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Benchmark on Computer Simulation of MASURCA Critical and Subcritical Experiments

MUSE-4 Benchmark

Final Report

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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NUCLEAR ENERGY AGENCY

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FOREWORD

In terms of radioactive waste transmutation, accelerator-driven systems (ADS) are considered to be efficient minor actinide burners. However, much R&D work is still required in order to demonstrate the desired capability of the system as a whole, and the current methods of analysis and nuclear data for minor actinide burners are not as well established as those for conventionally fuelled reactor systems.

Recognising a need for code and data validation in this area, the Nuclear Science Committee of the OECD Nuclear Energy Agency (NEA) has organised various theoretical benchmarks on ADS burners. Many improvements and clarifications in nuclear data and calculation methods have been achieved. However, following an initial series of benchmarks, some significant discrepancies in important parameters were not fully understood and still required clarification.

Therefore, this international benchmark based on MASURCA experiments, which were carried out under the auspices of the EC 5th Framework Programme, was launched in December 2001 in co-operation with CEA (France) and CIEMAT (Spain). A total of 16 different institutions participated in this first experiment-based benchmark providing 34 solutions. This report presents the comparative analysis of the results provided against experimental data.

Many of the figures included in this report are quite complex, as are the calculation details; it was thus determined that the figures and appendices mentioned in the text should be included on the enclosed CD-ROM.

Acknowledgements

The Secretariat expresses its sincere gratitude to the participants who willingly devoted their time and effort to this benchmark exercise, and to CEA-Cadarache for the release of valuable experimental data. Special thanks go to Dr. Ved Bhatnagar of the European Commission for his co-operation.

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EXECUTIVE SUMMARY

The efficient and safe management of spent fuel produced during the operation of commercial nuclear power plants is an important issue. In this context, partitioning and transmutation (P&T) of minor actinides and long-lived fission products can play an important role, significantly reducing the burden on geological repositories of nuclear waste and allowing their more effective use.

Various systems, including existing reactors, fast reactors and advanced systems have been considered to optimise the transmutation scheme. Recently, many countries have shown interest in accelerator-driven systems (ADS) due to their potential for transmutation of minor actinides. Much R&D work is still required in order to demonstrate their desired capability as a whole system, and the current analysis methods and nuclear data for minor actinide burners are not as well established as those for conventionally-fuelled systems.

Recognising a need for code and data validation in this area, the Nuclear Science Committee of the OECD/NEA has organised various theoretical benchmarks on ADS burners. Many improvements and clarifications concerning nuclear data and calculation methods have been achieved. However, some significant discrepancies for important parameters are not fully understood and still require clarification.

Therefore, this international benchmark based on MASURCA experiments, which were carried out under the auspices of the EC 5th Framework Programme, was launched in December 2001 in co-operation with the CEA (France) and CIEMAT (Spain). The benchmark model was oriented to compare simulation predictions based on available codes and nuclear data libraries with experimental data related to TRU transmutation, criticality constants and time evolution of the neutronic flux following source variation, within “liquid” metal fast subcritical systems.

A total of 16 different institutions participated in this first experiment based benchmark, providing 34 solutions. The large number of solutions provided has allowed to analyse the calculation results with many different combinations of simulation methods, including deterministic and Monte Carlo methods, and nuclear databases. The intercomparisons of these results and their direct comparison against experimental results (when available), were helpful to identify the sources of discrepancies observed among different solutions.

Nevertheless, this MUSE-4 benchmark could not answer all the questions raised. A follow-up exercise may be useful for a more thorough investigation on external fast neutron source propagation within the multiplier media and thermal neutron transport in large and nearly transparent reflectors.

Chapter 1

INTRODUCTION

Partitioning and transmutation (P&T) of nuclear waste has been proposed to reduce the amount of high-level waste inventory and the associated radiotoxicity inventory in the final repository. This can alleviate the burden on the final repository and improve public acceptance, contributing to ease nuclear waste management and help the sustainability of nuclear energy as a future energy source.

In order to efficiently reduce the radiotoxicity inventory, plutonium as well as minor actinides must be transmuted. This leads to many advanced nuclear fuel cycle scenarios suggesting fuels with a high minor actinide content and a low uranium content for the transmutation reactors. In addition to the flexibility required to achieve an efficient fuel management, the degradation of safety parameters when the new type of fuels is used in conventional critical reactors has lead to the potential use of subcritical reactors to transmute the nuclear waste, in particular for the minor actinide transmutation. To maintain the reactor neutron flux and power an external neutron source is required. In order to generate a sufficient number of neutrons, accelerator-driven spallation neutron sources had been proposed, leading to accelerator-driven subcritical systems (ADS). The optimisation of the ratio of capture over fission during transmutation, which allows to minimise the content of high mass actinides in the final wastes sent to the repository, has suggested the choice of fast neutron spectra for most of the ADS proposed for transmutation.

