# Benchmarking of $^{235}$U Fission Spectra

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## Background

Within the scope of the IAEA CRP on fission spectra, several evaluations of the $^{235}$U fission spectra were produced. In the present work the impact of these evaluations on thermal criticality benchmarks is investigated. The ENDF/B-VII.1 data are taken as reference. Only the prompt fission spectra of $^{235}$U in the library were changed, unless indicated otherwise.

## Scope

Evaluations by the authors listed below were considered. The average neutron energies calculated from the spectra are also given.

- ENDF/B-VII.1    ($E_{av}$=2.03 MeV)
- Kornilov    ($E_{av}$=1.97 MeV)
- Maslov    ($E_{av}$=1.96 MeV)
- Morillon    ($E_{av}$=1.97 MeV)
- Pronyaev    ($E_{av}$=1.96 MeV)
- Shu    ($E_{av}$=2.08 MeV)
- Talou    ($E_{av}$=2.00 MeV)
- Vogt    ($E_{av}$=1.91 MeV)

The spectra and their ratio to the Maxwellian at a temperature of 1.32 MeV are shown in Figure 1. Note that the spectra differ in the behaviour of the low- and high-energy tails, as well as in the position of the peak, hence the differences in the average neutron energies.
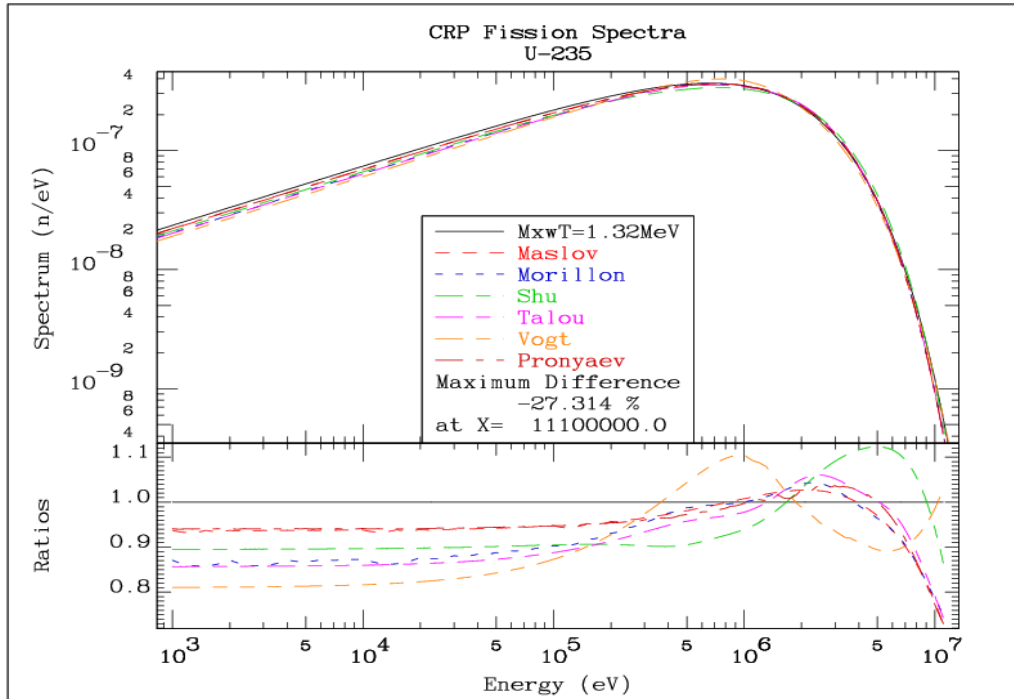
Figure 1: Comparison of prompt fission spectra of $^{235}$U for thermal neutrons by different authors.

Criticality benchmarks from the ICSBEP compilation were analysed. The focus was on the thermal solution benchmarks, which were also reported in the paper on the validation of the ENDF/B-VII.1 Library (Kahler et al., ENDF/B-VII.1 Neutron Cross Section Data Testing with Critical Assembly Benchmarks and Reactor Experiments, Nuclear Data Sheets 112, 12, 2011). Calculations were performed with the MCNP5 code on a Linux machine with the cross section data based on the ENDF/B-VII.1 library from LANL, except for the $^{235}$U data being tested.

