Analysis of the Rossendorf SEG experiments using the JNC route for reactor calculation

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Abstract

The integral experiments performed at the Rossendorf fast-thermal coupled reactor RRR/SEG have been reanalyzed using the JNC route for reactor calculation JENDL3.2 / SLAROM / CITATION / JOINT / PERKY. The Rossendorf experiments comprise sample reactivity measurements with pure fission products and structural material in five configurations with different neutron and adjoint spectra. The shapes of the adjoint spectra have been designed to get high sensitivities to neutron capture or the scattering effect.
The calculated neutron and adjoint spectra are in good agreement with former results obtained with the European route JEF2.2 / ECCO / ERANOS. The C/E-values of the central reactivity worths of samples under investigation are given. Deviations in the results of both routes are due to the different libraries, codes, and self-shielding treatments used in the calculations. Results outside of the error are discussed.

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サイクル機構の核特性評価手法による ルッセンドルフ研究所SEG実験解析

(研究報告書)

クラウス・ディーツェ*

要 旨

核燃料サイクル開発機構の炉心核特性解析手法JENDL-3.2/SLAROM/CITATION/JOINT /PERKYを用いて、ルッセンドルフ研究所の高速・熱中性子炉心RRR/SEGで行われた積分実験の解析を行った。このルッセンドルフの実験の一部として、中性子束及び随伴中性子スペクトルの異なる5つの体系において、純粋な核分裂生成物及び構造材についてのサンプル反応度の測定が行われた。この実験では、中性子捕獲や散乱の効果に対して大きな感度を持つような随伴中性子スペクトルとなるよう設計がなされている。

今回の解析で得られた中性子スペクトル及び随伴中性子スペクトルは、以前に欧州解析手法JEF2.2/ECCO/ERANOSにより解析された結果と良く一致した。また、炉中心のサンプル反応度のC/E値についても検討している。両解析手法による結果には差が見られ、これらの差は、核データライブラリ、計算コード、自己遮蔽効果の取扱方法の違いにより生じたものである。誤差範囲を超えて違いの見られる結果についての議論も行っている。

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

The NEA NSC Working Group on International Evaluation Cooperation proposed that the STEK and SEG experiments (performed at ECN Petten / Netherlands and RC Rossendorf / Germany) should be used as a joint data base for the validation and convergence of the latest versions of JEF, JENDL, and ENDF/B, especially for capture and inelastic data of structural materials and fission product nuclides [1].

In Cadarache / CEA France the reanalysis of the SEG and STEK experiments has been performed using the European scheme for reactor calculation JEF-2.2 / ECCO / ERANOS. The results are discussed and given in many CEA and JEF/DOC reports, and publications, e.g. see [2,3,4,5]. Corrections in JEF data have been recommended based on perturbation theory calculations accompanied and confirmed by adjustment studies [6]. The SEG information has been documented in the SNEDAX data base.

For completion, a similar work is proposed using the JENDL library and codes (JNC route) available at O-arai Engineering Center to check the latest version of JENDL-3.2. The results of the JNC and European routes can not be compared directly because there are used different data libraries, codes, self-shielding treatments, and energy group structures. Nevertheless, sufficient information should be obtainable.

The Rossendorf SEG experiments, including sample reactivity measurements at the central position of the fast-thermal coupled facility RRR/SEG, are well described and documented [7,8]. The SEG experiments are considered as "clean" integral experiments; i.e., simple and clear in geometry and well suited for calculation. By using a precisely defined combination of unit cells or concentric rings, fast insertion lattices (SEG) with specially designed adjoint spectra at central position were arranged.

In the case of an energy-independent adjoint spectrum (SEG-4, SEG-5), the slowing-down effect disappears and the sample reactivity is only due to absorption. On the other hand, in configurations with a strong dependence, the scattering effect is dominant. When the adjoint function is monotonously rising, as in both SEG-6 lattices, the scattering effect is always negative. The SEG-7A was characterized by a very soft neutron spectrum and monotonously rising adjoint function, consequently both the capture and scattering effect are negative. Thus, having configurations with hard or soft neutron spectra and with different shapes of the adjoint function, separate information about capture and scattering data can be obtained.

2. The Rossendorf RRR/SEG facility and measurements

The fast-thermal coupled facility RRR/SEG [7,8] was a zero power reactor of Argonaut type. Because of the construction, this facility is well suited for calculations in R,Z-geometry.

The annular thermal driver consists of 24 rectangular cassettes filled with fuel sections beginning from inside and graphite in the outer region. Due to the fact that the loading of the cassettes was not uniform (mostly 8 fuel sections, but also 9 or 12) and because graphite wedges were placed between the cassettes, the thermal driver can be divided into two zones with an "effective" border-line. Neutron and adjoint fluxes have been calculated for the "critical thickness" of the thermal driver zone.

In the RRR/SEG facility, a graphite converter was installed. Only in the case of SEG-6, natural uranium was used.

The insertion lattice (SEG) is a cylindrical matrix of aluminum with 72 cylindrical holes. The holes were filled with cylindrical pellets in defined order (unit cells or concentric rings). According to the SEG configuration pellets of enriched uranium (36% enriched in U-235), natural uranium, graphite, boron-graphite, polyethylene, aluminum, and cadmium were used.

The special shapes of the adjoint function were obtained by decreasing the curves more or less at lower and higher energies. To accomplish this, additional absorber material B-10 (for SEG-4 cadmium) and more U-238 were used.

The SEG-4, -5, and -7A were arranged with unit cells. To decrease the adjoint function in the lower energy region, cadmium pellets were added in SEG-4 and mixed B-10/graphite-pellets in SEG-5 and –7A. In SEG-7A, polyethylene pellets were additionally inserted into the unit cell to soften the neutron spectrum. In case of the SEG-6, the Al matrix was filled, starting from inside, by enriched uranium pellets, natural uranium pellets, and aluminum pellets. Both SEG-6 versions differ in the diameter of the experimental channel (EK). EK10 and EK45 were used for samples with diameters up to 10 mm and 45 mm, respectively. The experimental channel (Al tube) was filled with graphite bars surrounded by a stationary absorber zone of boron carbide. In all SEG configurations, the samples were placed in special sample holders of graphite that moved through a window in the Al tube. In this way, simple and clear geometric and material conditions surrounded the sample.

The geometry of the RRR/SEG facility, the SEG lattices, the unit cells and characteristics of pellets used in each lattice are documented and is described in detail in reference [8]. In all SEG configurations only a few materials were used: Al, C, B-10, B-11, U-235, U-238, and in special cases Cd and H. Most of the materials are standards.

The sample reactivity measurements were performed by pile-oscillator technique developed to a high precision [9,10,11]. The dependence of the specific reactivity on sample size was determined for a wide mass range. Small sample reactivities were measured with an accuracy of ± 0.3 millicent. The extrapolation to infinitely dilute values (CRW) has been performed using different codes and data for self-shielding correction [9,11]. The most important measurements are likewise documented in [8] and SNEDAX.

3. The JNC route for SEG analysis

For the analysis of the SEG experiments, the library JENDL-3.2 and the codes SLAROM, CITATION, JOINT, and PERKY were used [12,13,14]. The order of carrying out the calculation is similar to the European scheme JEF-2.2 / ECCO / ERANOS [15,16,17].

At first, all zones of the RRR/SEG facility cell calculations with SLAROM were performed using the 70 group library of JENDL-3.2 (JFS3J3.Y9511). Most zones were treated in homogenous way, only the SEG itself was heterogeneous (slab geometry) according to the unit cells of the SEG configurations. The PDS files were then used in the following CITATION calculation to determine the neutron fluxes in 70 groups. The R,Z-geometry was taken from former calculations with ECCO / ERANOS [2]. The sample position at the center of the facility was introduced as a separate small cylindrical zone in order to use the route later in calculations for real samples. In the next step the PDS files and the fluxes were collapsed to 18 groups using JOINT. After this, a CITATION calculation in 18 groups was performed to prepare neutron and adjoint fluxes in 18 groups for use in PERKY. In this CITATION calculation, the critical thickness of the thermal driver zones is also optimized to get the fluxes for the critical condition. In the last step, perturbation calculations are performed with PERKY (mapping version) to get the total sample reactivity worths and the partial contributions in 18 energy groups for all reaction types at the central position.