There is no experience of ADS operation at sizable power, and very little at low power for a realistic ADS representative of the future ADS dedicated to nuclear waste transmutation. For this reason two initiatives were set up. First, new experiments devoted to study the physics of ADS, with its peculiarities as concerns kinetic behaviour and the coupling between the multiplicative assembly and the external source were undertaken. Probably the most relevant experiment is MUSE-4, a project performed by a large collaboration in the MASURCA installation of CEA at Cadarache, in the form of a shared cost action of the 5th Framework Programme of R&D of the European Commission, FP5. Second, a number of computational benchmarks were organised by the OECD/NEA and the IAEA to compare computer simulations of ADS behaviour.

In particular, the OECD/NEA has set up a Working Party on Scientific Issues in Partitioning and Transmutation (WPPT) within the framework of its Nuclear Science Committee to deal with the status and trends of scientific issues in partitioning and transmutation (P&T), comprising different disciplines such as accelerators, chemistry, material science, nuclear data and reactor physics. The reactor physics and safety subgroup of the WPPT, jointly with the international MUSE-4 collaboration team, decided to launch the present benchmark in 2001 with the intention of joining both efforts by proposing a computational benchmark based on the MUSE-4 experiments. This benchmark, along with the intercomparison of calculated results, will provide a comparative analysis of calculated results against some experimental results aiming at providing a definitive guidance on the evaluation of systematic uncertainties and indications of future development required both in the simulation codes and the associated nuclear databases.

The benchmark model was therefore oriented to compare simulation predictions based on available codes and nuclear data libraries with experimental data related to: TRU transmutation, criticality constants and time evolution of the neutronic flux following source variation, within “liquid” metal fast subcritical systems.

The benchmark has been divided in three steps. The first step will allow an understanding of the simulation methods of the different groups and tuning of the simulation programs with the experimental data of one already-measured configuration (COSMO). Geometrical fluence distributions, spectral index and global parameters such as the k_{eff} and kinetic parameters were evaluated and compared with the already-available experimental results. In the second step, the MUSE-4 reference configuration was proposed to simulate different reactor parameters (criticality constant, flux distribution...) in a nearly critical configuration. Finally, the third step was oriented toward the simulation of reactor response to the external source in the subcritical reference configuration with k_{eff} close to 0.97. The external neutron source was based on the D-T reactions with the tritium target placed in the MASURCA centre. The simulation of the subcritical configuration included the calculation of the same parameters of the critical configurations with additional attention to two specific aspects of the subcritical systems: the propagation and multiplication of the source inside the multiplication assembly, and the kinetic behaviour of the ADS. In the two later phases, the simulations were made blindly before the experimental results became available.

A large participation has allowed analysing the calculation results with many different combinations of simulation methods, including deterministic and Monte Carlo methods, and nuclear databases. The intercomparisons of these results were helpful to identify the sources of discrepancies among different solutions.

A large number of EC FP5 MUSE-4 collaboration teams participated in the benchmarks and also many valuable contributions were provided by the members of the WPPT. The two groups regularly hold joint meetings to discuss and analyse the results together, and this report is the outcome of both the WPPT and the MUSE-4 groups.

For the analysis of the provided results, a huge amount of data was processed. For the sake of simplicity, it was decided to present the results in graphical form, avoiding too many tables with numerical values in the report. All detailed and individual results can be found on the enclosed CD-ROM.

Chapter 2

BENCHMARK DESCRIPTION

The MASURCA reactor is an experimental nuclear assembly that can be configured as critical or subcritical by loading a different number of fuel tubes. The core, in the central zone, is based on a uranium/plutonium MOX fuel. The installation was recently modified for the MUSE-4 experiments, with the addition of an external neutron source based on a deuteron accelerator and the deuterium-tritium or deuterium-deuterium reactions in a target placed in the centre of the fuel core. An evacuated aluminium tube allows the deuterons produced outside the reactor to reach the target. In addition the recent MUSE-4 configurations include a central lead region, simulating the spallation target in future ADS. Finally, a reflector region made of a mixture of sodium and steel surrounds the core, and after this a shielding region built exclusively of steel.