Data processing was done with the NJOY99.393 code. To validate the processing steps, calculations were done with the original ACE library for MCNP from LANL and with $^{235}$U data from ENDF/B-VI.1 processed locally. The results agreed to within the statistical uncertainties.

The list of benchmarks included in the analysis is given in Table 1, giving the full ICSBEP label, the short label and the common name, where applicable.

# Benchmark Results

## Prompt Neutron Fission Spectra

The benchmark results with different spectra are given in Figure 2. The calculations with the original ENDF/B-VII.1 library are labelled "e71"; the results with locally-processed $^{235}$U data are labelled "e71_Original". The "common names" as defined in Table 1 are used to label the benchmarks.

Table 1: List of thermal solution $^{235}$U benchmarks

| ICSBEP full name | Short name | Common name | Description |
|---|---|---|---|
| HEU-SOL-THERM-009 | hst009-1 | ORNL_S1 | ORNL spheres |
| HEU-SOL-THERM-009 | hst009-2 | ORNL_S2 | |
| HEU-SOL-THERM-009 | hst009-3 | ORNL_S3 | |
| HEU-SOL-THERM-009 | hst009-4 | ORNL_S4 | |
| | | | |
| HEU-SOL-THERM-013 | hst013-1 | ORNL_T1 | ORNL borated solutions |
| HEU-SOL-THERM-013 | hst013-2 | ORNL_T2 | |
| HEU-SOL-THERM-013 | hst013-3 | ORNL_T3 | |
| HEU-SOL-THERM-013 | hst013-4 | ORNL_T4 | |
| | | | |
| HEU-SOL-THERM-032 | hst032 | ORNL_T5 | |
| | | | |
| HEU-SOL-THERM-001 | hst001-01 | Rockwell-01 | |
| HEU-SOL-THERM-001 | hst001-02 | Rockwell-02 | |
| HEU-SOL-THERM-001 | hst001-03 | Rockwell-03 | |
| HEU-SOL-THERM-001 | hst001-04 | Rockwell-04 | |
| HEU-SOL-THERM-001 | hst001-05 | Rockwell-05 | |
| HEU-SOL-THERM-001 | hst001-06 | Rockwell-06 | |
| HEU-SOL-THERM-001 | hst001-07 | Rockwell-07 | |
| HEU-SOL-THERM-001 | hst001-08 | Rockwell-08 | |
| HEU-SOL-THERM-001 | hst001-09 | Rockwell-09 | |
| HEU-SOL-THERM-001 | hst001-10 | Rockwell-10 | |
| | | | |
| HEU-SOL-THERM-042 | hst042-1 | ORNL_C1 | ORNL cylinders |
| HEU-SOL-THERM-042 | hst042-2 | ORNL_C2 | |
| HEU-SOL-THERM-042 | hst042-3 | ORNL_C3 | |
| HEU-SOL-THERM-042 | hst042-4 | ORNL_C4 | |
| HEU-SOL-THERM-042 | hst042-5 | ORNL_C5 | |
| HEU-SOL-THERM-042 | hst042-6 | ORNL_C6 | |
| HEU-SOL-THERM-042 | hst042-7 | ORNL_C7 | |
| HEU-SOL-THERM-042 | hst042-8 | ORNL_C8 | |