In addition, the route was modified for the analyses of SEG-6 and SEG-7A to separate elastic and inelastic scattering contributions. For this purpose, further calculations were performed with special versions of SLAROM, JOINT, and PERKY.

At long last, the ratios of the calculated to experimental sample reactivity (infinitely dilute worth CRW) were determined by hand for each material under investigation. These C/E-values have been related to the C/E-value of an appropriate reference material (standard) measured in the same condition.

4. Reference material and error

In order to avoid the determination of the normalization integral of the reactor, the C/E-values of the materials under investigation were related to a reference material that preferably should be a standard. In SEG-4, SEG-5, and SEG-7A, boron-10 was used for this because of the high sensitivity to neutron capture in these configurations. The experimental value was deducted from measurements with natural and high enriched (81% in B-10) boron carbide, and with carbide. In SEG-6, a scattering material should be used. Preferred candidates are carbon or hydrogen. Hydrogen has been chosen, because carbon was present in the immediate vicinity, as the filling for the experimental channel. The experimental value for hydrogen was deducted from measurements with polyethylene and water.

The total error of the C/E-values was estimated using the following partial errors:

- Statistical error of the measurement with the material,
- Statistical error of the measurement with the reference material,
- The errors of the extrapolation to infinitely dilute values of the sample and reference material,
- The error when the experimental value was deducted from molecular samples,
- The data uncertainty of the reference material,
- An additional error due to uncertainties in compositions and moisture.

The determination of the total error of the C/E-values is described in detail in [18,11].

5. Preliminary interpretation and results

The calculated neutron and adjoint spectra of the SEG configurations are shown in Figures 1 - 5. All curves are reasonable and their shapes were as expected comparing with former results. In former calculations, either 33 energy groups (European scheme ECCO / ERANOS) or 26 groups (ABBN system [19] in Rossendorf analyses) were used. Because of the different group boundaries, only a direct comparison of the group contributions with results of ECCO / ERANOS in the MeV region is possible. A good agreement to the European scheme was found for the critical thickness; the differences were only a few mm.

The comparison of the calculated reactivities obtained with the various routes is very difficult because different input libraries, codes, and self-shielding treatments were used. Nevertheless, some indications were found.

The leakage values are very small, as expected. The differences for the capture effect are also small. But for the scattering effect there were discrepancies in value and sign. Because of the monotonously rising adjoint function in SEG-6 and SEG-7A the total scattering effect in the reactivity and also the group contributions should only be negative. The signs were exactly calculated, but there were large differences in the percentage to the total reactivities as well as for group contributions, where comparisons could be performed.

In SEG-4 and SEG-5, the percentage of the scattering effect should be very small. The sign should follow accordingly if the neutron is scattered into a energy group of higher or lower importance (adjoint function). Because of the slight depression in the adjoint function calculated in both routes, the positive and negative signs were obtained for group values as expected, but with large differences in the values. In the European route, the calculated total scattering effect for various samples were negative or positive and mostly smaller. The JNC route calculates only negative sign as a consequence that the main contribution is coming from inelastic scattering in the first energy groups (1 - 6 MeV). As an example, the PERKY output for some materials under investigation in the SEG-6 / EK45 is given in Table 1.

The C/E-values of the central reactivity worths (CRW) are compiled in Tables 2 - 6. The experimental (extrapolated infinitely dilute) CRW's are taken from [8]. The C/E-values of SEG-4, SEG-5, and SEG-7A are highly sensitive to capture, whereas both SEG-6 versions are sensitive to inelastic or elastic scattering according to the percentage given in the Tables. The results of SEG-5 and SEG-6 should be considered reliable. In SEG-4, Cd was used to design the adjoint function. There is the indication that the resonance data of Cd are not very accurate (see also results of SEG-6). Because of the very soft neutron spectrum in the SEG-7A the results of materials with large thermal and epithermal cross-sections should be treated carefully (Sm-149). The same was found in the results obtained with the European route. Furthermore, the results for materials which are present in the vicinity of the samples, e.g., Graphite and Aluminum, could probably be doubtful in how far the resonance interaction is exactly taken into account in the calculation. In ECCO this interaction is treated by macrocell calculations.

In the following, a preliminary summary is given: For most FP nuclides, a good agreement in the C/E-values exists. Significant discrepancies have been found for Ag-

109 (underestimation) and Pd-105 (overestimation). But there are many C/E-values of structural materials outside of the error; e.g., for the steel components Fe, Cr, Ni, and also for Zr, Cu, W. This fact can not be explained by the larger calculated total scattering effect. Further discrepancies have been found for Pb and Cr due to inelastic scattering and for Al, Mg, and Be caused by elastic scattering. The reason was mostly found in a few energy groups. Sensitivities will be calculated next time with SAGEP. Cases of obvious discrepancy are printed in bold in the Tables.

The large C/E-values for U-235 in the SEG-4, SEG-5, and SEG-7A are consistent with the U-235 / B-10 discrepancy in sample reactivity measurements. It was found that in many reactor configurations (e.g. SNEAK, ZEBRA, BFS, ZPR, KBR, etc.), the C/E-values of U-235 related to C/E of B-10 are overestimated, mostly outside of experimental errors and data uncertainty [19, p.123]. This effect is independent of fuel loading or neutron spectrum softness [8, p.51]. It is noteworthy that this effect was not found in SEG-6 / EK45, because the C/E-values are related to hydrogen.

