat{\alpha}$(U-235)	Cornish	0.188 ± 0.014			
	Durham	0.175 ± 0.002	0.172 ± 0.001	0.172 ± 0.001	0.157 ± 0.006
	Lounsbury	0.172 ± 0.0015			
	Okazaki	0.1705± 0.002			
DeBoisblanc	$\hat{\eta}$(U-233/U-235)	1.115 ± 0.012	1.098 ± 0.004*	1.101 ± 0.003	1.101 ± 0.007
Gwin	$(\hat{\eta} - 1)\sigma_a$ = y(U-235)	724 ± 11	723 ± 9	706 ± 5	716 ± 6
	y(U-233/U-235)	1.025 ± 0.008	1.029 ± 0.007	1.035 ± 0.005	1.030 ± 0.010
Laponche	y(Pu-239/U-235)	1.606 ± 0.018	1.606 ± 0.016	1.635 ± 0.010	1.615 ± 0.020

Table 18: DISCREPANCIES BETWEEN MAXWELLIAN INPUT DATA AND 2200 m/s DATA

		Input	Same expression deduced from fit (3) of 2200 m/s data, $\bar{\nu}$ data and g-factors	Difference * = disturbing
Lounsbury	$\hat{\sigma}_f$(U-233/U-235)	0.938 ± 0.013	0.924 ± 0.006	0.014
	$\hat{\sigma}_f$(Pu-239/U-235)	1.392 ± 0.012	1.367 ± 0.008	0.025*
Keith	$\hat{\sigma}_f$(U-233/U-235)	0.938 ± 0.008	0.924 ± 0.006	0.014*
	$\hat{\sigma}_f T_{1/2}$(Pu-239/U-233)	2.282 ± 0.035	2.254 ± 0.016	0.028
Bigham	$\hat{\sigma}_f$(U-233/U-235)	0.931 ± 0.004	0.924 ± 0.006	0.007
	$\hat{\sigma}_f T_{1/2}$(U-233)	834 ± 8	844 ± 5	10
	$\hat{\sigma}_f T_{1/2}$(Pu-239/U-233)	2.276 ± 0.009	2.254 ± 0.016	0.022
	$\hat{\sigma}_f T_{1/2}$(Pu-239)/σ_f(U-235)$T_{1/2}$(U-233)	2.116 ± 0.009	2.082 ± 0.010	0.034*
	$\hat{\sigma}_f$(Pu-241)/$\sigma_f T_{1/2}$(Pu-239)	0.553 ± 0.006	0.561 ± 0.007	0.008
mean of	$\hat{\alpha}$(U-233) data	0.090 ± 0.0006	0.080 ± 0.006	0.010*
mean of	$\hat{\alpha}$(U-235) data	0.172 ± 0.001	0.157 ± 0.006	0.015*
Halperin	$\hat{\sigma}_\gamma$(U-233)	50 ± 3	42 ± 3	8
Cabell	$\hat{\sigma}_\gamma$(U-233)/[$\hat{\sigma}_a$(U-233)-$\hat{\sigma}_\gamma$(U-234)]	0.098 ± 0.005	0.089	0.009*
Gwin	$(\hat{\eta}-1)\hat{\sigma}_a$(U-235)	724 ± 11	716 ± 6	8
	$(\hat{\eta}-1)\hat{\sigma}_a$(U-233/U-235)	1.025 ± 0.008	1.030 ± 0.010	0.005
Laponche	$(\hat{\eta}-1)\hat{\sigma}_a$(Pu-239/U-235)	1.606 ± 0.018	1.615 ± 0.020	0.009
Cabell, Dimple	$(\hat{\eta}-1)\sigma_a g_f$(Pu-239/U-233)	1.537 ± 0.044	1.604 ± 0.015	0.067*
	$(\hat{\eta}-1)\sigma_a g_f$(Pu-239/U-235)	1.608 ± 0.048	1.656 ± 0.014	0.052
Muehlhause	$(\hat{\eta}-1)\sigma_a g_f$(Pu-239/U-235)	1.513 ± 0.103	1.656 ± 0.014	0.143

Table 19: DIRECT AND INDIRECT VALUES OF α(U-233) AND α(U-235)

