THE STATUS OF NUCLEAR DATA OF IMPORTANCE FOR LMFBR APPLICATIONS PRIOR TO THE EVALUATION OF ENDF/B-VI

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ABSTRACT

The evaluation of nuclear data of importance to the LMFBR program has shifted to a Nuclear Data Evaluation Task Force. It is anticipated that the results of these evaluations will be incorporated in ENDF/B-VI. However, several cross sections for reactor applications are included in a simultaneous evaluation of the standard cross sections for ENDF/B-VI organized by the Standard Subcommittee of CSEWG. Cross sections included in this simultaneous evaluation are those of ^{6}Li(n,α), 6Li(n,n), ^{10}B(n,α_o), ^{10}B(n,α_1), ^{10}B(n,n), ^{197}Au(n,γ), ^{235}U(n,f), ^{238}U(n,γ), ^{238}U(n,f), and ^{239}Pu(n,f). The change of the evaluation methodology for ENDF/B-VI will result in a much improved definition of the data, their uncertainties and cross correlations. Trends which can be seen in new data and which are caused by the change of the evaluation procedure are toward, lower ^{239}Pu(n,f), ^{235}U(n,γ), modestly lower ^{235}U(n,f), and higher ^{10}B(n,α) data. The data base for ^{238}U(n,γ) below 30 KeV remains poorly defined and a resolution of the C/E discrepancy of C^{28}/F^{49} cannot be expected from the infinite dilute capture cross section of ^{238}U. $\bar{\nu}$ of ^{252}Cf remains unchanged and therefore also the ν(E) of the fissile isotopes, except at thermal energy.

I. INTRODUCTION

Great importance of nuclear data for reactor design and development can be claimed for many materials based upon numerous aspects of their applications. It is clearly impossible to touch on all of these and the present considerations are restricted to some of those quantities which are of major interest to reactor neutronics, reactor design goal, and operating requirements, and for which some trends toward a new version of ENDF/B can already be seen.

As this review is intended to give a preview of the possible changes and the impact of the present data base on ENDF/B-VI, a look at the present situation regarding ENDF/B-VI will be useful: support for the evaluations required for a new evaluated nuclear data file has changed and the evaluations of nuclear data for the LMFBR program has shifted to a Nuclear Data Evaluations Task Force. It is anticipated that these evaluations will be incorporated in ENDF/B-VI. However, several of the cross sections of major importance for reactor neutronics are included in a simultaneous evaluation of the standard cross sections which has been organized by the Standards Subcommittee of CSEWG. Presently, the support for any activity is such that only slow progress can be expected.

The thermal parameters which affect some of the other data and which will be most likely included in ENDF/B-VI will be considered in Section II, with the major emphasis on $\bar{\nu}$ of ^{252}Cf. The simultaneous evaluation of the standards and other principle cross sections will be discussed in Section III. The emphasis of the discussion will be on those cross sections which are of importance for LMFBR applications. In Section IV some other expected data changes will be discussed, and some conclusions will be drawn in a final section.

II. THE THERMAL PARAMETERS AND $\bar{\nu}$ OF ^{252}Cf

The various cross sections as well as ν, η and the Westcott g-factors of the principle fissile nuclides, ^{233}U, ^{235}U, ^{239}Pu, and ^{240}Pu are not only of importance for thermal reactors, but also because many measurements of cross sections at higher neutron energies are normalized to the thermal cross sections. These thermal parameters are interrelated by consistency requirements and correlated by ratio measurements. Thus, the thermal parameters are usually being evaluated simultaneously.[1-3] However, the thermal cross sections of ^{235}U for ENDF/B-V were derived from an independent analysis of the ^{235}U cross sections and cross section shapes.[4] A similar study of the thermal cross sections of ^{239}Pu resulted in substantial differences with ENDF/B-V values.[5] The major reasons for these changes of thermal cross sections, which were believed for many years to be well known, is the recent changes of the half-lives of some of the actinides (^{234}U, ^{239}Pu) which were used for the determinations of sample masses. These trends of changing ^{239}Pu cross sections have been confirmed in an analysis of the 2200 m/s data of the fissile nuclides,[6] as well as in a more conventional simultaneous analysis of the 2200 m/s and Maxwellian averaged data.[3] The result from the latter analysis has been tentatively adopted for ENDF/B-VI.

Whereas in the past the simultaneous evaluations of the thermal parameters were beset by internal inconsistencies which led to various interpretations -- like the perceived ν-η discrepancy -- these inconsistencies seem to be mostly resolved in the most recent fit. This is the result of the new accurate measurements of the half-lives of some of the actinides,[7] re-evaluation of measurements of ν of ^{252}Cf,[8] and of α and η with Monte Carlo techniques,[9] and new ν measurements of ^{252}Cf and of the fissile nuclides.[10] Table I shows a comparison of some of the ENDF/B-V and the proposed ENDF/B-VI values for ^{235}U and ^{239}Pu.

Though the improved consistency between the thermal parameters is very much appreciated, a variety of problems remain which are disconcerting but cannot be resolved at the present time. These problems are:

(1) The thermal parameters were evaluated without taking into account the cross section shapes, thus the shape discontinuity at 2200 m/s must be resolved.

(2) The correlations between input data and auxiliary data (e.g. the thermal cross sections of ^{10}B(n,α), Au(n,γ) were not taken into account, thus the result as well as the variance-covariance information is to some extent arbitrary.

TABLE I

Comparison of Some Thermal Parameters of ENDF/B-V and the Proposed ENDF/B-VI

	^{235}U		Changes	^{239}Pu		Changes
	ENDF/B-V	ENDF/B-VI	%	ENDF/B-V	ENDF/B-VI	%
σ_f	583.5	582.6	-0.2	741.7	748.1	+0.9
σ_γ	98.4	98.3	-0.1	270.2	269.3	-0.3
η	2.083	2.0751	-0.5	2.119	2.115	-0.2
α	0.1686	0.1687	--	0.3643	0.3600	-1.2
g_a	0.9781	0.9788	+0.1	1.0764	1.0784	+0.2
g_f	0.9775	0.9761	-0.1	1.0582	1.0558	-0.2
σ_s	14.7	14.0	-5.0	8.0	7.3	+9.6
ν_t	2.437	2.425	-0.5	2.891	2.877	-0.5
ν_t (^{252}Cf)	3.766	3.7675				

(3) The absolute thermal data are interrelated with absolute data measured [illegible] higher neutron energies by shape measurements. As long as substantially lower uncertainties could be claimed for the thermal cross sections, this needed not to be a concern. However, the evaluated data at higher neutron energies now have results with comparably low uncertainties and inconsistencies between the thermal parameters and the result from the simultaneous evaluation of the standard cross sections might be expected.