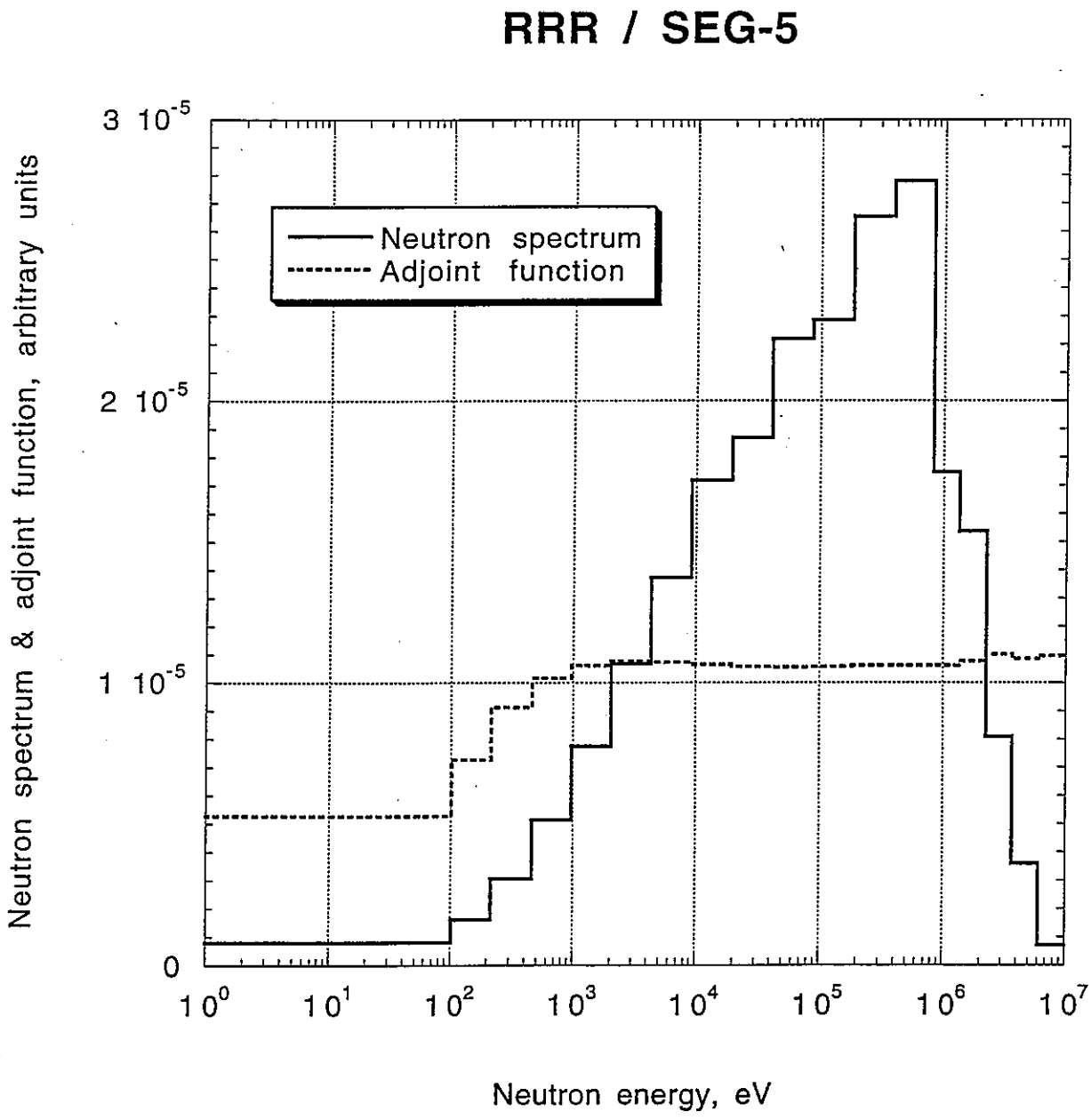

Fig.1: Calculated neutron spectrum and adjoint function at the central position of the RRR/SEG-5

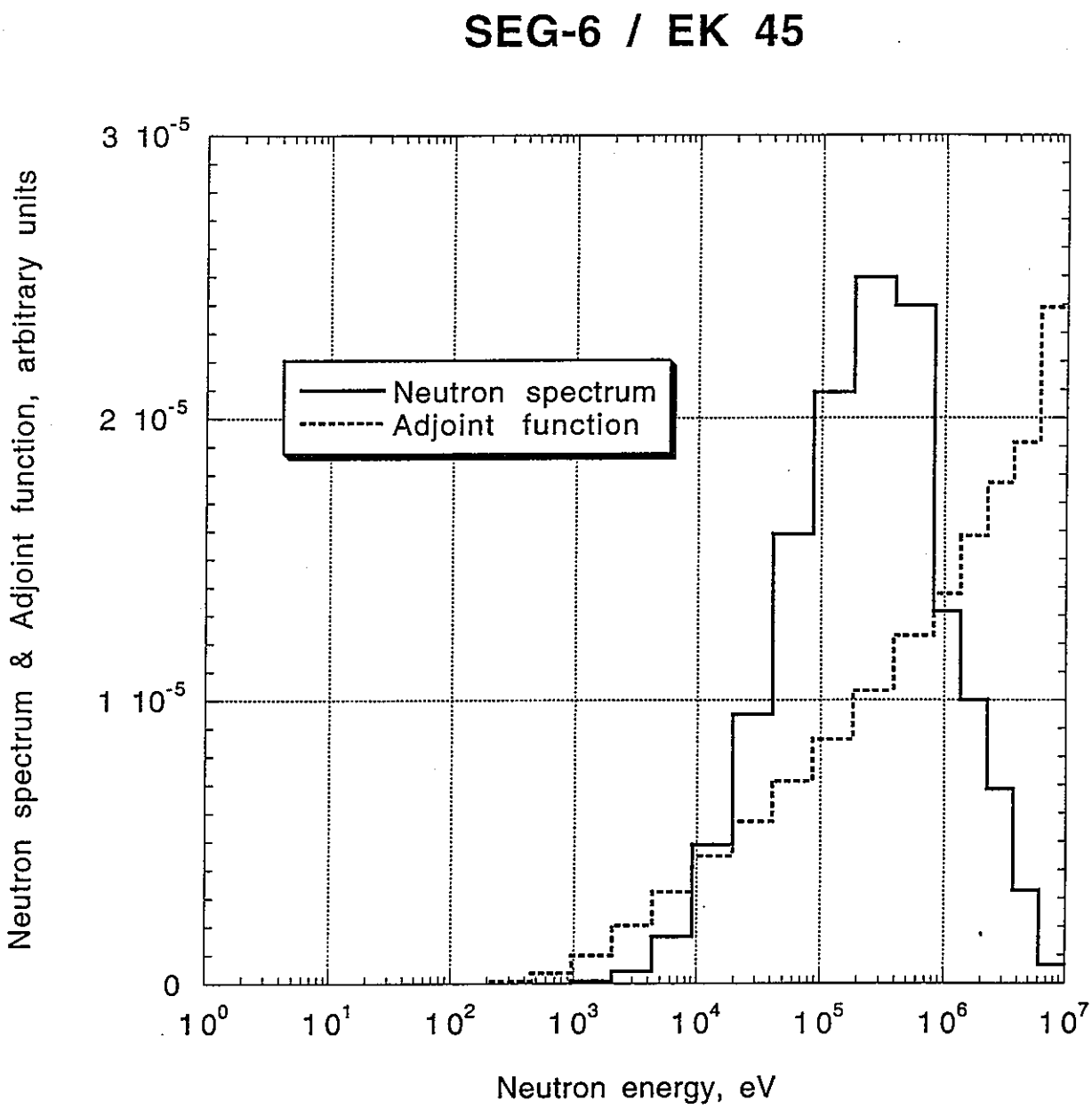

Fig.2: Calculated neutron spectrum and adjoint function at the central position of the RRR/ SEG-6 EK45