	α(U-233)	α(U-235)
Mean of direct experimental data	0.090 $\pm$ 0.0006	0.172 $\pm$ 0.001
Fit (12) of Maxwellian data without input for $\hat{\alpha}$(U-233) and $\hat{\alpha}$(U-235)	0.090 $\pm$ 0.004	0.173 $\pm$ 0.008
Fit (13) of all input data without input for $\hat{\alpha}$(U-233) and $\hat{\alpha}$(U-235)	0.086 $\pm$ 0.003	0.161 $\pm$ 0.004
Fit (3) of 2200 m/s data, $\bar{\nu}$ data and g-factors	0.080 $\pm$ 0.006	0.157 $\pm$ 0.006
$\hat{\alpha} = \bar{\nu}_f - y/\hat{\sigma}_f - 1$, see section 8.5	0.069 $\pm$ 0.036	0.129 $\pm$ 0.028

Table 20: g-FACTORS $*10^3$

	Input	g_f/g_a computed from (Smith), $\hat{\alpha}$ (Lounsbury), and $\bar{\nu}_t$ from fit (2)	Fit (9) of Maxwellian data and 2200 m/s data without g-factor input	Fit (10) of Maxwellian data, 2200 m/s data and $\bar{\nu}$ data without g-factor input	Fit (11) of all input data except $\hat{\alpha}$(U-233) and $\hat{\alpha}$(U-235), without g-factor input	For comparison: Input used in Paper 2
U-233 g_f	996.5 ± 2		997 ± 8	995 ± 8	996 ± 8	996 ± 2
g_a	999 ± 3		1004 ± 7	1006 ± 7 *	1006 ± 7	996 ± 1
g_f/g_a	997	0.985 ± 0.005	993 ± 6	989 ± 4 *	991 ± 5	1000 ± 2
g_γ	1027 ± 28		1085 ± 84 *	1145 ± 62*	1123 ± 73	
U-235 g_f	977.5 ± 1.5		970 ± 7	971 ± 6	970 ± 6	977 ± 1.5
g_a	977 ± 4		976 ± 7	981 ± 7	971 ± 8	979 ± 1
g_f/g_a	1001	0.985 ± 0.006	993 ± 4	990 ± 3 *	999 ± 5	998 ± 2
g_γ	971		1015 ± 29	1040 ± 25*	980 ± 39	
Pu-239 g_f	1053 ± 3		1056 ± 7	1059 ± 7 *	1057 ± 7	1052 ± 3
g_a	1079 ± 5		1088 ± 9 *	1088 ± 8 *	1084 ± 8	1076
g_f/g_a	976	0.970 ± 0.006	977 ± 6 *	973 ± 4 *	975 ± 4	978 ± 3
g_γ	1153		1177 ± 27*	1172 + 20*	1160 ± 20	
Pu-241 g_f	1045 ± 6		1042 ± 14	1042 ± 13	1041 ± 13	1051 ± 5
g_a	1039 ± 3		1039 ± 13	1042 ± 12	1040 ± 12	1038 ± 1
g_f/g_a	1006		1003 ± 12	1000 ± 8	1001 ± 8	1013 ± 5
g_γ	1022		1031 ± 41	1043 ± 31	1037 ± 31	

