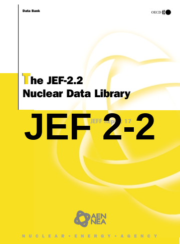

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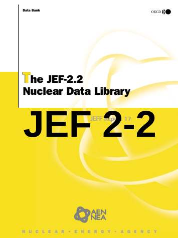

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ABSTRACT

The neutron and nuclear data which are needed by reactor physicists to perform core calculations are brought together in the evaluated neutron data files. Since several years the integral experiments are used to validate the nuclear data of these files. In these types of experiments, we measure synthetic parameters such as buckling or reaction rates which characterize the cell and the neutron spectrum. In the case of very simple geometries and asymptotic spectrum, such as uniform lattices or homogeneous media, the difference between the computed values of the synthetic parameters and the measured ones can be attributed to the inaccuracy of the neutron data. From these differences we can deduce informations about the nuclear data. It is the tendency research method. This method was used for the validation of the major actinides of the second version of the Joint evaluated file: ^{235}U, ^{238}U and ^{239}Pu. Sixty six buckling measurements were used for this qualification. The results are compared with recent recommended values.

INTRODUCTION

Since several years the integral experiments are currently used to validate the nuclear data of the main evaluated files. In these types of experiments we measure synthetic parameters which characterize the cell and the neutron spectrum. For example we can measure bucklings, reaction rates or chemical composition of irradiated fuels. If we choose integral experiments with very simple geometries and asymptotic spectrum such as uniform lattices or homogeneous media we can perform the calculation of these experiments without numerical approximations. So the difference between the computed values of the synthetic parameters and the experimental ones can be attributed to the inaccuracy of the neutron data used in the calculation. These neutron data depend on the evaluated files but also on the processing. It is very important to handle very carefully the processing codes which generate the multigroup cross sections used by the reactor physics. The second important thing is to solve the Boltzmann equation without bias. For this it is necessary to check the geometrical description of the cell and the energy mesh of the multigroup cross sections for each integral experiment. Only if all these conditions are achieved, we can deduce modifications of the neutron data from the difference between the computed and the measured values of a set of integral experiments. For this purpose, we intensively use in France the tendency research method[1,2]. In this method the difference between the computed and the measured values of an integral parameter, effective multiplication coefficient for example, is expressed as a linear function of the cross section modifications. These modifications are expected to be small. The coefficients of the function are simply the sensitivity coefficients of the integral result to the cross section modifications. The cross section modifications are obtained by a least square computation. Therefore, it is necessary to have different sensitivity coefficients. For the thermal neutron reactors this condition is achieved by using multiplying media with different kind of moderator: heavy water, light water and graphite. In addition, the number of integral experiments must be much higher than the number of sensitive neutron data.

The tendency research method was previously used for the validation of the first version of the joint evaluated file for thermal neutron reactors[3]. This study suggested some modifications of the basic nuclear data for uranium 235, uranium 238 and plutonium 239. The same validation was done again for the JEF2 neutron data of the same major actinides. Between the two evaluated files the main changes are: new resonance parameters and increasing of the resolved resonance range for uranium 238, use of the Reich and Moore formalism instead of the Breit and Wigner one for uranium 235 and plutonium 239. For these last isotopes, it was also taken into account the nu-bar structures versus the energy of the incoming neutron[4]. The set of integral experiments was also extended by using new critically coefficient measurements of tight pitch lattices and plutonium lattices representative of the neutron spectrum of the plutonium recycling reactors.

In the following sections, we will briefly remind you of the tendency research method fundamentals and of the new integral experiments added to the previous set. Then, we will discuss the results which were deduced from this research.