Of major interest for the fast neutron energy range is the outcome for the ν value of ^{252}Cf, because the majority of ν measurements of the fissile nuclides as a function of energy has been carried out relative to ^{252}Cf. The data which were available ~15 years ago were highly inconsistent. Results from the large-liquid-scintillator technique were consistently higher than results from the manganese-sulfate bath technique. Reanalysis of some of the older measurements improved the consistency between these values. The addition of new measurements further helped to better define the value of ν of ^{252}Cf. The present status of the available data is shown in Fig. 1. The current weighted average is shown as a solid line and the dotted lines indicate a ±0.3% range. Also indicated are the results from various evaluations.

The first observation to be made is that the presenty available values represent a reasonable data ensemble. The second observation is that the troublesome bias between the results from the two major techniques is substantially reduced (the group averages from the large-liquid-scintillator technique and the manganese-bath technique agree with the average of all data within their uncertainties). The agreement between the proposed ENDF/B-VI value obtained from the simultaneous evaluation of the thermal parameters and the straightforward weighted average of the experimental data indicates a satisfactory degree of consistency. One should also note that the proposed ENDF/B-VI is nearly identical to the ENDF/B-V value and in similar good agreement with the recent evaluation by Axton.[6] An observation which might be made in passing is that the two newest measurements had no impact whatsoever on the current best value for $\bar{\nu}$ of ^{252}Cf. The only discomforting point is that the most accurate measurement[11] disagrees with the average by more than two standard deviations. However, a simple assumption shows an important point: let us assume that additional effort is expended toward anotner measurement. The lower limit of uncertainty which could be achieved within a reasonable limit of expenditure (~3 manyears) will be similar tha that achieved by Spencer.[11] Let us further assume that the outcome will be a value at the upper end of the 1σ uncertainty of the result of Spencer. The average value for $\bar{\nu}$ of ^{252}Cf would then be changed by less than 0.1%

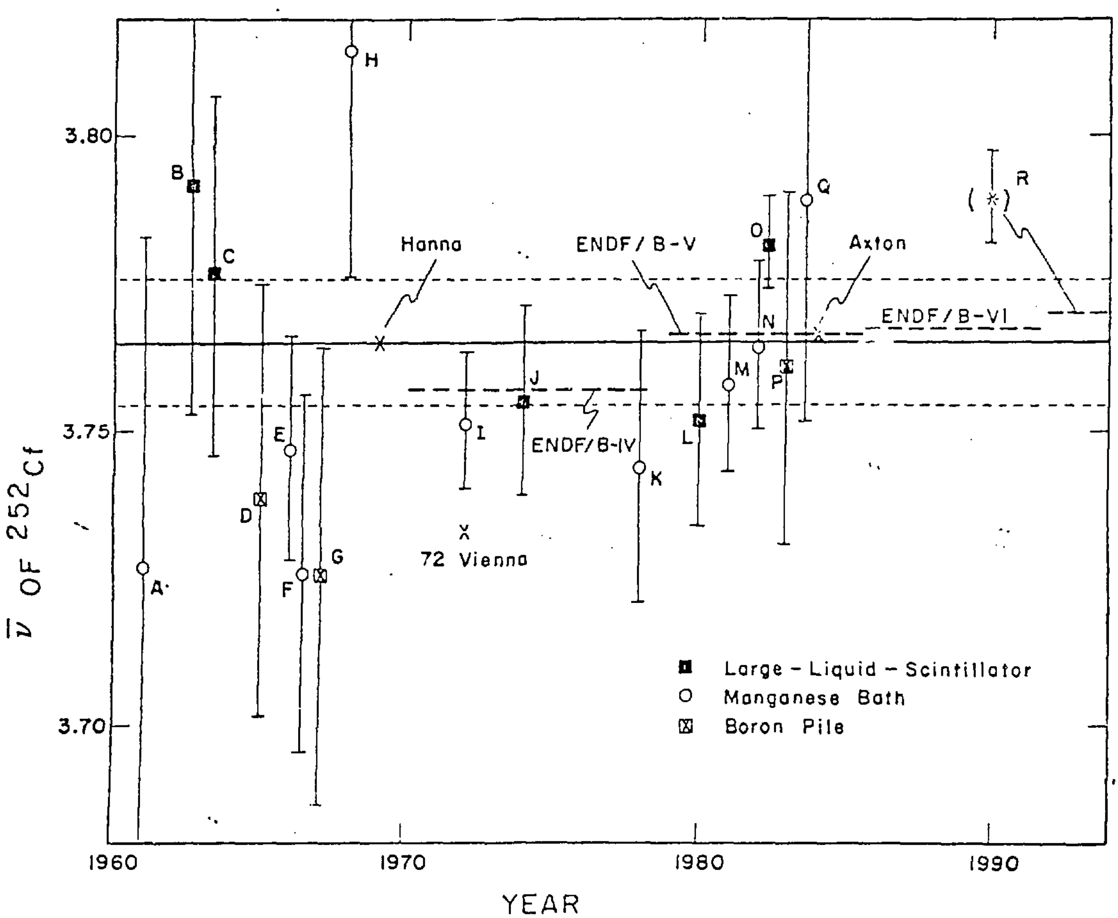

Fig. 1. The Present Status of $\bar{\nu}$ of ^{252}Cf. The Experimental Values are Given in Ref. 3, 10: A Moat, B, Asplund and Nielson, C Hopkins and Diven, D Colvin and Sowerby, E DeVolpi and Porges, F Colvin, G Fieldhouse, H Axton and White, I Axton, J Boldeman, K Bozorgmanesh, L Zhang, M Alexandrov, N Smith, O Spencer, R Edwards, and Q Gilliams. Evaluated values are indicated with crosses (1,6) and ENDF/B values with dashed lines. The effect of a hypothetical additional measurement, R, is shown.

relative to the proposed ENDF/B-VI -- thus an insignificant change would be the result. This means that along with any new experimental effort a reanalysis of the available experimental data would have to be performed. As the latter has been done repeatedly in the past, little hope for further improvements exist. One possibility of a bias in the data obtained with the manganese bath technique had been proposed by Smith:[12] if the capture cross section of sulfer would be higher than used in the analysis of these experiments, then the ν value derived would be too low. However, several experiments carried out since then do not support this suggestion.[13,14]

The conclusion is discouraging: the only way out is adding new measurements, however, the limitations given by available resources exludes any impact on the ν value of ^{252}Cf. It appears we have worked ourselves into a corner with the values already available and will have to live with the somewhat unsatisfactory situation of the most accurate value suggesting a ν value about 0.4% higher than the current average.