		Present work (1975)	IAEA 1969 [2]	Change	De Volpi [5] (1971)	Steen [G7] (1972)	ENDF/B-4	Fit of 2200 m/s data and $\bar{\nu}$ data only (prese wor
U-233	σ_a	575.2 ± 1.3	577.6 ± 1.8	-2.4	575.6	572.2 ± 0.9	579.9 ± 1.5	573.8 ± 1.8
	σ_f	529.9 ± 1.4	530.6 ± 1.9	-0.7	531.9	526.3 ± 0.8	533.7 ± 1.3	532.6 ± 3.0
		2.283 ± 0.006	2.284 ±0.006	-0.001	2.284	2.277 ± 0.005	2.284 ± 0.004	2.291 ± 0.009
	$\bar{\nu}_t$	2.479 ± 0.006	2.487 ±0.007	-0.008	2.472	2.476 ± 0.005	2.482 ± 0.005	2.468 ± 0.008
	g_a	1.001 ± 0.002	0.997 ±0.001	+0.004			0.999	
	g_f	0.997 ± 0.002	0.995 ±0.002	+0.002			0.997	
	$T_{1/2}$	159000 ± 200	159300 ±2400	-300			0.997	
U-235	σ_a	680.9 ± 1.7	678.5 ± 1.9	+ 2.4	683.0 ± 1.9	675.8 ± 1.3	682.9 ± 1.4	680.6 ± 1.8
	σ_f	583.5 ± 1.3	580.2 ± 1.8	+ 3.3	585.7 ± 1.8	577.5 ± 1.1	585.7 ± 1.1	587.7 ± 1.9
		2.071 ± 0.006	2.072 ±0.006	- 0.001	2.058 ± 0.006	2.062 ± 0.005	2.074 ± 0.003	2.075 ± 0.008
	$\bar{\nu}_t$	2.416 ± 0.005	2.423 ±0.007	- 0.007	2.400 ± 0.007	2.412 ± 0.005	2.419 ± 0.004	2.403 ± 0.006
	g_a	0.980 ± 0.003	0.979 ±0.001	+ 0.001			0.979	
	g_f	0.976 ± 0.002	0.977 ±0.002	- 0.001			0.977	
U-234	$T_{1/2}$	244700 ± 200	248800 ±1600	- 4100				
Pu-239	σ_a	1011.2 ± 4.1	1012.9 ± 4.1	- 1.2	1013.4± 4.6		1011.8 ± 3.6	1010.8± 4.7
	σ_f	744.0 ± 2.5	741.6 ± 3.1	+ 2.4	742.5± 3.1		742.0 ± 2.1	745.9± 3.8
		2.106 ± 0.007	2.109 ±0.007	- 0.003	2.091 ± 0.007		2.107 ± 0.007	2.112± 0.008
	$\bar{\nu}_t$	2.862 ± 0.008	2.880 ±0.009	- 0.018	2.854 ± 0.007		2.873 ± 0.008	2.862± 0.010
	g_a	1.081 ± 0.004	1.075 ±0.003	+ 0.006			1.075	
	g_f	1.056 ± 0.003	1.055 ±0.003	+ 0.001			1.055	
	$T_{1/2}$	24290 ± 70	24380 ± 50	+ 90				
Pu-241	σ_a	1378 ± 9	1375 ± 9	+ 3			1373 ± 7	1377 ± 13
	σ_f	1015 ± 7	1007 ± 7	+ 8			1009 ± 4	1021 ± 11
		2.155 ± 0.010	2.149 ±0.014	+ 0.006			2.156 ± 0.007	2.162± 0.013
	$\bar{\nu}_t$	2.924 ± 0.010	2.934 ±0.012	- 0.010			2.934 ± 0.008	2.915± 0.010
	g_a	1.039 ± 0.003	1.038 ±0.001	+ 0.001		Axton [N4](1972)	1.038	
	g_f	1.044 ± 0.005	1.049 ±0.005	- 0.005			1.049	
Cf-252	$\bar{\nu}_t$	3.746. ± 0.009	3.765 ±0.012	- 0.019		3.734 ± 0.008	3.757 ± 0.007	3.740± 0.009

		2200 + $\bar{\nu}$ data	diff	all data	diff	Maxwellian data alone
U-233	σ_a	573.8±1.8	1.4	575.2±1.3	0.5	574.7± 3.9
	σ_f	532.6±3.0	2.7	529.9±1.4	1.3	528.6± 3.6
σ_f(U-233/U-235)		0.9239±0.0058	0.0036	0.9275±0.0020	0.0036	0.9311± 0.0024
	$\bar{\nu}_p$	2.462 ±0.008	0.010	2.472 ±0.006	0.024	2.496 ± 0.021
	η	2.291 ±0.009	0.008	2.283 ±0.006	0.029	2.302 ± 0.020
	$\hat{\alpha}$	0.0799±0.0055	0.01	0.0897±0.0006	0.0002	0.0899± 0.0006
U-235	σ_a	680.6±1.8	0.3	680.9 ±1.7	5.2	675.7 ±17.6
	σ_f	587.7±1.9	4.2	583.5 ±1.3	4.8	578.7 ± 4.0
	$\bar{\nu}_p$	2.387±0.006	0.013	2.400 ±0.005	0.035	2.435 ± 0.019
	η	2.075±0.008	0.004	2.071 ±0.006	0.028	2.099 ± 0.051
	$\hat{\alpha}$	0.1569±0.0062	0.015	0.1717±0.0009	0.0005	0.1722± 0.0010
	$(\hat{\eta}-1)\hat{\sigma}_a$	716±6	7	709±3	14	723 ± 9
Pu-239	σ_a	1010.8±4.7	0.4	1011.2±4.1	2.6	1008.6±28.5
	σ_f	745.9±3.8	1.9	744.0±2.5	1.5	745.5± 5.7
$\hat{\sigma}_f$(Pu-239/U-235)		1.367±0.008	0.012	1.379±0.004	0.009	1.388± 0.005
	$\bar{\nu}_p$	2.856±0.010	0	2.856±0.008	0.008	2.864± 0.027
	η	2.112±0.008	0.006	2.106±0.007	0.016	2.122± 0.057
	$\hat{\alpha}$	0.3908±0.0086	0.0003	0.3911±0.0020	0.0002	0.3909±0.0021
Pu-241	σ_a	1377.3±12.6	0.3	1377.6±8.5	0	1377.6±13.1
	σ_f	1021.3±10.8	5.9	1015.4±7.1	2.3	1013.1±11.3
	$\bar{\nu}_p$	2.899 ± 0.010	0.009	2.908 ±0.009	0.04	2.948 ±0.048
	η	2.162 ± 0.013	0.007	2.155 ±0.010	0.025	2.180 ±0.035
	$\hat{\alpha}$	0.341 ± 0.012	0.009	0.350 ±0.006	0.002	0.352 ±0.008
Cf-252	$\bar{\nu}_p$	3.731 ± 0.008	0.006	3.737 ±0.008		