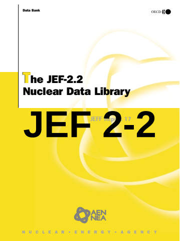
THE TENDENCY RESEARCH METHOD

For each integral experiment (criticality factor, reaction rate...), we know the experimental result Y_i and the measurement uncertainty E_i. In any case, we can compute the same quantity which is a function of the neutron parameters x_k. The result of this calculation is $F_i(\ldots, x_k, \ldots)$. If we change the value of the neutron parameter k, which becomes $x_k + \Delta x_k$, the result of the computation is now $F_i(\ldots, x_k + \Delta x_k, \ldots)$.

The principle of the tendency research method is to choose the modification Δx_k of the neutron parameters in such a way that the quantity

$$Q = \sum_i \frac{1}{E_i^2} \left[Y_i - F_i(\ldots, x_k + \Delta x_k, \ldots) \right]^2$$

for all the set of integral experiments becomes minimum. Nowadays the magnitude of the main neutron cross sections are more or less well known. So, the modifications Δx_k are expected to be small and we can make a first order expansion of the computed value



$$F_i(\ldots, x_k, \Delta x_k, \ldots) = F_i(\ldots, x_k, \ldots) + \sum_k \Delta x_k \frac{\partial F_i}{\partial x_k} .$$

We can also replace the partial derivatives by the sensibility coefficients

$$S_{ik} = \frac{\Delta F_i}{\Delta x_k} .$$

These sensibility coefficients (variation of the integral quantity F_i for a one per cent change of the parameter x_k) can be computed by the perturbation theory or a variational method.

With these assumptions we must now minimize the quantity

$$Q = \sum_i \frac{1}{E_i^2} [Y_i - F_i(\ldots, x_k, \ldots) - \sum_i S_{ik} \Delta x_k]^2 .$$

or if ΔY_i represents the difference between the experimental result and the computed value for the integral experiment i

$$Q = \sum_i \frac{1}{E_i^2} [\Delta Y_i - \sum_k S_{ik} \Delta x_k]^2$$

The minimization is done with the least square method. That is why, if we want to determine the modification Δx_k with a good accuracy, it is absolutely necessary to use a set of integral experiments for which the sensitivity coefficients are as different as possible. This can be very easily understood in the case of a two parameter tendency research. When the sensibility coefficients are not very different, the slope of the curves which represent each integral experiment are almost the same. As in reality, these slopes are known with an uncertainty which depends on the integral experimental error bar E_i, the coordinates of the mean intersection point are not known with a very good accuracy. On the contrary if we use integral experiments with different sensitivity coefficients we can improve the accuracy of the intersection point coordinates. We can obtain different sensibility coefficients by using integral experiments corresponding to various types of reactors.

From the mathematical point of view, the least square calculation leads to the Δx_k values which minimize the quantity Q. But we must take two remarks into account. First, the Δx_k are assumed to be small (don't forget that we have made a first order expansion of F_i). Secondly the cross sections are measured by differential experiments with an experimental uncertainty ε_k. The Δx_k must be lower or of the same order than ε_k. This is why, instead of minimizing the Q value, we prefer minimize the following quantity:

$$Q' = \sum_i \frac{1}{E_i^2} [\Delta Y_i - \sum_k S_{ik} \Delta x_k]^2 + \lambda \sum_k \left(\frac{\Delta x_k}{\varepsilon_k} \right)^2$$

In this expression, λ is the weighting coefficient of the microscopic data in the tendency research.