III. THE SIMULTANEOUS EVALUATIONS OF THE STANDARDS AND OTHER PRINCIPAL CROSS SECTIONS

The general concept for the evaluations of past verions of ENDF/B has been to proceed in steps: first, the "super-primary" standard, H(n,n), was evaluated or decided upon, then the "primary" standards ^{6}Li(n,α), ^{10}B(n,α_0), and ^{10}B(n,α_1) were evaluated, finally followed by the "secondary" standards Au(n,γ) and ^{235}U(n,f). The other cross section data were evaluated based on these standards. Close scrutiny of this concept shows that it is based on the unacceptable assumption that the standards are different from other cross sections. Any cross section is a derived quantity and not a basic unit. Thus, the definition of some cross sections as "standards" is for convenience only. In reality, any absolutely measured cross section is equivalent as far as information on interaction probabilities is concerned.

Thus it is a substantial improvement that a simultaneous evaluation procedure has been adopted for ENDB/B-VI. Such evaluation should involve all absolutely measured cross sections which are interrelated by ratio and total cross section measurements. Fortunately, such data are essentially restricted to the "defined standards," ^{6}Li, ^{10}B, Au(n,γ), and ^{235}U(n,f), and several cross sections of importance to reactor applications, ^{238}U(n,f), ^{238}U(n,γ), and ^{239}Pu(n,f). That a simultaneous evaluation of a data base of this size can be handled with present day computers has been demonstrated.[15]

The evaluation now in progress includes the following cross sections:

^{6}Li(n,α), ^{6}Li(n,n), ^{10}B(n,α_0), ^{10}B(n,α_1), ^{10}B(n,n), ^{197}Au(n,γ), ^{238}U(n,γ), ^{235}U(n,f), ^{239}Pu(n,f), ^{238}U(n,f).

The process desirable for the evaluation would involve the following steps:

(1) Establishment of a file of the experimental data, including their uncertainty components and correlations. It should be noted that this is the most work-intensive step of all, as it requires the evaluator to rediscover the originally measured quantities, establish the currently valid data, estimate, in most cases, uncertainties not given by the experimentor, apply corrections where appropriate, and to establish correlations in the experiment under consideration as well as with prior experiments.

(2) The simultaneous evaluation of all the experimental cross sections by generalized least-squares. This is mainly a question of available computer technology. A matrix of minimum size equal to the square of the parameters involved in the evaluation has to be inverted.

(3) The simultaneous multi-nuclear-model fit of the result of the evaluation of the experimental data, resulting in a parameter set. This should be done by utilizing the variance-covarience information obtained from the evaluation of the experimental data and not by a simple χ^2 minimization as now commonly used in nuclear model fitting.

(4) The derivation of the evaluation result from the nuclear models and parameter set, and the variance-covariance of the result derived from error propagation.

Though this procedure would possibly be achievable with present technology, the task would be substantial indeed. The major problem proves to be Step 3 which would have to involve R-matrix codes, statistical nuclear model codes and optical-model codes. The most sophisticated of the latter involve coupled-channel calculations which are at present still too slow to be effectively used in a fitting procedure. Therefore the evaluation procedure agreed upon by the members of the standards subcommittee of CSEWG is a compromise which includes the following steps:

(1) Pre-evaluation of some quantities or adoption of other evaluations of some quantities to be used as reference values. These include for example the thermal parameters discussed above, and the H(n,n) cross section which was evaluated by Dodderer.[16]

(2) A file of the experimental data suitable for the evaluation is being established at Argonne National Laboratory and is being evaluated with the generalized least squares program GMA.[15]

(3) Some data sets of the ^{7}Li and the ^{11}B compound systems are being fitted with the Los Alamos National Laboratory R-matrix code.[17]

(4) The results from both evaluations and their variance-covariance matrix are combined in a final step to derive an adjusted result and the appropriate uncertainty information at Oak Ridge National Laboratory.

This evaluation is the only major present effort toward a future ENDF/B-VI. Results are not yet available. However, some trends can be seen in the additions to the data base since the evaluation of ENDF/B-V. These following discussions will be restricted mainly to those cross sections involved in the simultaneous evaluation and which have direct applications in the LMFBR program.

^{235}U(n,f)

The major feature of the ^{235}U(n,f) data base is that it is certainly the most extensive. No other cross section has been measured as often. Figure 2a shows some of the data which had become available prior to the evaluation of ENDF/B-V. Data differences of 10% cannot be understood and exceed the quoted uncertainties. Fortunately, some newer measurements, now available for the evaluation of ENDF/B-VI (see Fig. 2b), show substantial improvements. With the exception of a few values in some energy intervals, the new data agree usually within ±1-2% which is within the achieved uncertainties. No bias relative to ENDF/B-V is indicated by the new data above 1 KeV, and changes of the evaluated cross section due to the additional data below 100 KeV must be expected to be insignificant. The improvement of the cross section situation at lower energies can also be seen in the integral over the 7.8 to

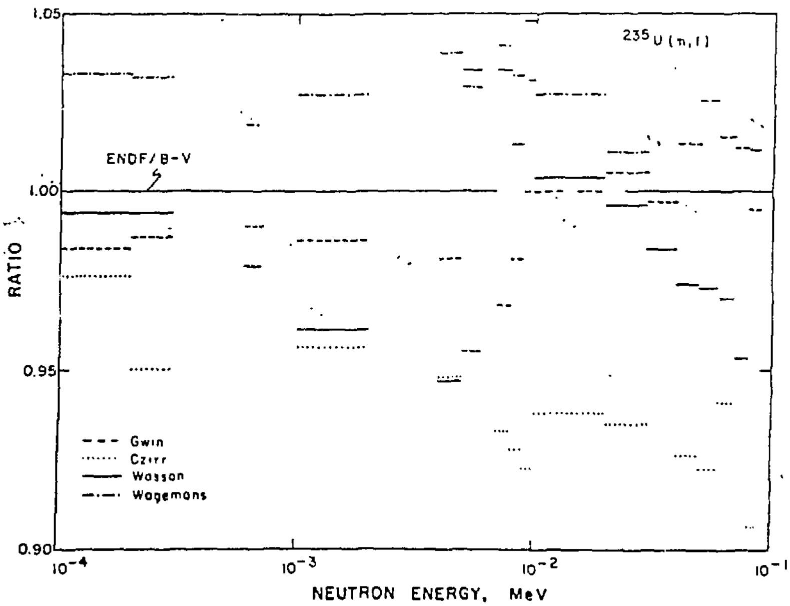

Fig. 2a. Comparison of Several Experimental Data Sets (18) with ENDF/B-V.