APPENDIX A

Supplementary notes on the error analysis of the Chalk-River irradiation experiment by Lounsbury et al. [C1], communicated by G.C.Hanna.

Summary of errors on fission cross-section ratios (percentage errors)

Pu-239/U-233

(a)	Isotopic analyses	U-238	0.368
		U-234	0.014
		Pu isotopes	0.223
		Quadrature sum	0.431
(b)	Other cross-sections	0.57% in $\hat{\sigma}_a$(233)	0.037
		others as for 239/235	———
		Quadrature sum	0.21
(c)	Spectrum uncertainty	30% in (R-1) for 239	0.267
		" " " " 233	0.018
		Algebraic sum	0.285

Pu-239/U-235

(a)	Isotopic analyses	U-238	0.339
		U-236	0.020
		Pu isotopes	0.244
		Quadrature sum	0.419
(b)	Other cross-sections	0.37% in $\hat{\sigma}_a$(235)	0.024
		0.7% in $\hat{\sigma}_a$(241)	0.06
		2% in $\hat{\sigma}_\gamma/\hat{\sigma}_a$(241)	0.13
		5% in $\hat{\sigma}_a$(242)	0.14
		± 0.5 y in $T_{\frac{1}{2}}$(241)	0.03
		Quadrature sum	0.21

(c)	Spectrum uncertainty	30% in (R-1) for 239	0.267
		" " " " 235	0.144
		Algebraic sum for ratio	0.411

U-233/U-235

(a)	Isotopic analyses	from 239/235	0.419
		from 239/233	0.431
		Quadrature sum	0.601
(b)	Other cross-sections	0.37% in $\hat{\sigma}_a$(235)	0.024
		0.57% in $\hat{\sigma}_a$(233)	0.037
		Quadrature sum	0.044
(c)	Spectrum uncertainty	0.144 - 0.018 =	0.126

Percentage Errors on Best Value Set

239/233 $(0.431^2 + 0.210^2 + 0.285^2)^{\frac{1}{2}} = (0.3111)^{\frac{1}{2}} = 0.558$

239/235 $(0.419^2 + 0.210^2 + 0.411^2)^{\frac{1}{2}} = (0.3886)^{\frac{1}{2}} = 0.623$

233/235 $(0.601^2 + 0.044^2 + 0.126^2)^{\frac{1}{2}} = (0.3790)^{\frac{1}{2}} = 0.616$

These errors are equivalent to variances (in % squared) of:

239/233 .15075 + .16035 $(\nu_1 + \delta)$

239/235 .22825 + .16035 $(\nu_2 + \delta)$

233/235 .15075 + .22825 $(\nu_1 + \nu_2)$

So that the equivalent independent variances (for input to a LSF) are:

239/233 .4170 i.e. 0.646%

239/235 .6314 0.795%

233/235 .5936 0.770%

which are very similar to the errors that were used for the LSF input, c Page 2
(Note that in CN-26/2, two lines above Table V, "larger" should be "smaller".)

G.C. Hanna
12/13/73

U-233/U-238 System

Increase of	in	Percent change in $\hat{\alpha}$(233)	$\hat{\sigma}_f$(233)	$\hat{\sigma}_a$(234)	I
0.002	initial 234	-0.0784	+0.0065	-0.0522[a]	0
0.002	" 235	-0.0578	+0.0048	-1.4179	0
0.008	" 238	+0.2732	-0.0226	+0.1793	-0.2053
0.004	final 234	+0.1048	-0.0087	-0.0952	0
0.002	" 235	+0.0615	-0.0051	+1.5069	0
0.014	" 238	-0.3174	+0.0263	-0.2083	+0.2396
(b) 1%	$\hat{\sigma}_a$(233)	-0.0122	+1.0004	+0.5413	-0.9943
(b) 1%	$\hat{\sigma}_a$(235)	+0.0189	-0.0016	+0.4621	0
(b) 1%	$\hat{\sigma}_\gamma/\hat{\sigma}_a$(235)	~0	~0	~0	0
(b) 10%	$\hat{\sigma}_a$(236)	~0	~0	~0	0
(b) 2%	$\hat{\sigma}_a$(238)	-0.0130	+0.0011	-0.0086	+0.0098