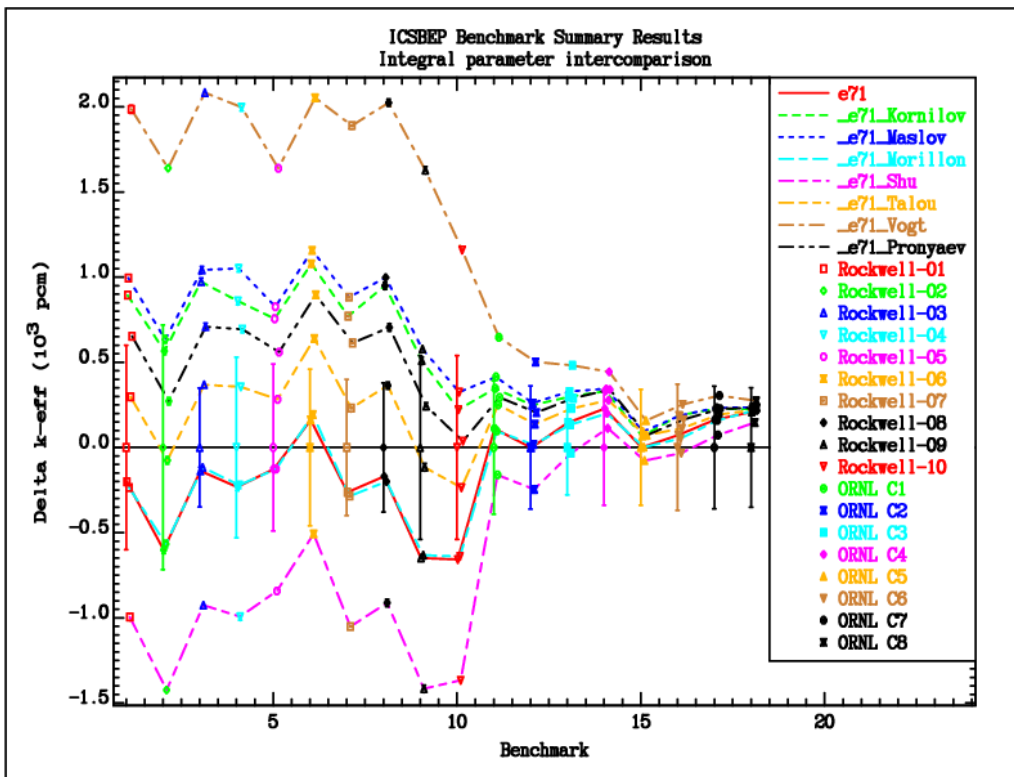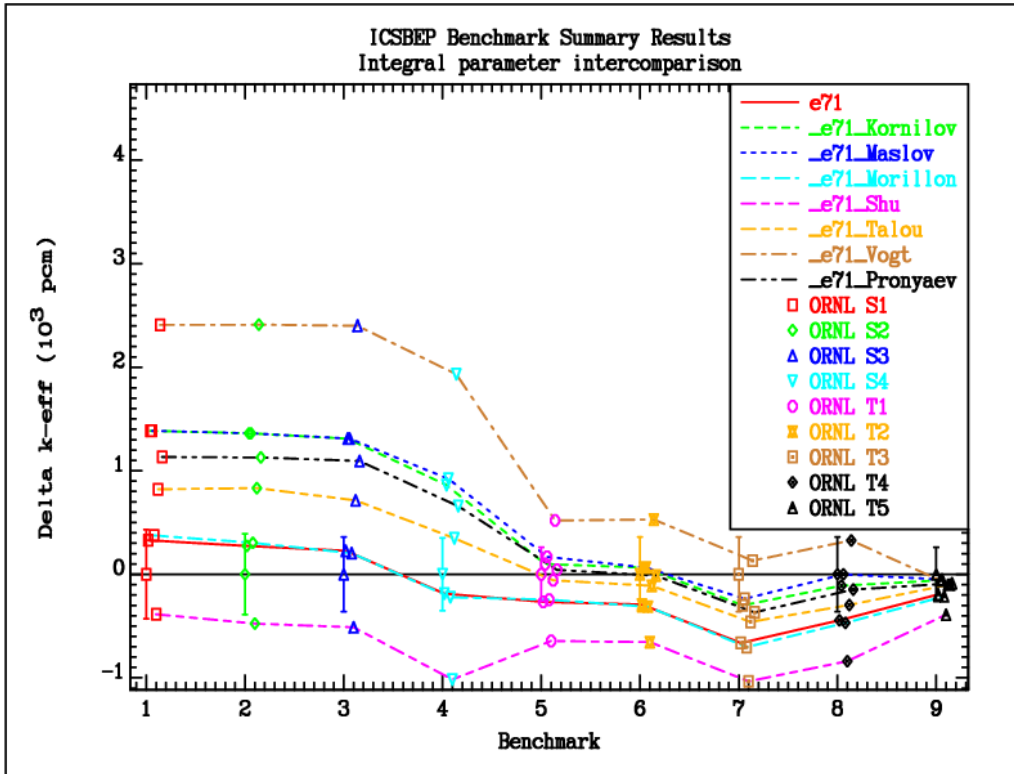Figure 2: Benchmark results with different fission spectra of 235U.