Three configurations of the MASURCA facility were simulated in the benchmark. The detailed geometry descriptions and material compositions of each configuration were provided to the participants in the benchmark specifications (Appendix A). A model of the facility has been described and homogenised at the tube level. The errors introduced by the homogenisation approximation were checked by CIEMAT, and they appeared very small, typically from less than 0.1% in k_{eff} to a maximum of 8% in the absolute flux at the worst tube (k_{eff} = 0.995).

COSMO is the first configuration. It corresponds to a critical experiment performed in the past and for which the available experimental data was provided by CEA to the benchmark participants. It is a very simple and symmetrical configuration and has no external source, vacuum tube nor lead buffer. The main aim of this simulation is to tune and verify the different codes and libraries in a “classical” fast reactor exercise.

The second configuration corresponds to the reference critical MUSE-4 configuration with 1 112 fuel cells. This is a full MUSE-4 setup with the evacuated aluminium tube for the external deuteron accelerator and the lead buffer. The only missing element was the tritium/deuterium target itself. This configuration, like the COSMO setup, is able to self-sustain its flux and is operated without an external source. Despite the small intrinsic source produced by the Pu spontaneous fission and the (α,n) reactions, in all the simulations of the COSMO and MUSE-4 critical configurations the flux is assumed to be computed as the transport equation eigenvector. The goal of the simulations for this configuration is to evaluate the effects of the inhomogeneities introduced by the new elements included in the MUSE-4 experiments, but without introducing the effects of a source-operated experiment. The experiments corresponding to the reference critical MUSE-4 experiments were performed in 2001.

The third phase corresponds to the SC2 reference MUSE-4 configuration with 976 fuel cells and the expected k_{eff} was close to 0.97. As for the previous phase, this is a full MUSE-4 configuration but some fuel elements were replaced by reflector elements and the tritium target was put into place. The experiments, which took place during 2002 and 2003, were performed with the help of the deuterium tritium source. For the simulated experiments, the intrinsic source contribution can be ignored. For this reason, it was requested to make most of the simulations of this phase in the source mode. However, for the evaluation of global and kinetic parameters, transport equation eigenvector calculations are requested.

Finally, it should be noted that, in order to isolate the different sources of possible simulation discrepancies, relative values are requested for most cases.

Chapter 3

PARTICIPANTS, CODES AND DATA USED

A total of 16 participants, 10 of them members of the MUSE-4 project, provided a total of 34 solutions with several combinations of Monte Carlo and deterministic codes and three libraries (JEF-2.2, ENDF/B-6 and JENDL-3.2) with several variants both in the codes and in the data. The most frequently used code is MCNP in different versions and with more or less options. ERANOS is the most frequently employed deterministic code. The complete list of combinations of codes and libraries of the different solutions is presented in Table 3.1. Additional calculation details provided by the participants can be found in Appendix B.

1. Argonne National Laboratory, ANL (USA)
   Participants: G. Aliberti, G. Palmiotti, R.N. Blomquist, C.G. Stenberg
   Codes: MC2-ERANOS and VIM
   Basic libraries: JEF-2.2, ENDF/B-6 and ENDF/B-5

2. Commissariat à l'Énergie Atomique, CEA (France)
   Participants: J.F. Lebrat, R. Soule
   Codes: ERANOS2.0
   Basic libraries: ERALIB1 (JEF-2.2)

3. Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, CIEMAT (Spain)
   Participants: E. Gonzalez-Romero, D. Villamarín
   Codes: MCNP4c3
   Basic libraries: JEF-2.2

4. Centre National de la Recherche Scientifique, ISN-IN2P3, CNRS (France)
   Participants: A. Billebaud
   Codes: MCNP4c
   Basic libraries: ENDF/B-6

5. Ente Nationale Energia e Ambiente, ENEA (Italy)
   Participants: M. Carta, F. Gabrieli, V. Peluso
   Codes: ECCO-ERANOS
   Basic libraries: JEF-2.2

6. Research Centre Jülich, FZJ (Germany)
   Participants: H. Brockmann
   Codes: MCNP4c3
   Basic libraries: ENDF/B-6

7. Japan Atomic Energy Research Institute, JAERI (Japan)
   Participants: K. Tsujimoto
   Codes: MVP
   Basic libraries: JENDL-3.2