Three essential conditions must be satisfied to obtain accurate tendencies on the basic neutron data: very simple experiments with an asymptotic neutron spectrum, different sensitivity coefficients and the possibility to disconnect the effects of uranium from the ones of plutonium. The asymptotic neutron spectrum can be observed in critical facilities which used cells with only one kind of fuel. In this case, the buckling can be define without ambiguity and the reactor calculation can be made with a one cell computation. If this buckling is measured with a very good accuracy, this type of clean experiment is very interesting for the tendency research. Unfornutately they are scarce. The homogeneous experiments for which we know exactly the critical composition and the geometrical dimensions are also interesting because some of them contain only plutonium and for that they are not perturbed by uranium. American and French experiments exist in this category. At last various sensitivity coefficients can be obtained with lattices moderated by heavy water, light water or graphite. For JEF1 qualification fifty six buckling measurements were used[3]. Ten new experiments were added for JEF2.0 validation. Several of these extra measurements concern uranium fuel lattices representative of a power pressurized reactor. The others contain uranium and plutonium oxide fuel. They are representative of plutonium recycling in light water reactor and were performed in France; several moderating ratio were used to cover a wide range of neutron spectrum with the same fuel element. A set of spectrum index measurements was also included in this search.

The k_{eff} calculation of all the critical experiments was performed by a transport computation with a very fine description of the geometry and of the energy. From five to fifteen points were used to describe the cell, according to the moderating ratio. To represent the energy dependence of the nuclear properties, ninety nine energy groups were used. It is obvious that it is impossible to obtain informations about all the cross sections and all the groups. But one can define some synthetic parameters which represent the general trend of the nuclear properties versus the energy of the incoming neutron. As we are interested in the thermal reactor, the synthetic parameters can be related to three categories: the parameters which describe the thermal energy behaviour, those which represent the resonance region where the self-shielding effects occur and the ones which reproduce the high energy behaviour. In the thermal range we have assumed that the shapes of the cross sections were accurately given by the differential measurements and we chose as unknown the magnitude of the various cross sections for the 0.025 eV energy. The shapes of the cross sections were those of the evaluated file. In the resonance region we adopted as parameter the effective integral for the heavy nuclei and the migration area for the moderators. In the high energy range, the level of the cross sections seems to be a good parameter. Finally, sensitivity calculations allow us to define twenty four synthetic parameters. They are:

- ν values for ^{235}U, ^{239}Pu and ^{241}Pu,
- thermal and epithermal capture and fission cross sections for ^{235}U and ^{239}Pu,
- high energy fission cross section and effective capture integral of ^{238}U,
- thermal absorption cross section of ^{240}Pu and ^{241}Pu,
- first resonance radiative width for ^{240}Pu,
- thermal capture cross section and migration area of the various moderators.

RESULTS AND ANALYSIS

A first least square calculation was performed using the sixty six criticality factor measurements and the twenty four sensitive synthetic parameters. A detailed analysis of this first run showed that the modifications suggested for several parameters were very small and unaccurate. Consequently these modifications can be considered as having no physical meaning and there was no inconvenience to fix these parameters to the initial values. Then a second calculation was made with a reduced number of free parameters. We observed a very small increase of the chi-square.

In these conditions, the tendency research suggests strong modifications for only two parameters: the capture of the uranium 238 in the resonance region and the migration area of the light water. For the other parameters the required modifications are very small and the best estimated values are very close to the initial values of the file. With these modifications, the computation of all the integral experiments is satisfactory. On the figures 1 and 2, we have displayed the difference between the computed value k_{eff} and the experimental value which is equal to unity. The error bars represent the experimental uncertainty. Each integral experiment is identified by the slowing down density q. It is the number of neutrons which becomes thermal for one emitted fission neutron. This quantity is representative of the neutron spectra. The high values of q correspond to the soft spectra of the well thermalized lattices (mainly with heavy water or graphite as moderator) and the low values to the hard spectra of the tigh pitch lattices (light water with a low moderator to fuel ratio). The figure 1 is relative to the multiplying media which contain only uranium. The average discrepancy of $k_{eff} - 1$ is equal to -34.10^{-5} and the dispersion is equal to 436.10^{-5}. We do not observe any shift as a function of the spectrum hardness. On figure 2, we have the same representation for the multiplying media which contain only plutonium or a mixture of plutonium and uranium. In this second case, the average $k_{eff} - 1$ is $(135 \pm 508).10^{-5}$. Even if the scattering is greater with the plutonium than with the uranium the agreement between the computed values and the experimental ones is good enough. For the whole set of integral experiments, the average deviation is $(+ 37 \pm 470).10^{-5}$. The statistical distribution of the reduced deviation $|k_{eff} - 1|/\Delta k_{eff}$ is represented by the figure 3. The dotted line is the gaussian distribution. Taking into account the number of experiments which is not very high, this distribution is satisfactory. The difference with a pure Gauss distribution seems indicate that some experimental error bars are systematically too low.