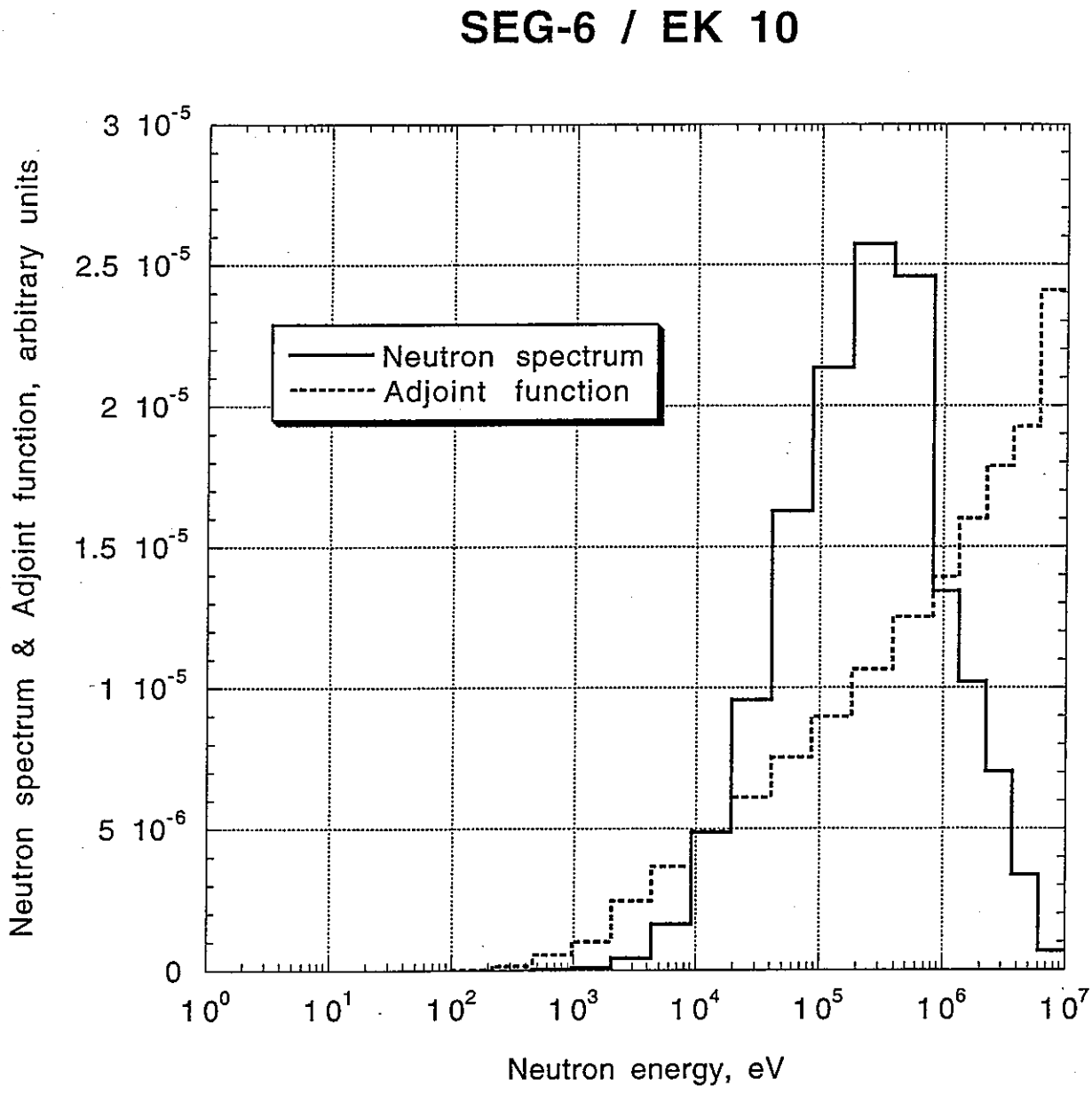

Fig.3: Calculated neutron spectrum and adjoint function at the central position of the RRR/SEG-6 EK10

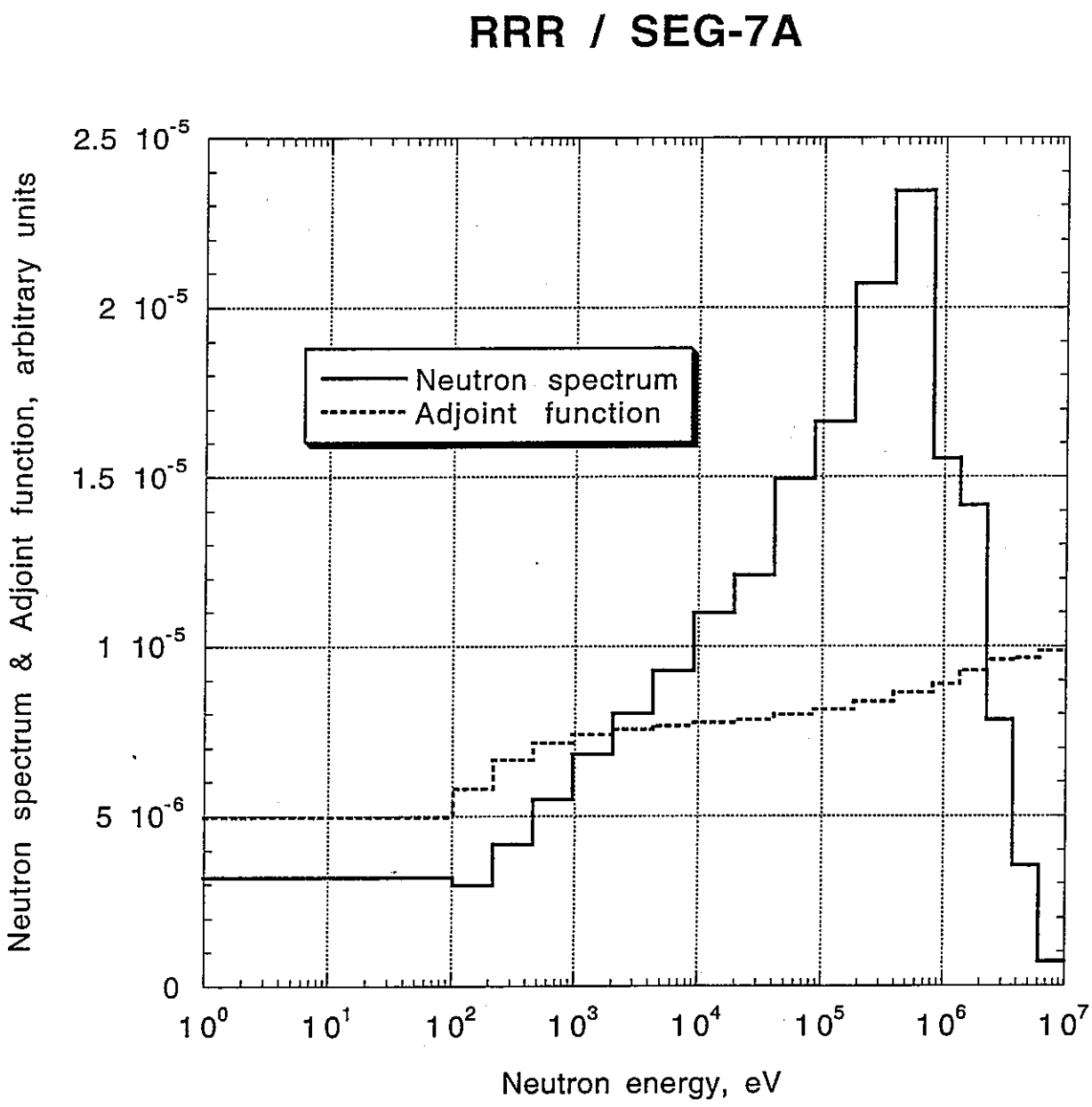

Fig.4: Calculated neutron spectrum and adjoint function at the central position of the RRR/SEG-7A