11.0 eV energy range which is often used for the normalization of measurements not extending to thermal energies.[22] Values available and used for ENDF/B-V and for ENDF/B-VI are compared in Table II. The greater consistency is the result of revisions, withdrawals, and additions of data.

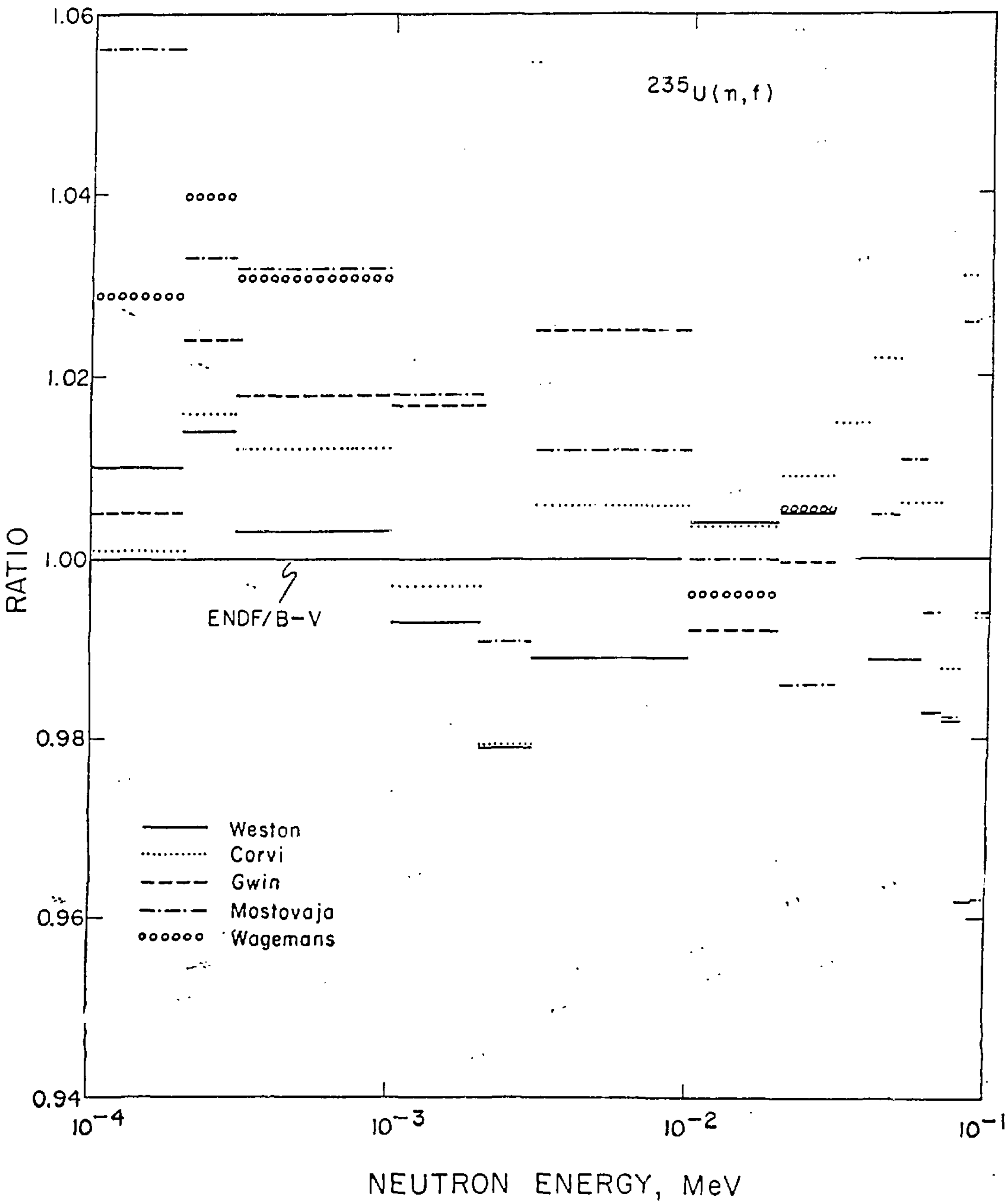

Fig. 2b. Comparison of Several New Experimental Data Sets (19) with ENDF/B-V.

TABLE III

Comparison of Recent 14 MeV Data Which Have Become Available for the Evaluation of ENDF/B-VI

Reference	E/Mev	$^{235}U(n,f)$	$^{239}Pu(n,f)$	$^{238}U(n,f)$
Cance and Grenier[30]	13.9	2.053 ± 0.039	2.321 ± 0.058	1.138 ± 0.025
	14.6	2.054 ± 0.039	2.290 ± 0.052	1.144 ± 0.025
Arlt et al.[31]	14.7	2.079 ± 0.022	2.385 ± 0.019	1.166 ± 0.020
Alkharov et al.[31]	14.0	2.084 ± 0.036		
	14.5	2.101 ± 0.036		
	14.7	2.094 ± 0.028	2.320 ± 0.029	1.171 ± 0.023
Wasson et al.[32]	14.1	2.080 ± 0.030		
Mahdavi et al.[33]	14.6	2.070 ± 0.046	2.44 ± 0.09	
Li Jingwen et al.[34]	14.7	2.098 ± 0.040	2.532 ± 0.050	
Weighted Average	14.4	2.081 ± 0.005	2.372 ± 0.026	1.157 ± 0.008
ENDF/B-V		2.093		

TABLE IV

Comparison of the $^{235}U(n,f)$ Cross Sections Averaged over the ^{252}Cf Fission Neutron Spectrum Available for the Evaluations of ENDF/V and -VI