Generally, the spectra with a lower average energy increase the reactivity. The average energy of 2.03 MeV in the ENDF/B-VII.1 appears to be a compromise that works well for the majority of the benchmarks. However, several authors argue (Pronyaev, Kornilov) that the ENDF/B-VII.1 spectrum does not represent well the differential measurements of the spectra. Indeed, normalisation of the measured spectra is problematic because the spectra cannot be measured in the low and the high energy tails, but there are important differences in shape even in the energy range where abundant data are available. The evaluations, which are primarily based on measured differential data, are those by Kornilov and by Pronyaev, but overall they cause a severe over-prediction of reactivity. The evaluation by Talou is based on the Los Alamos model, but tries to follow the data as much as possible. The results with the spectra by Talou are in between the Pronyaev and the original ENDF/B-VII.1 results. The results of Morillon lie very close to the ENDF/B-VII.1 results. The results by Shu, which have the highest average neutron energy in the fission spectrum, are the lowest and the results by Vogt, which have the lowest average neutron energy are by far the highest

The benchmark analysis shows that the Oak Ridge spherical solution assemblies and the Rockwell assemblies (HEU-SOL-THERM-009 and HEU-SOL-THERM-001, respectively) are the most sensitive to the average spectrum energy. These are the high-leakage assemblies. However, in the final analysis where small details may be important, all relevant benchmarks must be included.

## Average number of neutrons per fission (nu-bar)

A global effect that can compensate the increase of reactivity is the number of neutrons per fission (nu-bar). An analysis of the historic evolution of the measured and recommended values was made. Selected data sets of energy-dependent nu-bar values are shown in Figure 3. Selected average measured values are compared to the evaluations by different authors in Figure 4. It seems that there is a distinct bias towards higher nu-bar values in the recommended data, which might be driven by earlier benchmark results. The average of the experimental data is very close to the recommended value by Gwin and is 2.4275 (current B-VII value is 2.4367, IAEA STD value is 2.4355+/-0.0023). Substitution of this value (2.4367 goes to 2.4275) into the data file containing the fission neutron spectra by Talou almost completely compensates the bias introduced by the lower average neutron energy. The results are shown in Figure 5.