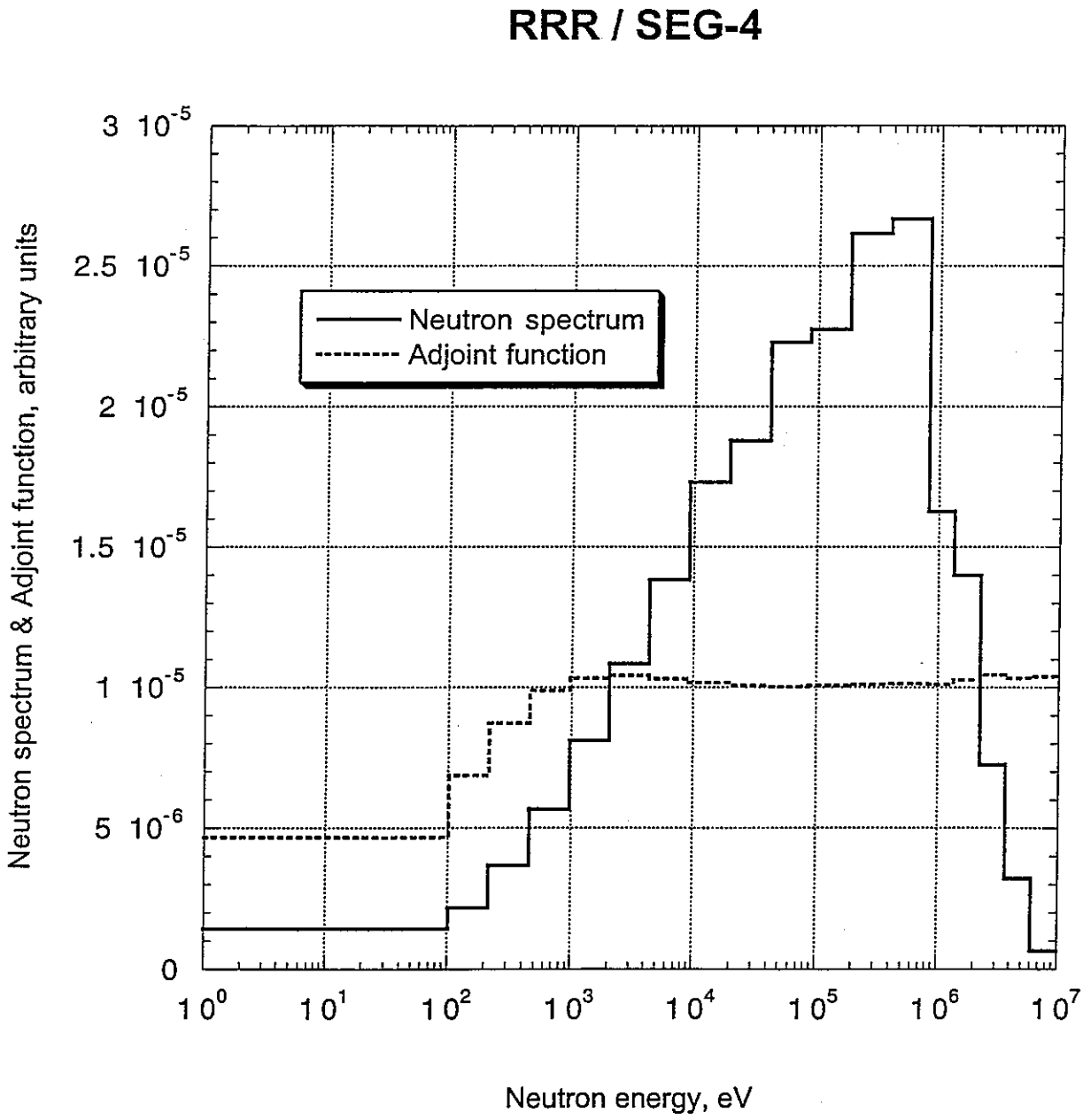

Fig.5: Calculated neutron spectrum and adjoint function at the central position of the RRR/SEG-4