Reference	ENDF/B-V	ENDF/B-VI
Adamov et al.[35]	1.266 ± 0.019	1.254 ± 0.017
Heaton et al.[36]	1.205 ± 0.027	1.216 ± 0.019
Davis et al.[37]	1.215 ± 0.022	1.215 ± 0.022
NBS[38] (Preliminary)		1.235 ± 0.015
Weighted Average	1.236 ± 0.019	1.233 ± 0.009
ENDF/B-V	1.236	

based on sensitivity coefficients[41] the C/E problem for C^{28}/F^{49} and the current k_{eff} bias would be simultaneously resolved, at least qualitatively, by reducing the $^{238}U(n,\gamma)$ cross section across a wide energy range by ~5-10%. Cross section changes of this size appear to be contradicted by the improved data base above 30 KeV,[42] and indeed, a recent data adjustment puts the blame nearly entirely on the $^{238}U(n,\gamma)$ cross section below ~10 KeV.[43] However, it has to be realized that in this energy range not only the infinitely dilute cross section, but also the self-shielding determines the neutron capture in ^{238}U.

Unfortunately, the data base for the lower energy range remains poor. Figure 3a shows the "classical" discrepancy every evaluator faced ~10 years ago. The capture

TABLE II

Comparison of the 7.8 to 11.0 eV Resonance Integral Data Available for the ENDF/B-V and -VI Evaluations

Reference	ENDF/B-VI[a]	ENDF/B-VI[b]
Bowman et al.[21]	246.02 ± 7.4	245.64 ± 7.4
ORNL/RPI[22]	241.30 ± 4.5	240.93 ± 4.5
Deruytter and Wagemans[23]	243.07 ± 2.4	242.70 ± 2.4
Gwin et al.[24]	235.92 ± 3.5	---
Czirr and Sidhu[25]	240.57 ± 2.4	---
Czirr and Carlson[26]		243.53 ± 1.9
Wagemans and Deruytter[27]		244.11 ± 2.0
Gwin et al.[28]		246.24 ± 2.2
Weston and Todd[29]		241.62 ± 3.7
Weighted average	240.95 ± 1.3	243.85 ± 0.6

[a]Referenced to ENDF/B-V 2200 m/s value, data as quoted in Ref. 20.

[b]Referenced to ENDF/B-VI 2200 m/s values.

Very few new measurements have been carried out at neutron energies above 100 KeV, except at ~14 MeV where a wealth of new data has become available which are given in Table III. These 14 MeV values, though not of direct importance for LMFBR applications, are of interest for the normalization of cross section shape measurements which extend to the lower MeV and KeV range. Uncertainties of ~1-2% have been achieved in these 14 MeV measurements with the time-correlated-associated particle technique and agreement between the various results is very good. However, agreement is also excellent with ENDF/B-V (~1/2%) which indicates that large changes of the evaluated cross section cannot be expected from these new measurements.

Another quantity which is of importance for the normalization of the evaluated cross section is the fission cross section averaged over the ^{252}Cf prompt fission neutron spectrum. This average is essentially independent of the fission spectrum and can be measured like a differential cross section, but possibly with higher accuracy. Table IV compares the data bases available for the evaluations of ENDF/B-V and -VI. Some improvements can be seen in the data base and agreement with ENDF/B-V is again very good. This will limit the lowering of the ^{235}U(n,f) cross section which appears to be the result of a simultaneous evaluation of many cross sections.[15]

The presently available data base for ^{235}U(n,f) apparently poses a similar problem as discussed in the case of ν of ^{252}Cf above; the large amount of past data results in an evaluated cross section of 0.5 - 1.0% uncertainty.[15,39] Thus, it cannot be expected, that a new measurement will have any significant impact on the evaluated cross section. However, as data with uncertainties as low as those of the evaluation result are not present in the data base, confidence could be improved with a few measurements at selected energies with uncertainties of ~1.0%. This might be in reach with the present state-of-the-art and would confirm or dispute the evaluated cross sections at the uncertainty level required for fast-reactor applications.

^{238}U(n,γ)

The capture cross section of ^{238}U is obviously of major importance for LMFBR applications. Unfortunately, it has been a substantial problem for more than 20 years. The persistent calculated versus experiment (C/E) discrepancy for capture in ^{238}U versus fission in ^{239}Pu or ^{235}U (C^{28}/F^{49}, C^{28}/F^{25}) in fast reactor test facilities[40] has been commonly attributed to data problems. It should be noted that