The results of this tendency research are the following ones:

- For the moderators we only need a small decrease of the light water migration area of (1.0 ± 0.5) percent. This modification affects the leakage of the small critical experiments. It is not important for the usual power reactors which have greater sizes.

- For the fissile nuclei, ^{235}U and ^{239}U the requested modifications are very small and within the errors bars, it is possible to keep the initial values. The obtained results are given in Table 1 and compared with the initial values of JEF2.0 and ENDF/B5 and with the recommendations of Divadeenam[5] and Axton[6]. The agreement is very good and we observe a strong convergence between the recommendations deduced from the microscopic data and the values suggested by the integral experiments. In particular we no more observe a discrepancy between the ^{239}Pu nu-bar of Axton and the integral experiment suggestion. It is probably the consequence that in JEF2 it is taken the nu-bar structure in the thermal range into account, although all the previous files adopted a flat behaviour.

- For the uranium 238, the situation is less satisfactory because we need to decrease the effective capture integral of this nucleus by (0.26 ± 0.10) barn. For a typical light water reactor this represents 1.3 ± 0.5 percent. It is important and leads to a reactivity modification of about 350.10^{-5}. This effect must be very carefully investigated before requiring a revision of the evaluation.

CONCLUSION

The use of clean integral experiments and tendency research method is an efficient tool to improve the basic neutron data and to get the accuracy which is required by the reactor physicists. The JEF2.0 evaluations of ^{235}U and ^{239}Pu took into account the last informations given by the recent microscopic measurements. These evaluations are quite satisfactory in the case of the thermal neutron reactor when we are at room temperature. But it still remains a discrepancy in the temperature coefficient. The computed value is always too negative by about -2.9.10-5/°C. The modification of the shape of the neutron data in the thermal range (eta for ^{235}U and nu-bar for ^{239}Pu) explains only one third of the previously observed discrepancy. In the case of ^{238}U, the evaluation does not give satisfaction to the reactor physicist and a feedback to the evaluation seems necessary.

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Table 1. Actinide Thermal Data

		ENDF/B5	JEF2.0	Divadeenam	Axton	Tendency Research
U 235	ν	2.4367	2.437	2.425±0.003	2.426±0.005	2.435 ± 0.004
	σ_f	583.6	582.5	582.6±1.1	585.1±1.6	582.3 ± 1.1
	σ_c	98.4	98.8	98.3±0.8	96.1±1.7	98.0 ± 2.0
Pu 239	ν	2.8914	2.877	2.877±0.006	2.879±0.006	2.873 ± 0.007
	σ_f	741.7	747.2	748.1±2.0	748.5±2.6	745.8 ± 2.0
	σ_c	270.2	270.2	269.3±2.2	270.4±3.2	269.8 ± 3.9