Measured data for the nu-bar indicate distinct structure (in both Gwin84 and Reed72 measurements), which roughly corresponds to the resonances of 235U near 0.36 eV, 1.1 eV and a group of resonances below 10 eV. For the purpose of sensitivity study the structure similar to the one observed in the measured data was introduced into the file containing Talou evaluated PFNS. The nominal case is the one with a constant nu-bar taken from the recommendation by Gwin. The dips at around 0.4 eV, 2 eV and 10 eV were introduced in succession, labelled with suffixes n1,n2, and n3, respectively. Benchmark calculations were repeated for each case. Very little sensitivity to the structure in nu-bar was seen from the tests. Only the ORNL spherical solution assemblies and the Rockwell assemblies showed some sensitivity, generally below 100 pcm. The results can be seen in Figure 8.
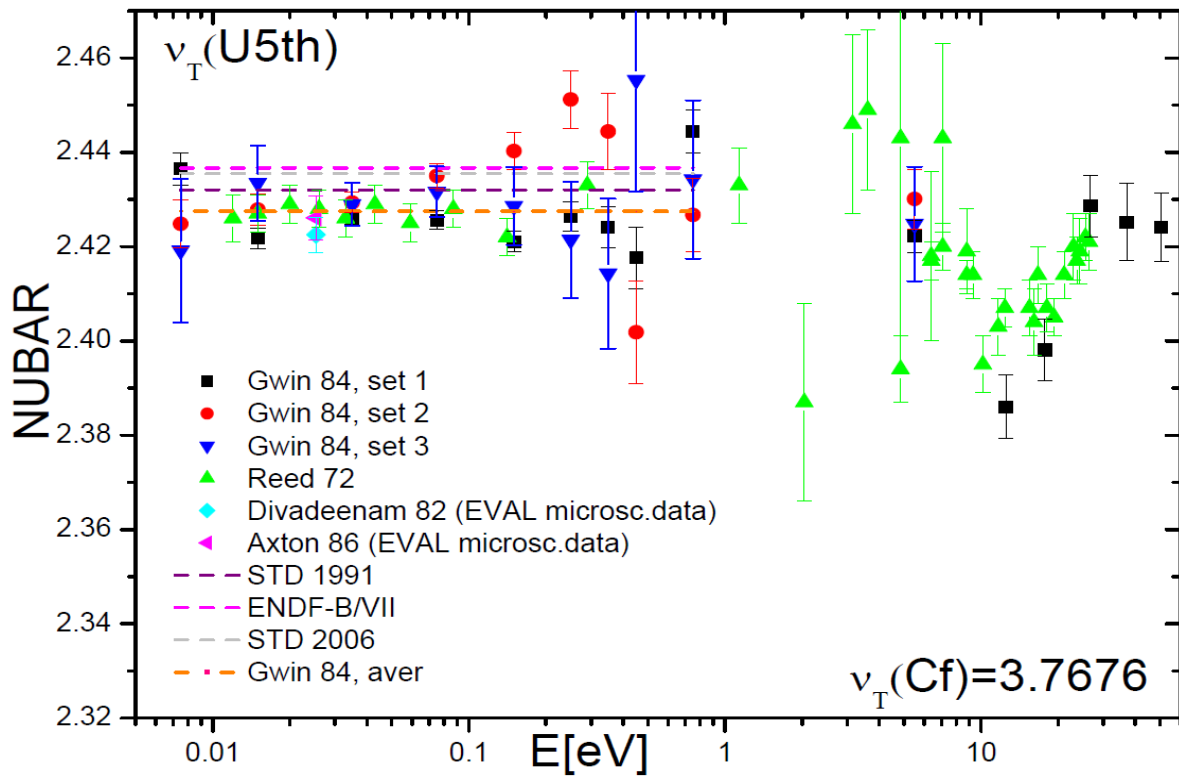
Figure 3: Comparison of energy-dependent measured values of nu-bar and some "Standards" and their evolution with time.
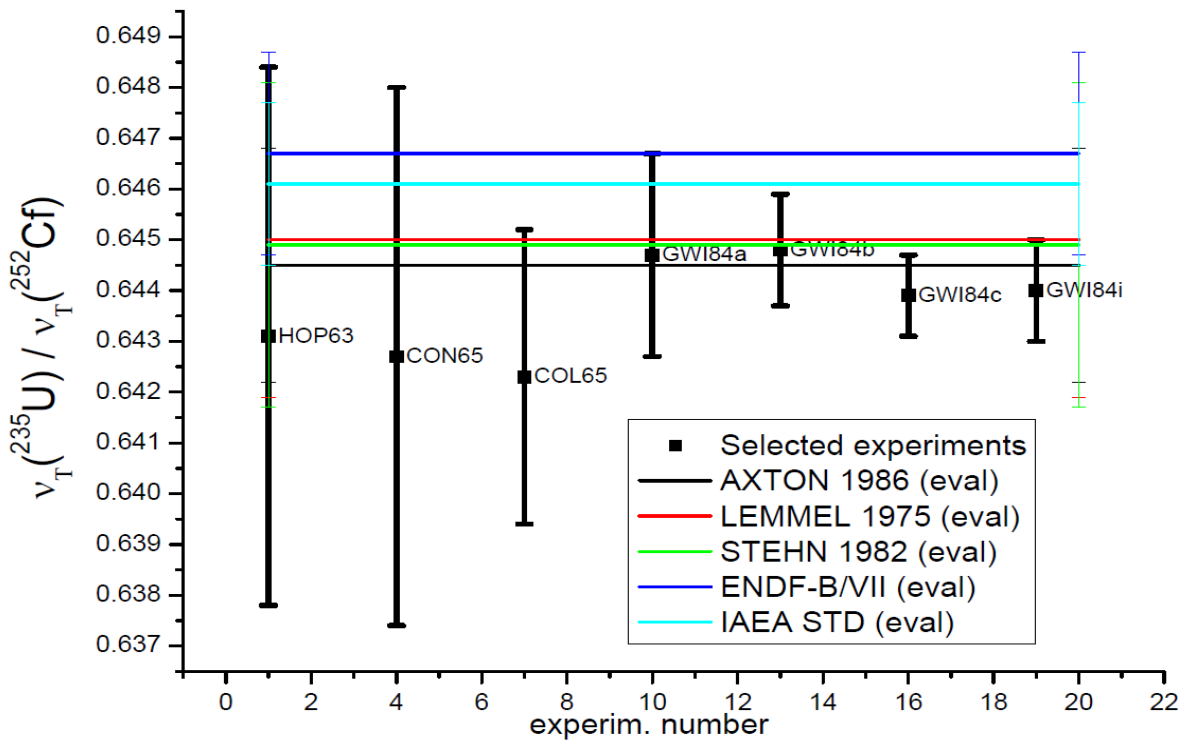