Tab.1: PERKY output for some materials under investigation (H, Cr, Pb, U-238). Total and partial reactivities, and their energy group contributions at the central position of the SEG-6 / EK45

```
                                *****     THREE DIMENSION PERTURBATION CODE     *****

    RRR/SEG6, SAMPLE REACTIVITY WORTH CALCULATION, CENTRAL POS. RZ-GEO. 18G

    EFFECTIVE MULTIPLICATION FACTOR =  1.000258E+00

    REACTIVITY WORTH MAPPING CALCULATION
         ITERATION COUNT OF REACTIVITY WORTH MAPPING CALCULATION  1
         PLANE NUMBER  1     NUMBER OF MESHPOINT    1
              ( 1,25)
*** real flux ***
 0.64936E-06 0.32646E-05 0.68448E-05 0.10000E-04 0.13149E-04 0.23941E-04
 0.24938E-04 0.20904E-04 0.15892E-04 0.95009E-05 0.48855E-05 0.16507E-05
 0.41824E-06 0.82186E-07 0.13418E-07 0.16600E-08 0.14253E-09 0.39384E-11
*** adjoint flux ***
 0.11943E-05 0.95596E-06 0.88572E-06 0.79107E-06 0.68867E-06 0.61407E-06
 0.51640E-06 0.43006E-06 0.35681E-06 0.28559E-06 0.22432E-06 0.16167E-06
 0.10211E-06 0.49815E-07 0.18145E-07 0.42789E-08 0.50466E-09 0.15814E-12
    REACTIVITY WORTH MAPPING CALCULATION (PLANE NUMBER =  1)

    NUCLIDE CODE    1
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1     25      2  -1.6457E-10  0.0000E+00 -1.3780E-06 -1.3781E-06  1.7203E-10 -1.3780E-06  0.0000E+00 -1.3780E-06
1     25      3  -3.1187E-10  0.0000E+00 -4.1083E-06 -4.1086E-06  3.3147E-10 -4.1083E-06  0.0000E+00 -4.1083E-06
1     25      4  -3.9515E-10  0.0000E+00 -7.1812E-06 -7.1816E-06  4.7252E-10 -7.1811E-06  0.0000E+00 -7.1812E-06
1     25      5  -4.5516E-10  0.0000E+00 -1.0155E-05 -1.0156E-05  5.4992E-10 -1.0155E-05  0.0000E+00 -1.0155E-05
1     25      6  -8.0024E-10  0.0000E+00 -2.4079E-05 -2.4080E-05  1.9363E-09 -2.4078E-05  0.0000E+00 -2.4079E-05
1     25      7  -9.9043E-10  0.0000E+00 -3.2735E-05 -3.2736E-05  2.7785E-09 -3.2733E-05  0.0000E+00 -3.2735E-05
1     25      8  -1.1779E-09  0.0000E+00 -3.2729E-05 -3.2730E-05  1.1147E-09 -3.2729E-05  0.0000E+00 -3.2729E-05
1     25      9  -1.2803E-09  0.0000E+00 -2.9480E-05 -2.9481E-05  1.7363E-09 -2.9479E-05  0.0000E+00 -2.9480E-05
1     25     10  -1.0133E-09  0.0000E+00 -1.8272E-05 -1.8273E-05  5.6284E-11 -1.8273E-05  0.0000E+00 -1.8272E-05
1     25     11  -6.4955E-10  0.0000E+00 -9.5446E-06 -9.5453E-06 -3.1327E-10 -9.5456E-06  0.0000E+00 -9.5446E-06
1     25     12  -2.4382E-10  0.0000E+00 -2.8846E-06 -2.8848E-06 -4.4664E-10 -2.8853E-06  0.0000E+00 -2.8846E-06
1     25     13  -5.7995E-11  0.0000E+00 -5.5589E-07 -5.5594E-07 -8.3989E-11 -5.5603E-07  0.0000E+00 -5.5589E-07
1     25     14  -8.0611E-12  0.0000E+00 -6.0537E-08 -6.0545E-08  7.1772E-12 -6.0538E-08  0.0000E+00 -6.0537E-08
1     25     15  -6.8348E-13  0.0000E+00 -3.9227E-09 -3.9234E-09  3.9108E-12 -3.9195E-09  0.0000E+00 -3.9227E-09
1     25     16  -2.8819E-14  0.0000E+00 -1.2190E-10 -1.2193E-10  3.6279E-13 -1.2157E-10  0.0000E+00 -1.2190E-10
1     25     17  -4.1993E-16  0.0000E+00 -1.2865E-12 -1.2869E-12  8.7800E-15 -1.2781E-12  0.0000E+00 -1.2865E-12
1     25     18  -5.2630E-21  0.0000E+00  0.0000E+00 -5.2630E-21  5.0590E-20  4.5327E-20  0.0000E+00  0.0000E+00
1     25  TOTAL  -7.5884E-09  0.0000E+00 -1.7353E-04 -1.7353E-04  8.3794E-09 -1.7353E-04  0.0000E+00 -1.7353E-04
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X     Y     GRP      CAPTURE      FISSION   SCATTERING NON-LEAKAGE     LEAKAGE DELTA K/KK'  INEL SCATT ELAST SCATT
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1     25      2  -5.3047E-08  0.0000E+00 -1.3224E-06 -1.3755E-06  5.6890E-10 -1.3749E-06 -1.2908E-06 -3.1596E-08
1     25      3  -4.0129E-08  0.0000E+00 -1.8969E-06 -1.9370E-06  8.6448E-10 -1.9361E-06 -1.7802E-06 -1.1662E-07
1     25      4  -3.0522E-08  0.0000E+00 -1.5012E-06 -1.5318E-06  1.0371E-09 -1.5307E-06 -1.2437E-06 -2.5751E-07
1     25      5  -4.3145E-08  0.0000E+00 -5.4207E-07 -5.8521E-07  9.8016E-10 -5.8423E-07 -1.7793E-07 -3.6414E-07
1     25      6  -7.1068E-08  0.0000E+00 -4.1457E-07 -4.8564E-07  2.8577E-09 -4.8278E-07 -5.0974E-08 -1.6359E-07
1     25      7  -8.3588E-08  0.0000E+00 -7.2043E-07 -8.0402E-07  3.2508E-09 -8.0077E-07  0.0000E+00 -7.2043E-07
1     25      8  -9.4033E-08  0.0000E+00 -1.9952E-07 -2.9355E-07  2.0614E-09 -2.9149E-07  0.0000E+00 -1.9952E-07
1     25      9  -4.7068E-08  0.0000E+00 -7.9410E-08 -1.2648E-07  1.4103E-09 -1.2507E-07  0.0000E+00 -7.9410E-08
1     25     10  -6.0477E-08  0.0000E+00 -9.7748E-08 -1.5822E-07  2.6296E-11 -1.5820E-07  0.0000E+00 -9.7748E-08
1     25     11  -7.8512E-09  0.0000E+00 -1.4501E-07 -1.5286E-07 -1.8723E-10 -1.5305E-07  0.0000E+00 -1.4501E-07
1     25     12  -2.1980E-08  0.0000E+00 -9.8418E-08 -1.2040E-07 -1.6521E-09 -1.2205E-07  0.0000E+00 -9.8418E-08
1     25     13  -2.5346E-09  0.0000E+00 -3.3063E-09 -5.8409E-09 -1.9609E-10 -6.0370E-09  0.0000E+00 -3.3063E-09
1     25     14  -9.3106E-10  0.0000E+00 -1.8387E-10 -1.1149E-09  3.5100E-12 -1.1114E-09  0.0000E+00 -1.8387E-10
1     25     15  -5.1870E-12  0.0000E+00 -1.0313E-11 -1.5500E-11  1.4159E-12 -1.4084E-11  0.0000E+00 -1.0313E-11
1     25     16  -2.2084E-13  0.0000E+00 -2.9774E-13 -5.1858E-13  1.3623E-13 -3.8235E-13  0.0000E+00 -2.9774E-13
1     25     17  -3.4226E-15  0.0000E+00 -2.4439E-15 -5.8665E-15  3.6365E-15 -2.2300E-15  0.0000E+00 -2.4439E-15
1     25     18  -4.5280E-20  0.0000E+00  0.0000E+00 -4.5280E-20  2.2757E-20 -2.2523E-20  0.0000E+00  0.0000E+00
1     25  TOTAL  -6.0191E-07  0.0000E+00 -7.5312E-06 -8.1331E-06  1.1296E-08 -8.1218E-06 -5.0333E-06 -2.4968E-06
    NUCLIDE CODE   82
X     Y     GRP      CAPTURE      FISSION   SCATTERING NON-LEAKAGE     LEAKAGE DELTA K/KK'  INEL SCATT ELAST SCATT
1     25      1  -1.1610E-09  0.0000E+00 -1.1442E-06 -1.1453E-06  5.0944E-10 -1.1448E-06 -9.9068E-07 -8.8822E-09
1     25      2  -8.1303E-09  0.0000E+00 -3.3053E-06 -3.3134E-06  1.1483E-09 -3.3122E-06 -3.2843E-06 -2.0999E-08
1     25      3  -2.2024E-08  0.0000E+00 -3.1482E-06 -3.1702E-06  1.8630E-09 -3.1683E-06 -3.0777E-06 -7.0425E-08
1     25      4  -3.7346E-08  0.0000E+00 -1.6545E-06 -1.6919E-06  1.9185E-09 -1.6900E-06 -1.5555E-06 -9.9040E-08
1     25      5  -4.1402E-08  0.0000E+00 -1.1144E-06 -1.1558E-06  1.6679E-09 -1.1542E-06 -9.0006E-07 -2.1437E-07
1     25      6  -5.4481E-08  0.0000E+00 -3.8391E-07 -4.3839E-07  4.7740E-09 -4.3362E-07 -2.0040E-07 -1.8351E-07
1     25      7  -3.1753E-08  0.0000E+00 -3.1730E-07 -3.4905E-07  6.8914E-09 -3.4216E-07  0.0000E+00 -3.1730E-07
1     25      8  -6.1485E-08  0.0000E+00 -2.4027E-07 -3.0175E-07  2.6326E-09 -2.9912E-07  0.0000E+00 -2.4027E-07
1     25      9  -3.7994E-08  0.0000E+00 -2.4160E-07 -2.7960E-07  4.0653E-09 -2.7553E-07  0.0000E+00 -2.4160E-07
1     25     10  -2.4625E-08  0.0000E+00 -8.2301E-08 -1.0693E-07  9.8735E-11 -1.0683E-07  0.0000E+00 -8.2301E-08
1     25     11  -1.2865E-08  0.0000E+00 -3.6010E-08 -4.8875E-08 -5.3686E-10 -4.9412E-08  0.0000E+00 -3.6010E-08
1     25     12  -1.4331E-09  0.0000E+00 -1.0309E-08 -1.1742E-08 -7.4160E-10 -1.2483E-08  0.0000E+00 -1.0309E-08
1     25     13  -1.8851E-09  0.0000E+00 -2.2404E-09 -4.1255E-09 -1.3840E-10 -4.2639E-09  0.0000E+00 -2.2404E-09
1     25     14  -1.3599E-10  0.0000E+00 -1.9218E-10 -3.2817E-10  1.1756E-11 -3.1641E-10  0.0000E+00 -1.9218E-10
1     25     15  -4.7719E-13  0.0000E+00 -1.1041E-11 -1.1518E-11  6.3072E-12 -5.2107E-12  0.0000E+00 -1.1041E-11
1     25     16  -1.5259E-14  0.0000E+00 -2.8601E-13 -3.0127E-13  5.8434E-13  2.8307E-13  0.0000E+00 -2.8601E-13
1     25     17  -2.2099E-16  0.0000E+00 -2.0988E-15 -2.3198E-15  1.4133E-14  1.1813E-14  0.0000E+00 -2.0988E-15
1     25     18  -2.7641E-21  0.0000E+00  0.0000E+00 -2.7641E-21  8.1400E-20  7.8636E-20  0.0000E+00  0.0000E+00
1     25  TOTAL  -3.3672E-07  0.0000E+00 -1.1681E-05 -1.2017E-05  2.4171E-08 -1.1993E-05 -1.0009E-05 -1.5275E-06
    NUCLIDE CODE  928
X     Y     GRP      CAPTURE      FISSION   SCATTERING NON-LEAKAGE     LEAKAGE DELTA K/KK'  INEL SCATT ELAST SCATT
1     25      1  -5.6264E-09  1.2159E-06 -1.1153E-06  9.4952E-08  5.6379E-10  9.5516E-08 -6.1219E-07 -4.2379E-09
1     25      2  -4.3207E-08  3.5320E-06 -3.1584E-06  3.3037E-07  1.1791E-09  3.3155E-07 -3.1528E-06 -5.6094E-09
1     25      3  -1.7648E-07  6.3907E-06 -7.2730E-06 -1.0587E-06  1.9238E-09 -1.0568E-06 -7.2559E-06 -1.7065E-08
1     25      4  -5.3707E-07  7.6647E-06 -7.3745E-06 -2.4687E-07  2.1924E-09 -2.4468E-07 -7.3334E-06 -4.1138E-08
1     25      5  -1.4914E-06  6.5386E-07 -5.0413E-06 -5.8788E-06  1.9310E-09 -5.8769E-06 -4.9422E-06 -9.9043E-08
1     25      6  -2.4451E-06  5.4967E-08 -1.5887E-06 -3.9788E-06  5.7873E-09 -3.9730E-06 -1.4422E-06 -1.4648E-07
1     25      7  -2.2475E-06  6.0053E-09 -1.2879E-06 -3.5294E-06  7.6522E-09 -3.5218E-06 -9.9750E-07 -2.9040E-07
1     25      8  -2.0760E-06  2.5594E-09 -9.1586E-07 -2.9893E-06  2.8868E-09 -2.9865E-06 -6.6329E-07 -2.5257E-07
1     25      9  -2.2802E-06  2.4684E-09 -5.5511E-07 -2.8329E-06  4.0730E-09 -2.8288E-06 -3.5394E-07 -2.0117E-07
1     25     10  -1.7600E-06  1.4240E-09 -1.0771E-07 -1.8663E-06  1.2693E-10 -1.8661E-06  0.0000E+00 -1.0771E-07
1     25     11  -9.6151E-07  1.2421E-09 -5.2488E-08 -1.0128E-06 -7.1240E-10 -1.0135E-06  0.0000E+00 -5.2488E-08
1     25     12  -3.0193E-07  4.4419E-10 -1.7297E-08 -3.1879E-07 -1.0537E-09 -3.1984E-07  0.0000E+00 -1.7297E-08
1     25     13  -7.0508E-08  2.1249E-15 -2.6347E-09 -7.3143E-08 -2.5847E-10 -7.3401E-08  0.0000E+00 -2.6347E-09
1     25     14  -1.1079E-08  4.5988E-11 -3.3266E-10 -1.1365E-08  2.6662E-11 -1.1139E-08  0.0000E+00 -3.3266E-10
1     25     15  -1.1691E-09  4.3866E-11 -1.3070E-11 -1.1381E-09  1.3232E-11 -1.1251E-09  0.0000E+00 -1.3070E-11
1     25     16  -3.5541E-11  3.6180E-14 -5.7169E-13 -3.6076E-11  1.0499E-12 -3.5026E-11  0.0000E+00 -5.7169E-13
1     25     17  -1.4973E-12  1.0203E-14 -1.7538E-13 -1.6625E-12  1.1501E-13 -1.5475E-12  0.0000E+00 -1.7538E-13
1     25     18  -1.2237E-17  3.2718E-16  0.0000E+00  3.1495E-16  2.4577E-19  3.1519E-16  0.0000E+00  0.0000E+00
1     25  TOTAL  -1.4409E-05  1.9526E-05 -2.8491E-05 -2.3373E-05  2.6333E-08 -2.3347E-05 -2.6753E-05 -1.2382E-06
```