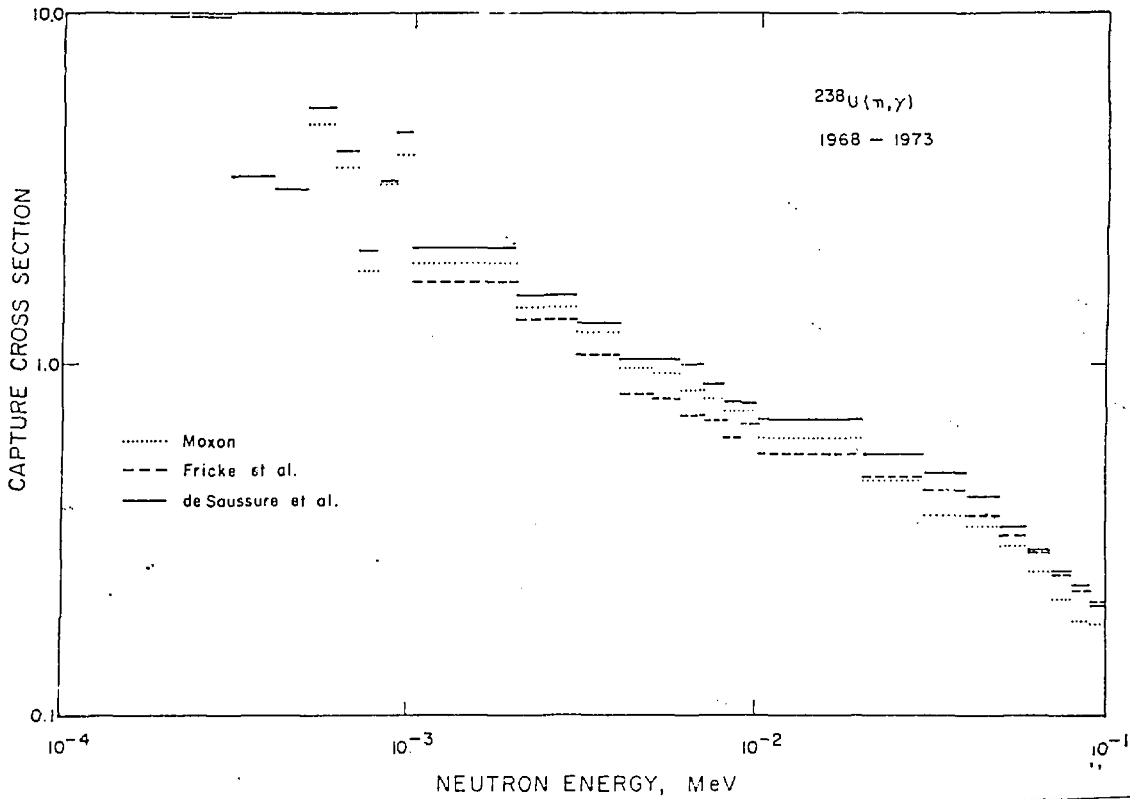

Fig. 3a. Comparison of $^{238}U(n,\gamma)$ Data Available for the Evaluation of ENDF/B-V.

cross sections measured by Fricke et al.[44] and by de Saussure et al.[45] differ by typically 20% and by up to 40%. Both measurements used the $^{10}B(n,\alpha)$ cross section as a reference, the same normalization technique (black resonance), and the same type of capture gamma ray detector (large liquid scitillator). The experiment by Moxon[46] involved the $^{10}B(n,\alpha_1)$ reaction as a reference, also the black resonance normalization technique, and a gamma detector with energy proportional response. New measurements have become available more recently which will be included in the evaluation of ENDF/B-VI. These data are shown in Fig. 3b. The data by Dietze[47] are the result of a spherical shell transmission measurement with a pulsed reactor as a neutron source. The measurement by Adamchuck et al.[48] were done with the newly developed multiplicity detector, and the experiment by Yamamuro et al.[49] involved the pulse-height weighting technique. The spherical shell transmission technique is inherently absolute, but both the multiplicity detector measurement and the pulse-height weighting technique measurement are normalized with the black resonance technique. It is unfortunate that the three new measurements reproduce rather closely the "classicial" discrepancy of the previous three measurements below 10 KeV. Thus the data situation in this very important energy range remains unresolved.

Figure 3b also shows the ENDF/B-V data. Below 4 KeV the ENDF/B-V values are based upon resolved resonance parameters.[50] However, a correction for unresolved (missed) p-wave resonances has been added. The addition is indicated by the upper row of circles in the figure. The fractional contribution from the resolved p-wave resonances is consistent with optical/statistical model calculations, thus the addition for the contribution of unresolved p-wave resonances appears rather large. It can also be noticed in Fig. 3b that the shape of the cross section as included in ENDF/B-V differs from shapes of the experimental capture data over the 1-4 KeV energy range because of the large amount of added ...

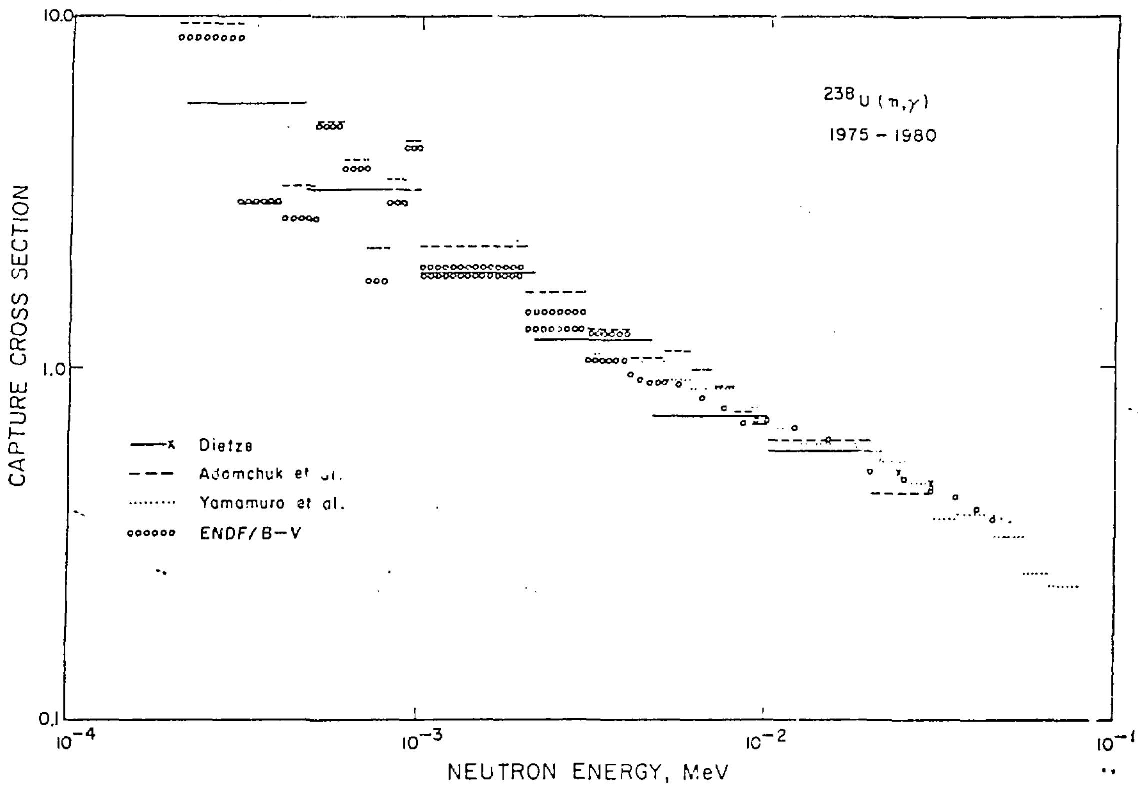

Fig. 3b. Comparison of New $^{238}U(n,\gamma)$ Data with ENDF/B-V.

The average capture cross section obtained from the independent resonance parameters -- aside from the unresolved p-wave resonance addition -- is in better agreement with the lower directly measured capture cross section data[46,47,49] than with the higher.[45,48] It is interesting that renormalization of the higher[45,48] and the lowest[44] data sets to the average capture cross sections based on resonance parameters below 2 KeV (where the question of unresolved p-wave resonances is not very important) would essentially resolve the existing data discrepancy. This suggests that the problem is due to the black resonance normalization in some of the experiments.