Notes

(a) It will be noted that the effects on $\hat{\sigma}_4$ of increases in initial and final U-234 contents are of the same sign. The effect of an increase in the final U-234 is a straightforward consequence of the increased production of U-234 increasing $\hat{\sigma}_\gamma$ of U-233 and correspondingly decreasing $\hat{\sigma}_\gamma$ of U-234 to maintain the U-235 production unchanged. An increase in the initial U-234 produces an inverse effect from this cause, but a larger effect of opposite sign arises from the increased production of U-235 from the increased initial U-234.

(b) While the other numbers in this column represent the actual uncertainties entering the measurement, these five are arbitrary values used by the computer program. The uncertainties actually assigned were 0.57% for $\hat{\sigma}_a$(233), 0.37% for $\hat{\sigma}_a$(235) and 0.6% for $\hat{\sigma}_a$(238), the others being unimportant.

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1/13/73

Pu-239/Pu-242 System[a]

Increase of	in	Percent change in $\hat{\sigma}_a(239)$	$\hat{\sigma}_f(239)$	$\hat{\sigma}_a(240)$
0.002	initial 240	-0.0169	+0.0046	-0.0062
0.002	" 241	+0.0015	-0.0054	-0.0480
0.005	" 242	+0.2140	-0.1619	+0.0176
0.030	final 240	+0.1210	-0.0344	-0.0848
0.004	" 241	+0.0323	-0.0134	+0.1291
0.012	" 242	-0.2352	+0.1786	-0.0194
1%	I	+0.1237	-1.0485	-0.5901
2.5%	$\hat{\sigma}_a(241)$	+0.4029	-0.2180	+1.0179
(b) 5%	$\hat{\sigma}_\gamma/\hat{\sigma}_a(241)$	+0.4256	-0.3216	+0.0350
10%	$\hat{\sigma}_a(242)$	-0.3696	+0.2810	-0.0306
0.5 y	$T_{\frac{1}{2}}(241)$	-0.0581	+0.0248	-0.223

Notes

(a) These numbers refer to the Pu + U-235 irradiation, but apply closely enough to the Pu + U-233 irradiation for purposes of e.g. correcting values for revised input values. For the latter irradiation the dates of analyses were different and the effects of a 0.5 yr increase in $T_{\frac{1}{2}}(241)$ are -0.0669%, + 0.0285% and -0.257% in columns 3, 4[2] and 5 respectively.

(b) While the other numbers in this column represent the actual uncertainties entering the measurement, these four are arbitrary values used by the computer program. For the uncertainties actually assigned see the accompanying notes on the fission cross section ratios.

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14/3/73

APPENDIX B

CINDA/EXFOR codes for laboratories given in the tables of input data

ALD	AWRE Aldermaston, UK
AMS	Amsterdam University, Netherlands
ANL	Argonne National Laboratory, Lemont, Ill., USA
AUA	AAEC Research Establishment, Lucs Heights, Australia
BAP	Bettis Atomic Power Laboratory, Pittsburgh, Pa., USA
BET	Westinghouse, Bettis Atomic Power Lab., Pittsburgh, USA
BNL	Brookhaven National Laboratory, Upton, N.Y., USA
BUC	Inst. for Atomic Physics, Bucuresti, Romania
CCP	USSR
COL	Columbia University, New York, N.Y., USA
CRC	AECL Chalk River, Ont., Canada
FAR	CEA Fontenay-aux-Roses, Seine France
FEI	Fiziko-Energeticheskij Inst., Obninsk, USSR
FOA	Research Inst. of National Defence, Stockholm, Sweden
GEL	CBNM Euratom, Geel, Belgium
GEV	General Electric, Vallecitas Atomic Lab., Calif., USA
HAR	AERE Harwell, UK
ITE	Inst. Teoret. i Exp. Fiziki, Moscow, USSR
KJL	Inst. for Atomenergi, Kjeller, Norway
KUR	Kurchatov Inst. At. En., Moscow, USSR
LAS	Los Alamos Scientific Lab., New Mexico, USA
LRL	Lawrence Livermore Lab., Univ. of Calif., USA
MOL	CEN, Mol, Belgium
MTR	Philips Petroleum Comp., now Aerojet Nucl. Corp., Idaho, USA
NPL	National Physics Lab., Teddington, UK
ORL	Oak Ridge National Lab., Tenn., USA
SAC	CEN Saclay, Seine-et-Oise, France
WIN	AEE Winfrith, UK