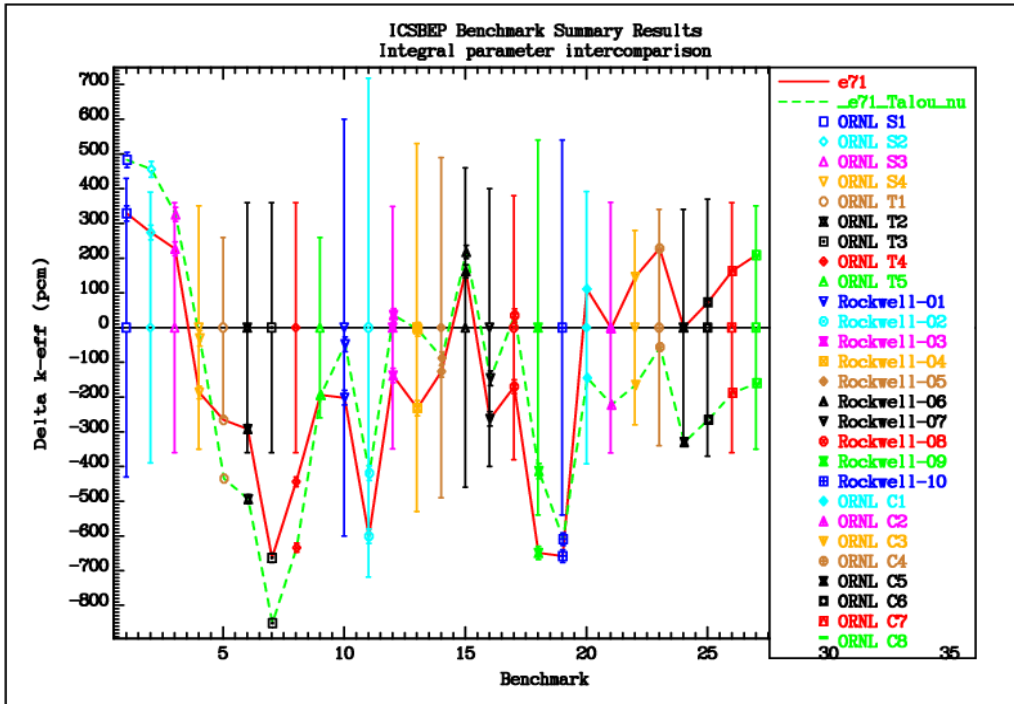Figure 4: Selected measured average values of nu-bar compared to the evaluations by different authors.

Figure 5: Comparison of benchmark results with the original ENDF/B-VII.1 data and the fission spectra by Talou with reduced thermal nu-bar.
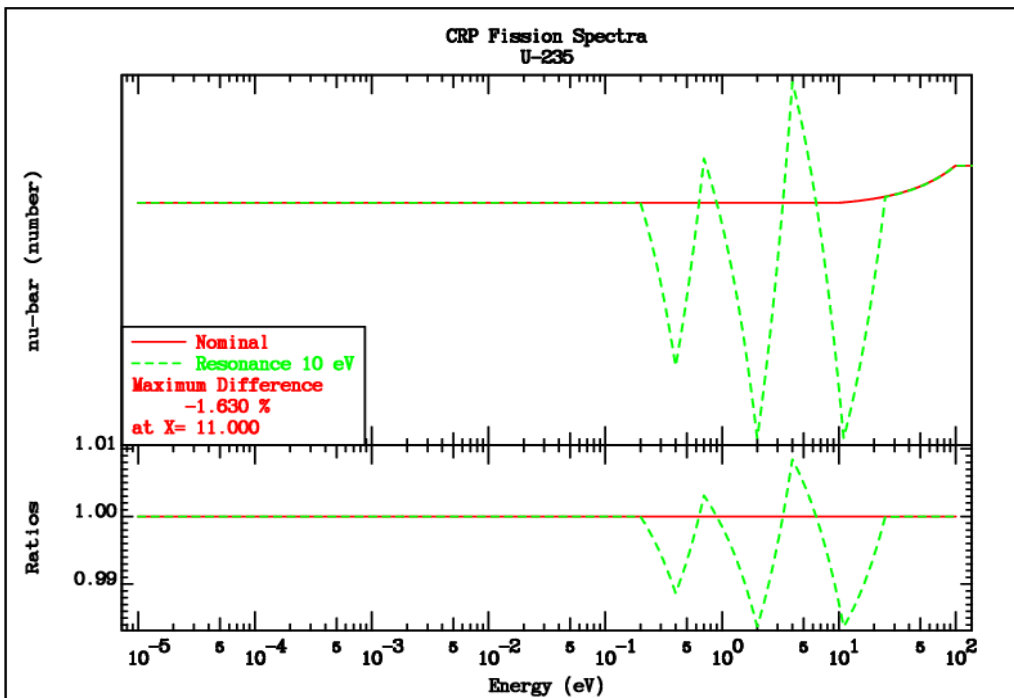