Table 2: C/E-values of materials under investigation in SEG-5, related to the C/E-value of boron-10, and scattering/total reactivity ratios

Material	ID-No.	CRW exp (millicent/g)	C/E-value (JENDL-3.2)	Error (%)	Scat./ tot. (%)
B-10	105	- 1230 ± 20	1.000	2	0.1
Ta	731	- 31.5 ± 1.0	0.921	7	0.45
U-235	925	+ 31.2 ± 2.0	**1.321**	**10**	0.1
Mo	42	- 7.4 ± 0.5	1.004	10	2.5
Mn	25	- 12.0 ± 0.5	**0.694**	**7**	9.3
Cd	48	- 10.0 ± 0.5	1.060	9	1.2
Nb	413	- 10.0 ± 0.6	1.119	9	1.6
Cu	29	- 4.5 ± 0.5	**1.278**	**14**	5.4
Zr	40	- 1.05 ± 0.1	**1.397**	**13**	7.5
W	74	- 10.0 ± 0.5	**0.877**	**8**	3.8
Fe	26	- 0.7 ± 0.06	**1.588**	**11**	19.6
Cr	24	- 0.8 ± 0.06	**1.216**	**10**	12.8
Ni	28	- 1.3 ± 0.1	**1.561**	**10**	11.2
Co	279	- 20.0 ± 1.5	0.865	10	1.5
B-10	105	- 1174 ± 20	1.000	2	0.1
Mo-95	425	- 14.5 ± 1.0	1.085	10	1.1
Mo-97	427	- 14.0 ± 1.0	1.006	10	1.3
Mo-98	428	- 5.0 ± 0.6	1.115	15	6.3
Mo-100	420	- 4.1 ± 0.5	1.031	16	3.4
Rh-103	453	- 27.0 ± 1.0	0.925	7	0.6
Pd-105	465	- 30.2 ± 1.0	**1.136**	**7**	0.4
Ag-109	479	- 31.5 ± 1.5	**0.863**	**8**	0.5
Cs-133	553	- 19.5 ± 2.0	0.889	13	0.6
Nd-143	603	- 16.0 ± 1.0	**0.835**	**9**	1.0
Nd-145	605	- 18.0 ± 1.0	1.008	9	2.0
Sm-149	629	- 83 ± 5	0.938	9	0.2
Eu-153	633	- 75 ± 5	1.031	10	0.2

Table 3: C/E-values of materials under investigation in SEG-6 / EK45, related to the C/E-value of hydrogen, and percentages of reaction type

Material	ID-No.	CRW exp (millicent/g)	C/E-value (JENDL-3.2)	Error (%)	Capture (%)	El. Sc. (%)	Inel. Sc. (%)
H	1	- 1099 ± 10	1.000	5	0.0	100.0	0.0
C	6	- 7.35 ± 0.06	**0.878**	**8**	0.4	98.4	1.2
B-10	105	- 95.9 ± 6.0	0.854	12	90.6	8.8	0.6
Mo	42	- 1.70 ± 0.04	0.923	7	27.1	11.3	61.6
Fe	26	- 1.22 ± 0.04	0.967	7	8.8	29.2	62.0
Cr	24	- 1.21 ± 0.04	**0.817**	**7**	7.3	30.7	62.0
Ni	28	- 1.55 ± 0.05	**0.875**	**9**	37.3	29.4	33.3
Al	13	- 2.00 ± 0.06	**1.176**	**8**	3.2	70.6	26.2
Zr	40	- 1.01 ± 0.03	0.937	8	10.0	26.3	63.7
Ti	22	- 1.93 ± 0.05	0.890	8	6.9	44.5	48.6
Cd	48	- 1.89 ± 0.05	**0.799**	**7**	41.5	6.7	51.8
Pb	82	- 0.32 ± 0.02	**1.145**	**12**	2.6	12.7	84.7
Bi	839	- 0.30 ± 0.02	0.896	12	4.1	14.5	81.4
Mg	12	- 3.01 ± 0.08	**1.167**	**13**	3.0	75.6	21.4
Be	4	- 14.04 ± 0.10	**1.133**	**7**	6.7	79.2	14.1
W	74	- 1.34 ± 0.03	0.914	9	26.2	3.6	70.2
Cu	29	- 1.45 ± 0.02	1.044	8	19.2	21.8	59.0
Mn	25	- 1.53 ± 0.03	0.946	8	6.7	37.1	56.2
Ta	731	- 2.15 ± 0.02	**0.881**	**7**	52.1	2.3	45.6
V	23	- 1.91 ± 0.05	0.885	9	5.5	44.5	50.0
Si	14	- 1.82 ± 0.09	1.069	11	4.9	74.1	21.0
Nb	413	- 1.96 ± 0.04	0.935	8	29.8	11.6	58.6
Co	279	- 1.25 ± 0.02	1.084	8	10.2	27.2	62.6
U-235	925	+ 10.9 ± 0.07	**0.899**	**7**	7.1 f:113.3	0.3	5.8
U-238	928	- 0.703 ± 0.04	0.884	12	61.7 f: 83.6	5.3	114.6
Th	902	- 1.35 ± 0.04	**0.852**	**9**	40.3 f: 8.7	3.1	64.0

Table 4: C/E-values of materials under investigation in SEG-6 / EK10, related to the C/E-value of hydrogen, and percentages of reaction type