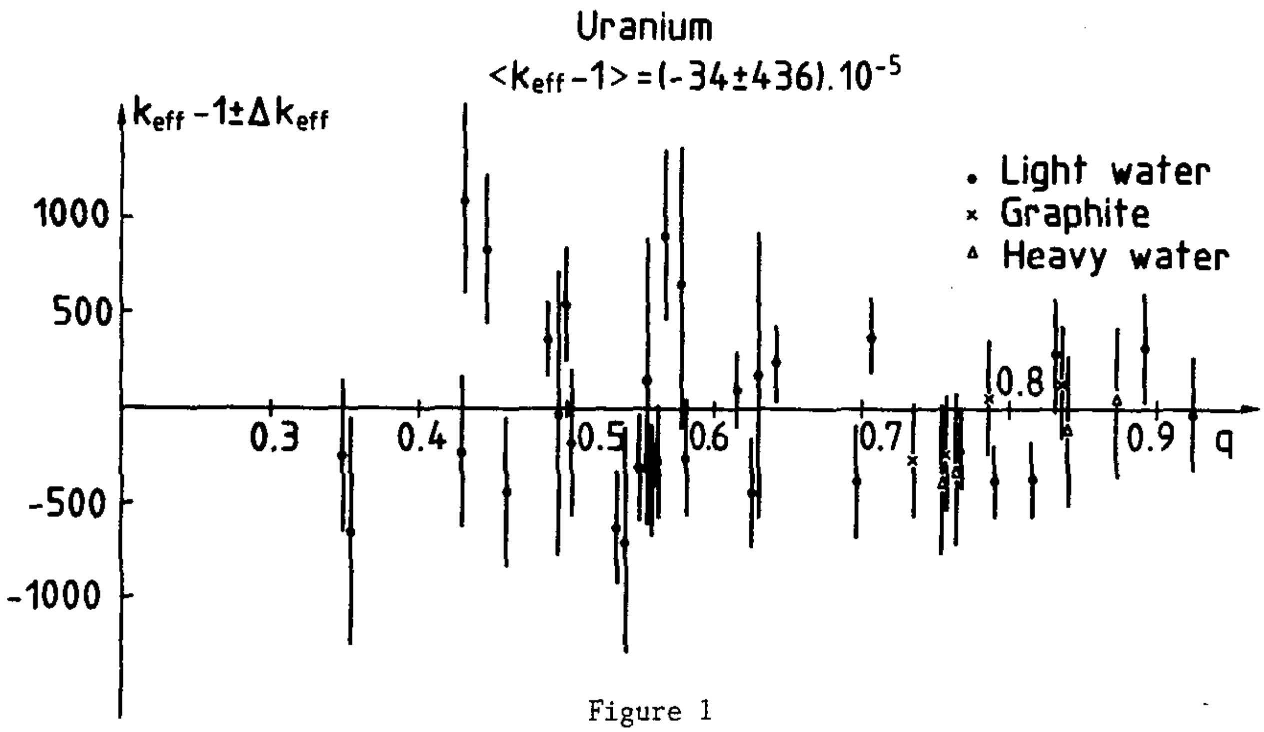

Figure 1

Residual deviations after tendency research for multiplying media which only contain uranium