8. KFKI Atomic Energy Research Institute, KFKI (Hungary)
   Participants: P. Vertes
   Codes: TORT Sn
   Basic libraries: JEF-2.2

9. The Nuclear Research & Consultancy Group, NRG (Netherlands)
   Participants: K. Meulekamp, A. Hogenbirk
   Codes: MCNP4c3
   Basic libraries: JEF-2.2

10. The Paul Scherrer Institute, PSI (Switzerland)
    Participants: M. Plaschy
    Codes: MCNP4c and ERANOS1.2
    Basic libraries: JEF-2.2, ENDF/B-6 and ERALIB1 (JEF-2.2)

11. Studie Centrum voor Kernenergie/Centre d'Etude de l'Energie Nucléaire, SCK•CEN (Belgium)
    Participants: N. Messaoudi
    Codes: MCNP4c3
    Basic libraries: JEF-2.2 and ENDF/B-6

12. Royal Institute of Technology, RIT (Sweden)
    Participants: P. Seltborg, W. Gudowski
    Codes: MCNP4c3
    Basic libraries: JEF2.2

13. RRC "Kurchatov Institute", RRCK (Russian Federation)
    Participants: K. Mikityuk
    Codes: LOOP2
    Basic libraries: ENDF/B-6

14. University of Mining and Metallurgy, UMM (Poland)
    Participants: P. Gronek
    Codes: MCNP4c3
    Basic libraries: JEF-2.2

15. Polytechnic University of Madrid, UPM (Spain)
    Participants: P.T. León, J.A. Fernández-Benítez, A. Abánades
    Codes: MCNP4b and 4c2.
    Basic libraries: ENDF/B-6

16. VTT Processes (Finland)
    Participants: J. Leppänen, M. Anttila
    Codes: MCNP4c
    Basic libraries: ENDF/B-6, JEF-2.2, JENDL-3.2

Table 3.1. Combinations of codes and libraries of the different solutions

	JEF-2.2	ERALIB1 JEF-2.2	ENDF/B-6	ENDF/B-5	JENDL-3.2
Deterministic					
MC2-ERANOS	**ANLjefe**		**ANLb6m**	**ANLb5m**	
ERANOS2.0		**CEA**			
ECCO-ERANOS	**ENEA**				
ECCO-ERANOS	**ANLjefm**				
ERANOS-1.2-33g	**PSIejf4** (New ^{239}Pu total)	**PSIeral**			
TORT Sn	**KFKI** (172 & 4 groups)				
LOOP2			**RRCK**		
Monte Carlo					
MCNP4b			**UPM**		
MCNP4c	**PSIjef2** (^{239}Pu partial X-sections)		**CNRS**		
MCNP4c	**PSIjef3** (^{239}Pu total X-sections J)		**PSIb6**		
MCNP4c	**PSIjef4** (^{239}Pu partial X-sections F)		**PSIb6ures** (Unresolved resonances)		
MCNP4c3	**CIEMAT** (^{239}Pu fr. CEA)				
MCNP4c3	**SCKjef** (^{239}Pu fr. CEA)		**SCKendf**		
MCNP4c3	**NRG** (+ ENDFB6.2+ JENDL3.2)		**FZJ** (+ ENDFB5)		
MCNP4c3	**RIT**				
MCNP4c2	**UMM** (+ ENDFB6.2)				
MCNP4c2	**VTT** (4 cases)		**VTT** (2 cases)		**VTTjjdl** (+ 1 case)
VIM			**ANLVIM**		
MVP					**JAERI** +^{197}Au (ENDFB6)

Chapter 4

SPATIAL REACTION RATE DISTRIBUTIONS

Requested results

Horizontal and vertical traverses with thermal and fast detectors were requested. In particular, for the COSMO configuration, reaction rates from detectors based on ^{235}U and ^{237}Np fission and $^{10}B(n,\alpha)$ reactions are available for different positions along horizontal and vertical channels. In the MUSE configurations, the expected results correspond to reaction rates of ^{235}U fission detectors in several positions along horizontal and vertical channels. The simulations cover some additional points not measured in the experiment.

In the case of the critical configuration, for the normalisation of requested results, the reactor power is defined by setting the ^{235}U fission rate to 1 in one of the measured positions close to the centre of the reactor. This normalisation also implies that it is unnecessary to define the mass of the ^{235}U detector. In all cases the detectors are assumed to be very thin, without shelf-shielding, and results are expressed per atom of the active isotope. In the case of the subcritical configuration, the source intensity is also defined by setting the ^{235}U fission rate to 1 in one of the measured positions close to the centre of the reactor. This will also avoid the first order effects of the possible difference in the reactivity obtained in the different solutions. In this case, special care must also be taken to avoid positions with large direct contributions from the source as a normalisation point.