Material	ID-No.	CRW exp (millicent/g)	C/E-value (JENDL-3.2)	Error (%)	Capture (%)	El. Sc. (%)	Inel. Sc. (%)
H	1	- 1059 ± 10	1.000	5	0.0	100.0	0.0
C	6	- 7.05 ± 0.06	**0.872**	**9**	0.3	98.4	1.3
B-10	105	- 85.1 ± 5.0	0.974	10	91.1	8.3	0.6
Mo	42	- 1.53 ± 0.03	0.998	6	28.1	11.1	60.8
Fe	26	- 1.20 ± 0.02	0.948	6	9.2	28.8	62.0
Ni	28	- 1.52 ± 0.05	**0.868**	**8**	38.2	28.7	33.1
Al	13	- 2.09 ± 0.04	1.077	7	3.3	70.2	26.5
Zr	40	- 0.99 ± 0.03	0.924	7	10.5	25.9	63.6
Ti	22	- 1.62 ± 0.04	1.019	7	7.3	43.9	48.8
Cd	48	- 1.71 ± 0.02	**0.868**	**6**	42.8	6.5	50.7
Pb	82	- 0.27 ± 0.02	**1.308**	**11**	2.7	12.6	84.7
Bi	839	- 0.29 ± 0.02	0.897	11	4.3	14.2	81.5
Mg	12	- 3.03 ± 0.24	1.107	11	3.1	75.2	21.7
Be	4	- 13.5 ± 0.2	**1.128**	**6**	6.9	78.8	14.3
W	74	- 1.26 ± 0.04	0.946	8	27.3	3.6	69.1
Cu	29	- 1.40 ± 0.04	1.048	7	20.0	21.4	58.6
Rh	453	- 2.87 ± 0.13	1.028	9	58.6	4.0	37.4

Table 5: C/E-values of materials under investigation in SEG-7A, related to the C/E-value of boron-10, and percentages of reaction type

Material	ID-No.	CRW exp (millicent/g)	C/E-value (JENDL-3.2)	Error (%)	Capture (%)	El. Sc. (%)	Inel. Sc. (%)
B-10	105	- 850 ± 10	1.000	2	99.7	0.3	0.0
C	6	- 1.90 ± 0.05	**1.377**	**6**	0.8	98.5	0.7
Mo-95	425	- 16.8 ± 2.5	0.812	18	96.1	0.5	3.4
Mo-97	427	- 8.0 ± 0.6	0.993	11	92.3	0.8	6.9
Mo-98	428	- 2.7 ± 1.0	1.264	40	84.4	4.8	10.8
Mo-100	420	- 8.1 ± 1.0	**0.324**	**13**	82.4	2.3	15.3
Rh-103	453	- 15.0 ± 2.0	1.199	16	97.4	0.3	2.3
Ag-109	479	- 36.0 ± 1.5	0.911	7	98.7	0.2	1.1
Sm-149	629	- 70.0 ± 3.0	**1.601**	**7**	99.5	0.1	0.4
Ta	731	- 26.0 ± 1.0	0.861	7	98.5	0.1	1.4
U-235	925	+28.0 ± 3.0	**1.208**	**13**	18.3 f:118.9	0.04	0.6

Table 6: C/E-values of materials under investigation in SEG-4, related to the C/E-value of boron-10, and percentages of reaction type

Material	ID-No.	CRW exp (millicent/g)	C/E-value (JENDL-3.2)	Error (%)	Capture (%)	El. SC. (%)	Inel. Sc. (%)
B-10	105	- 1326 ± 20	1.000	2	99.9	0.1	0.0
Mo-95	425	- 18 ± 1.0	0.893	10	99.1	0.2	0.7
Mo-97	427	- 11 ± 0.5	**1.281**	**9**	98.9	0.2	0.9
Mo-98	428	- 5.3 ± 0.4	1.079	12	93.4	5.0	1.6
Mo-100	420	- 3.5 ± 0.3	**1.213**	**13**	97.0	0.7	2.3
Rh-103	453	- 35 ± 3.0	0.958	12	99.6	0.1	0.3
Pd-105	465	- 30.5 ± 5.0	1.139	19	99.6	0.1	0.3
Ag-109	479	- 65 ± 5.0	**0.536**	**12**	99.7	0.0	0.3
Cs-133	553	- 22 ± 2.0	0.887	13	99.6	0.05	0.35
Sm-149	629	- 105 ± 5.0	**1.242**	**9**	99.9	0.05	0.05
Eu-153	633	- 93 ± 5.0	0.916	10	99.8	0.1	0.1
Ta	731	- 37 ± 2.0	**0.821**	**8**	99.6	0.15	0.25
Mo	42	- 6.2 ± 0.5	1.168	12	97.7	1.0	1.3
Nb	413	- 8.5 ± 0.5	**1.257**	**10**	98.6	0.4	1.0
Mn	25	- 8.3 ± 0.6	1.022	11	92.9	6.1	1.0
Fe	26	- 0.52 ± 0.07	**2.024**	**12**	81.2	12.9	6.9
Cr	24	- 0.50 ± 0.03	**1.749**	**10**	92.4	0.4	8.0
Ni	28	- 1.00 ± 0.08	**1.803**	**11**	89.2	8.0	2.8
Cd	48	- 7.5 ± 0.5	**1.806**	**10**	99.3	0.1	0.6
Cu	29	- 4.2 ± 0.3	**1.314**	**11**	96.4	1.8	1.8
Zr	40	- 0.90 ± 0.08	**1.538**	**12**	93.9	1.4	4.7
W	74	- 15 ± 1.0	**0.641**	**10**	96.4	2.8	0.8
U-235	925	+ 31.2 ± 2.0	**1.336**	**10**	23.1 f: 123.2	0.0	0.1
U-238	928	- 7.2 ± 0.5	0.993	10	112 f: 15.4	2.0	0.8

6. Conclusion and outlook

The sample reactivity worth measurements performed at 5 Rossendorf RRR/SEG configurations have been analyzed using the JNC route for reactor calculation JENDL-3.2 / SLAROM / CITATION / JOINT / PERKY. Starting with cell and flux calculations in 70 energy groups, the cross-sections and fluxes were then condensed to 18 groups for the subsequent perturbation calculation. The very broad 18^{th} energy group from 10^{-5} eV up to about 100 eV is a disadvantage for SEG configurations with soft neutron spectrum. Therefore, calculations without condensing are still planned to confirm the results.

The calculated shapes of neutron and adjoint spectra are reasonable and comparable with former calculations using JEF-2.2 / ECCO / ERANOS. The C/E-values differ because of the different data libraries, codes , and self-shielding treatments used in both routes. Because of the different energy group structure and condensation (70 => 18 and 1968/172 => 33 groups) in both routes, details (e.g., the contributions of reaction type in energy groups) can only be compared and interpreted with difficulty. In contrast to ECCO / ERANOS, the total scattering effect calculated by the JNC route is mostly larger and only negative whereas the group contributions differ in sign and value.

For most FP nuclides a good agreement was found, whereas for many structural materials discrepancies still exist. Special cases of larger deviations from 1.0 in C/E-values remain to be clarified. Integral tests are characterized by the specialty that the main reactivity effect of the sample is often determined by only one cross-section type in a small energy region. These data should be reviewed first. The calculation of averaged transmissions has been proved useful as an additional and complementary method to detect errors in the original data and to compare data libraries [20].

A cross-wise use of libraries and routes is desirable and could be judged based on large deviations in C/E-values. JNC route calculations with JEF-2.2 data are planned. On the other hand, the two methods of self-shielding treatment (self-shielding factors with interpolation against probability tables/sub-group method) should be compared. The extensive series of measurements of the dependence of the sample reactivity on sample size in the SEG facility could be used for this. The JNC route for SEG analysis has already been prepared to calculate the reactivity of real samples.

For completion, the analyses should be continued in the same way by using the valuable information obtained at STEK facilities (ECN Petten, Netherlands). Similar measurements have been performed there in five configurations of increasing hardness of the neutron spectrum and a great number of samples, especially with very many FP isotopes [21]. An analysis of the STEK experiments with the European route was recently completed in Cadarache [5].

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