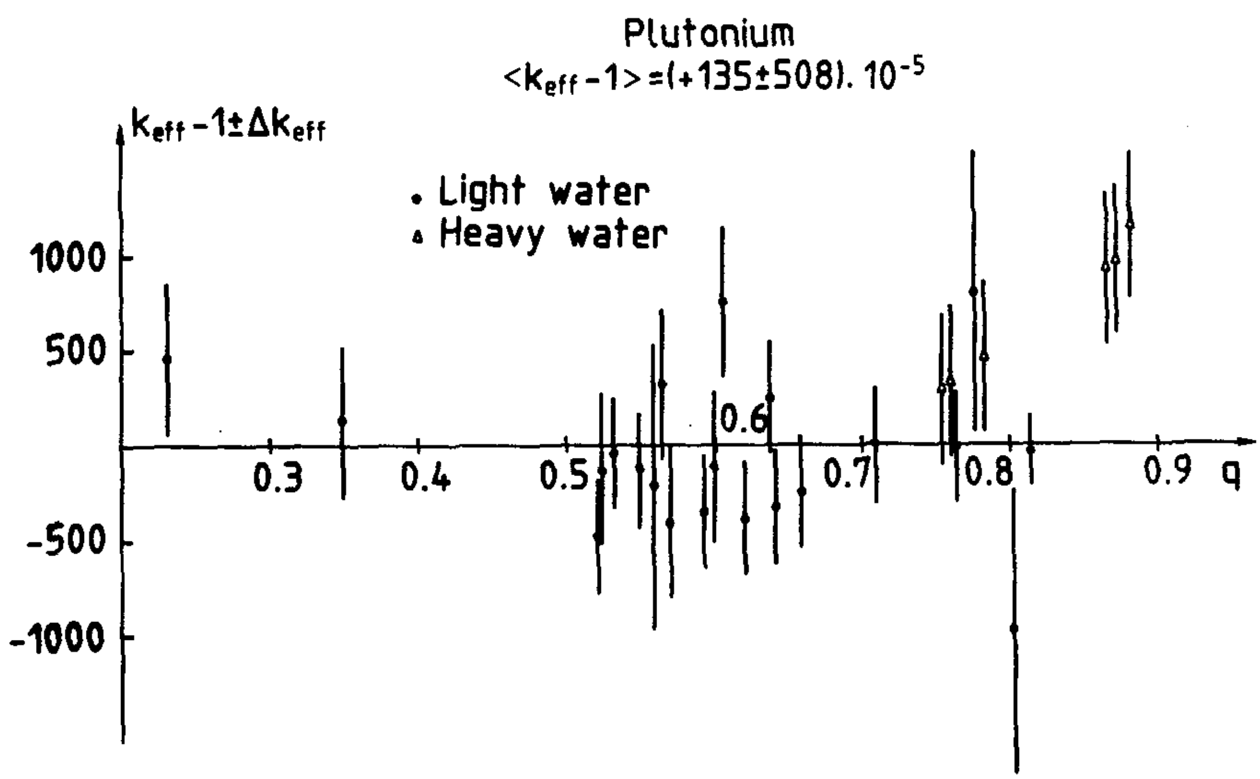

Figure 2

Residual deviations after tendency research for multiplying media which contain plutonium or a uranium and plutonium mixture.

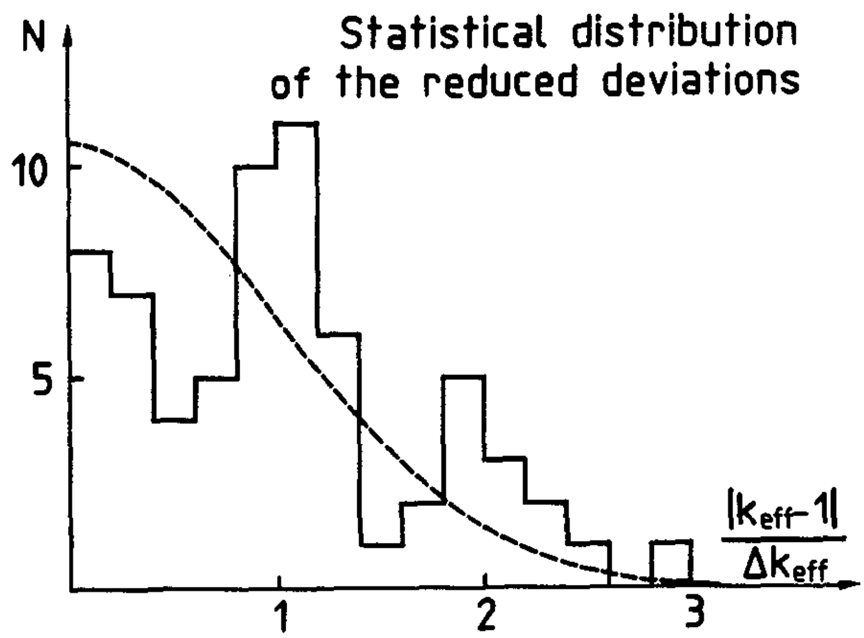

Figure 3

Comparison of the residual deviation distribution with a Gaussian distribution