Comparisons of the COSMO simulations

Figures 4.1 to 4.3 show the comparisons of simulation results and experimental data for the horizontal profiles of the ^{235}U and ^{237}Np fission and $^{10}B(n,\alpha)$ reactions rates, respectively. Figure 4.4 shows the corresponding data for the traverse through the vertical channel of the ^{237}Np fission rate. At the bottom of each figure, the relative deviation of the simulation results and the experimental data is presented.

Nearly all of the simulations provide excellent results for detectors inside the fuel region ($42.4 < Y$ (cm) < 137.8 for the horizontal channel and $51.60 < Z$ (cm) < 112.56 for the vertical channel), in agreement with experimental data (COSMO) within 5% for ^{235}U fission detectors, and within 10% for fast neutron ^{237}Np fission and thermal ^{10}B (n,α) detectors. Indeed, most results are within 2.5% and 5%, respectively. The agreement for the reflector is not as good as for the fuel region, with differences ranging from 10% for the ^{235}U fission to 30% for the ^{237}Np and ^{10}B (n,α) detectors. There is no clear correlation with the cross-section library. It can, however, be observed that solutions with high values for ^{237}Np fission rates provide low values for $^{10}B(n,\alpha)$. This observation points to the neutron spectrum as the origin of the discrepancies. It can also be noted that some of the largest discrepancies appear on deterministic calculations with a low number of energy groups.

Comparisons of the MUSE-4 critical configuration simulations

In this case, the simulation results were compared with the existing experimental values. When experimental data were not available, the average of selected solutions was used as a reference for the comparison.

Figures 4.5 and 4.6 show the ^{235}U fission rates as a function of position along two orthogonal horizontal channels (E-W Y = 86.71 cm and N-S X = 82.89 cm) for the MUSE-4 critical configuration. Figures 4.7 and 4.8 show the ^{235}U fission rates as a function of position along two vertical channels, C7 and C9, for the MUSE-4 critical configuration. The C7 channel passes very close to the centre of the reactor core, at 5.3 cm from the tritium target position, and crossing the lead buffer. The C9 channel crosses the fuel core but the closest distance to the tritium target is 33.9 cm, and is also far from the lead buffer.

The experimental values are available for points from 45 to 135 cm in the case of the E-W channel and for all simulated positions in N-S, C7 and C9 channels.

The boundaries between the fuel and the reflector regions are more complex in the case of the MUSE configurations. For the N-S horizontal channel, the fuel range is 31.8 < Y (cm) < 137.8 whereas for the E-W horizontal channel in the critical case the fuel covers 47.7 < X (cm) < 132.5 and in the subcritical core 53.0 < X (cm) < 127.2. The ranges for the vertical channels are 41.44 < Z (cm) < 122.72 for C7 and 51.60 < Z (cm) < 112.56 for C9, respectively.

The results for the reference critical MUSE-4 configuration are very similar to those of COSMO. Excellent agreement is found between the different solutions inside the fuel region. All solutions are included within ±6% of the mean value. In addition, it should be noted that no special effect is observed in the X = 82.89 cm N-S horizontal channel (see Figure 4.6) for the proximity of the lead buffer or the evacuated aluminium tube nor in the crossing of the lead buffer at the C7 vertical channel. Larger dispersions are found in the reflector and shielding areas reaching ±20% in the Y = 86.71 cm E-W horizontal channel (see Figure 4.5), and ±10% in all the other channels.

Comparisons of the MUSE-4 subcritical configuration simulations

The situation is a bit more complex in the simulation of the configuration with external source. The experimental values, when available (E-W and N-S channels), have been normalised to the average simulation result at the centre of the channel considered. The results for this MUSE-4 subcritical configuration are shown in Figures 4.9 and 4.10 for the two orthogonal horizontal channels (E-W Y = 86.71 cm and N-S X = 82.89 cm) and in Figures 4.11 and 4.12 for the two vertical channels, C7 and C9 (no experimental data available). Note that in this case the normalisation point is the centre of the C9 channel for the simulations. It is also to note that the results from KFKI, RRCK, UMM, PSIejf4 and PSIeral cannot be compared in this section as their results are based on calculations with the hypothetical self-sustained fission source (transport equation eigenvalue). The general pattern for the other solutions is still similar to the critical cases. Most simulations provide excellent results for detectors inside the fuel region, in agreement with the experimental values within 5% (^{235}U fission), and good results in the reflector with differences within 10% (except RRCK and CNRS solutions). Close to the source, however, even for a detector highly sensitive to thermal neutrons (^{235}U fission), the discrepancies in reaction rates are a bit larger, up to 7-10% (except VTTjjdl, which shows a very pronounced source fluence). It is worthwhile to note that there is an overestimation trend present in the N-S channel at the fuel north part, which corresponds to the vacuum tube.