The average of the new data in the unresolved resonance range appears to be consistent with ENDF/B-V so that a substantial change of the infinite dilute capture cross section of $^{238}U(n,\gamma)$ cannot be expected for ENDF/B-VI. A slight increase is indicated at higher neutron energies by the simultaneous evaluation of several cross sections.[15] However, significant changes might be expected from a planned extention of the resolved resonance energy range to ~10 KeV. The s-wave strength function in the unresolved resonance range of ENDF/B-V is constant and the p-wave strength function varies with energy in order to reproduce fluctuations of the average capture cross section data. This is in conflict with experimental estimates of the s- and p-wave strength functions and affects the calculated self-shielding factors.[51] The evaluation over this energy range should involve all relevant data, such as self-indication measurements etc., and thus should result in an improved representation for ENDF/B-VI.

In contrast to $\bar{\nu}$ of ^{252}Cf and the fission cross section of ^{235}U, the data situation for $^{238}U(n,\gamma)$ below 30 KeV requires a new measurement. Such a measurement, however, will have significant impact only if it results in data with an uncertainty would change the ratio of the fission cross sections averaged over a fission spectrum by ~1.5% relative to ENDF/B-V[56] and improve agreement with experimental determinations of this ratio. However, any difference for the softer spectra reactor test assemblies would be less than the above 1.5%.

It should be emphasized once more that the $^{238}U(n,f)/^{235}U(n,f)$ ratio is one of the best known differential quantities and any C/E value for F^{28}/F^{25} outside the range 0.98 and 1.02 indicates serious problems with other data or computational procedures and/or models.

$^{10}B(n,\alpha)$

The $^{10}B(n,\alpha)$ cross section is not only of importance as a reference cross section used in many cross section measurements, but also because of the use of B_4C in the control rods of the majority of all reactors. In spite of its definition as a "standard" the data base is rather poor. Remarkably rare are absolute measurements of the $^{10}B(n,\alpha_1)$ and $^{10}B(n,\alpha_o + \alpha_1)$ cross sections. Problems are apparent even for the total cross section. The help in evaluating these cross sections obtained from R-matrix theory is less in this case than for the ^7Li compound system because of a higher level density and very broad resonances. New data have become available for the inverse reaction $^7Li(\alpha,n)$ which provide values for the $^{10}B(n,\alpha_o)$ cross section. These data differ from ENDF/B-V values by up to 45%. C/E's for the near-center ^{10}B small-sample worth measured in U9 (a uranium fueled hard spectrum ZPR assembly) are typically 7-8% below unity based on ENDF/B-IV,[57] a discrepancy which would be larger for ENDF/B-V data. A similar discrepancy was found for the helium production cross section measured in CFRMF, Big 10, Sigma sigma, and a fission cavity facility.[58]

The new data available for $^{10}B(n,\alpha_o)$ as well as the change of the evaluation procedure (similar $\sigma(n,\alpha_o)$ values result from $\sigma(n,\alpha_1)$ and α_o/α_1 measurements) will certainly result in a substantial change in ENDF/B-VI $^{10}B(n,\alpha_o)$ values. However, because the changes at lower energies are less than at higher energies, and because the (n,α_o) becomes a smaller fraction of the total (n,α) cross section at lower energies, the change of the (n,α) cross section due to the changes of the (n,α_o) will be insufficient to remove the observed discrepancies. However, comparison of ENDF/B-V and the available data for $^{10}B(n,\alpha_1)$ and $^{10}B(n,\alpha_o + \alpha_1)$ shows that ENDF/B-V is biased toward the lower data, thus higher evaluated data might also be expected for the (n,α_1) channel.

IV. OTHER EXPECTED DATA CHANGES

New data sets for $\nu(E)$ of ^{235}U and ^{239}Pu have become available since the evaluation of ENDF/B-V, and a data set which had influenced the evaluation for ^{239}Pu has been revised. Most of the changes for ^{239}Pu have been incorporated in a Rev. 2 for ^{239}Pu[59] with consequent improvements for hard-spectra test assemblies like JEZEBEL. The new data for ^{235}U differ substantially less from ENDF/B-V values. Therefore, changes of $\nu(E)$ are expected to be small for ENDF/B-VI compared to verion V (^{235}U) and V Rev. 2 (^{239}Pu) because ν of ^{252}Cf remains essentially unchanged. An exception is the thermal and low energy range (see Table I).

New measurements of alpha of ^{235}U resulted in values up to 15% lower than those derived from corresponding ENDF/B-V data. These new data have lower uncertainties than previous data and are expected to affect the evaluation for version VI. Because the lower values of alpha for ^{235}U are the result of new and improved measurement techniques, it might be suspected that similarly different data might result for alpha of ^{239}Pu. Unfortunately, corresponding new measurement results are not available for ^{239}Pu. ENDF/B-V is based on version IV and only three data sets were utilized in the evaluation where 15 were available. Therefore some changes might result from a new evaluation.

^{239}Pu(n,f)

The data base for the fission cross section of ^{239}Pu below 100 KeV is substantially more uncertain than that of ^{235}U. Four new data sets[51] which have become available since the evaluation of ENDF/B-V differ typically by 5-10% (see Fig. 4). The problem of measuring ^{239}Pu(n,f) can also be seen in the new 14 MeV measurements (see Table III) which are inconsistent. Because the evaluation of ENDF/B-V[52] was based on one selected data set,[24] a lower fission cross section of ^{239}Pu can be expected over much of the energy region between 1 and 150 KeV. This should help to re-establish the consistency of the k_{eff} bias with uraniumn fueled reactor test assemblies,[53] but will contribute to an increase of the C/E discrepancy for C^{28}/F^{49}.

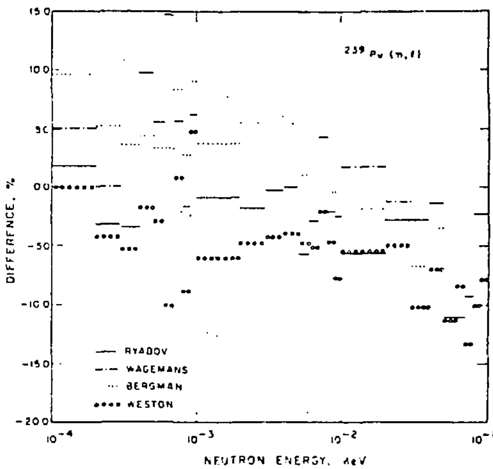

Fig. 4. Comparison of New Data for ^{239}Pu(n,f (51) with the Data by Gwin et. al (24) on which ENDF/B-V is Based.