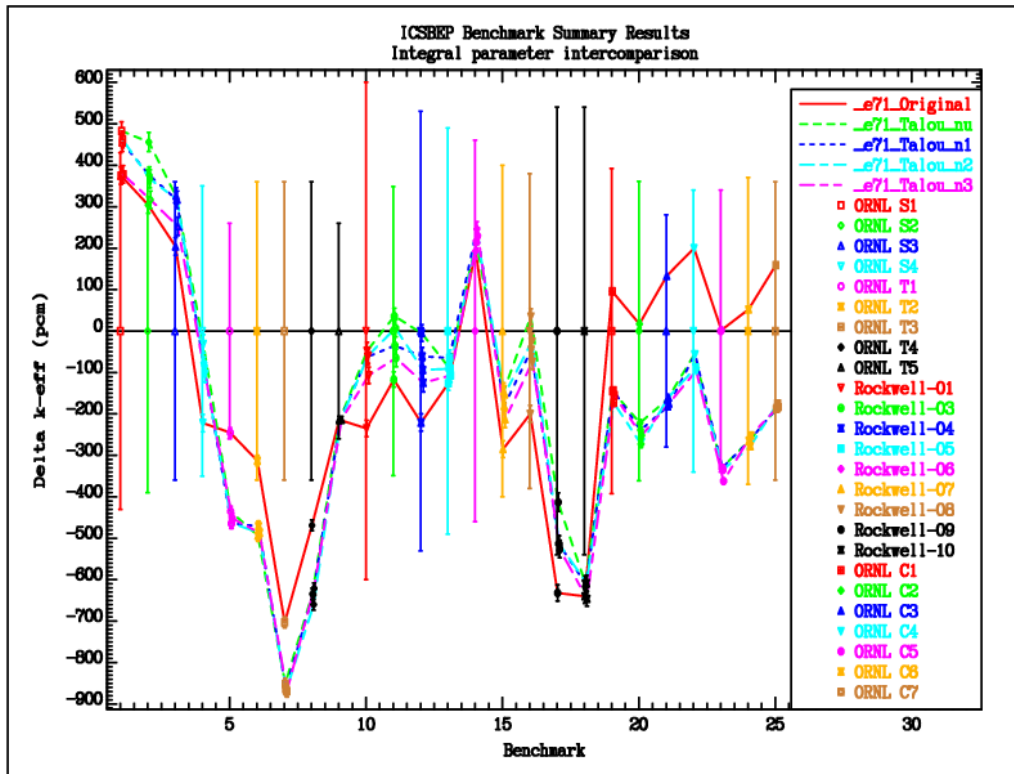Figure 7: The nu-bar modification below 10 eV for the sensitivity study.

Figure 8: Sensitivity of the multiplication factor on the structure in nu-bar at low energies.

## Conclusions

The impact of the prompt neutron fission spectra evaluated by different authors on criticality benchmarks was assessed. Generally it was found that:

- High leakage assemblies of highly enriched 235U solutions are most sensitive to the average neutron temperature of the prompt fission spectrum.
- The shape of the spectrum that represents well the experimental data is softer, but results in a strong overestimation of reactivity.
- An analysis of the historical evolution of the recommended values of thermal neutron nu-bar indicates a bias towards higher values compared to measurements.
- Restoring nu-bar to the best measured values generally compensates the increase in reactivity caused by the softer neutron spectrum.
- The structure in nu-bar that is evident in the experimental data has a very modest impact on the solution benchmark assemblies. However, benchmarks with harder spectra may be sensitive to these resonances.