The evaluated ^{239}Pu(n,f) cross section at higher neutron energies is mainly determined by ratio measurements of ^{239}Pu/^{235}U with which the evaluated ENDF/B-V data are consistent. A new measurement[54] of this ratio agrees well with the prior data. Thus changes of ENDF/B-VI are expected to be insignificant above 150 KeV except above 14 MeV where ENDF/B-V is identical with version IV and significantly higher than experimental data.

^{238}U(n,f)

^{238}U contributes only about 15% to the fission events in a fast reactor, therefore data requirements are less stringent. However, the reaction rate ratio F^{28}/F^{25} is an important diagnostic tool for fast reactor test assemblies and is measured on a routine basis.

The majority of the ^{238}U(n,f) data have been measured as ratios to ^{235}U(n,f). Good agreement exists between these measurements and consequently, very few new measurements have become available since the evaluation of ENDF/B-V. Some absolute 14 MeV values are given in Table III. The ratio of ^{238}U(n,f)/^{235}U(n,f) derived from these absolute values is in good agreement with the directly measured ratios which were used for the evaluation of ENDF/B-V. Thus changes for ^{238}U(n,f) of ENDF/B-VI are expected to be small. An unusually large spread exists between the measured data around ~2 MeV which is shown in Fig. 5 with some selected data sets. Choosing the latest measurement by Difilippo et al.[55]

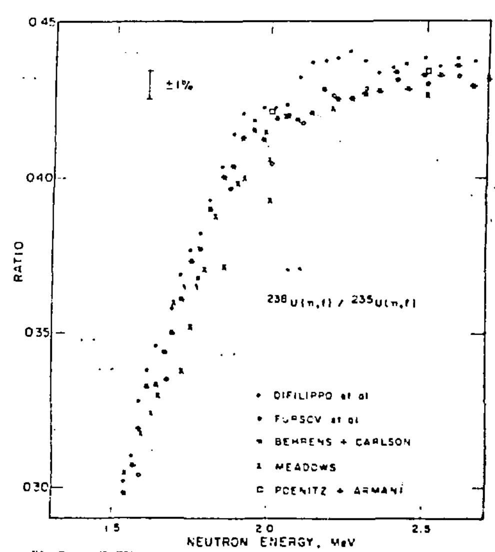

Fig. 5. Comparison of Some Data Sets of the ^{238}U(n,f)/^{235}U(n,f) Ratio Around 2MeV.

be reduced with the expected trend in the evaluated data, though probably not totally removed. However, the C/E discrepancies of the k_{eff} values and the central reaction rate ratio C^{28}/F^{25} of the LMFBR-type assemblies will increase. Therefore, if there will be an overall improvement based on the data, it will have to come from improved representation in the unresolved resonance range and an extention of the resolved resonance range of ^{238}U and possibly of the fissile nuclides as well.

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Changes of the inelastic cross sections of ^{235}U and ^{239}Pu were proposed based upon C/E's of the reaction rate ratios and leakage spectra of GODIVA and JEZEBEL. The elastic and inelastic cross sections of various actinides were recently measured and substantial differences were found in the comparison with ENDF/B-V for ^{239}Pu and ^{240}Pu. These data have been utilized in the Rev. 2 evaluation for ^{239}Pu. Whereas the changes affected the integral parameters of JEZEBEL, the effect on LMFBR-type test assemblies was found to be small. However, the agreement between the results from the new measurements and ENDF/B-V data is reasonably good for ^{235}U within the uncertainties of the experimental data of 10%. Therefore, if the inelastic cross sections are to explain the C/E discrepancies for GODIVA, it would have to be mainly for energies >3.5 MeV.

New measurements of the inelastic scattering cross section of ^{238}U appear to be consistent with ENDF/B-V. Thus there seem to be no additional indications that some of the C/E discrepancies for F^{28}/F^{25} found for several reactor test assemblies could be resolved with improved inelastic cross sections.[60]

V. SUMMARY AND DISCUSSION

Several cross sections of importance for LMFBR applications (^{235}U(n,f), ^{238}U(n,γ), ^{238}U(n,f), and ^{239}U(n,f)) are now included in the simultaneous evaluation of the "stndards" and other principal cross sections. This should result in improved evaluated data as systematic uncertainties are more randomized and biases are more likely removed. It will also yield more sensible variance-covariance information of the evaluated data as well as cross (materials) covariances required for data adjustments. New data which have become available and the more objective evaluation approach indicate that the ^{239}Pu(n,f), ^{10}B(n,α), ^{235}U(n,γ), and possibly the ^{235}U(n,f) cross sections are expected to change significantly relative to ENDF/B-V dat. Smaller changes might occur for ^{238}U(n,γ) and ^{239}Pu(n,γ). Virtually unchanged will be ν(E) and ^{238}U(n,f)/^{235}U(n,f) data. Changes are also expected for the total cross sections of ^{235}U and ^{240}Pu as well as the inelastic and capture cross sections of ^{240}Pu.

Improved measurements would be desireable for ^{239}Pu(n,f) below 200 KeV with uncertainties of ~2% and for ^{238}U(n,γ) below 100 KeV with uncertainties of ~3%. Even if such new data would become available within a reasonable time, the impact on the evaluated cross sections would probably be limited by the available data base. The impact of any new measurement of ν and of the ^{235}U(n,f) and ^{238}U(n,f) cross sections must be expected to be negligible.

Any new evaluated data file is commonly judged as improved or as worse, depending on whether the C/E's move closer to unity or not. This might be an one-sided view as substantial improvements have also been achieved by improved calculational methods and models. The new anticipated data changes can be expected to bring the C/E's for k_{eff} and the small sample worths of the fissile materials for the harder spectra assemblies (U9, Big 10, Flattop-25, Flattop-Pu, which are presently >1.0) closer to unity because of the expected lower fission cross sections. GODIVA with a C/E for k_{eff} of 0.99 is only an artificial exception; if the inelastic cross section is adjusted to remove the C/E discrepancy for F^{28}/F^{25}, the C/E for k_{eff} becomes larger than unity as for the other hard spectra assemblies cited above. The C/E discrepancies for the ^{10}B small sample worth and the He production rates should

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