Conclusions

In general, the spatial reaction rate distributions are rather well reproduced by the simulations, with dispersions lower than 5% in the fuel core region. The precision of the simulations becomes worse (typically within ±10%) in two cases: in the reflector or shielding region and in the regions very close to the neutron source. The first point looks to be related to the difficulty in correctly describing the neutron spectra in the reflector, and the second might be related to the high neutron energy (14 MeV) of the D-T source and its transport.

Chapter 5

SPECTRAL INDEXES AND FLUENCE SPECTRA

Requested results

A number of reaction rates of different isotopes are measured with specific fission chambers and activation foils at different positions in the reactor. These data allow the verification in an integral form of the predicted neutron spectra from the different solutions at different positions in the MASURCA configurations.

For the COSMO experiment, the fission reaction rates of ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am and the capture in ^{55}Mn, ^{115}In, ^{197}Au relative to ^{235}U fission were studied in two positions, the centres of the horizontal and vertical channels.

For the MUSE-4 configurations the requested reaction rates were the fission in ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, and the capture in ^{55}Mn, ^{115}In, ^{197}Au relative to ^{235}U fission in the centres of the four (two horizontal and two vertical) channels described for the spatial distributions in the previous chapter.

In addition, to obtain a further understanding of the sources of discrepancies, the neutron fluence spectrum in 172 energy bins was requested, and in the same positions where the spectral index measured, to be normalised in such a way that the integral will be 1. These results were used only for intercomparisons of calculated solutions since no experimental values are available.

Comparisons of the COSMO simulations

Figure 5.1 presents the ratios of the reaction rates of the different isotopes at the centre of the horizontal channel of the COSMO experiment, comparing the experimental and calculated values. Figure 5.2 presents the corresponding results to the centre of the vertical channel, and Figures 5.3 and 5.4 show the same data as a ratio of the simulation solutions to the experimental values. In all of these figures the solutions are ordered according to the principal database used in the simulation. The experimental data is displayed on the left, followed by the ENDF based results, then the JENDL-3.2 results, and the JEF-2.2 based solutions are on the right.

With very few exceptions, the agreement is rather good and some nuclear data dependencies are observed among the provided results; the results seem to be essentially independent of the codes used for calculations. The fact that the two positions are very close implies that no difference is observed between the corresponding data. The main trends are:

- For ^{239}Pu, ^{241}Pu, ^{235}U, ^{197}Au and ^{10}B, all simulations show a good agreement (< 5%) with the experiment. The VTTjjdl deviation on ^{197}Au can be explained by a large statistical uncertainty.

- For ^{55}Mn, the simulations based on ENDF/B-6 and JENDL-3.2 provide good results (< 5%) but those based on JEF-2.2 overestimate the reaction rate between 30-40%.

- For ^{240}Pu, ^{242}Pu, ^{241}Am and ^{243}Am, the simulations based on JEF-2.2 provide good results (< 5%) but the simulations based on ENDF/B-6 overestimate the reaction rate between 5% and 10%. No clear statement can be made about JENDL-3.2, since the two available solutions show different behaviours.

- For ^{238}U, the simulations based on ENDF/B-6 provide good results (< 5%) but those based on JEF-2.2 underestimate the reaction rate up to 5%. No clear statement can be made about JENDL-3.2, since the two simulations show different behaviour.

- For ^{238}Pu, all simulations overestimate the experimental data between 5% and 10%.

- For ^{115}In, the simulations based on ENDF/B-6 and JENDL-3.2 overestimate the reaction rate up to 35% and the simulations based on JEF-2.2 overestimate the reaction rate by 10%.

Comparisons of the MUSE-4 critical configuration simulations

The ratios of the reaction rates for the different isotopes at the centre of the E-W and N-S horizontal channels and the C7 and C9 vertical channels of the MUSE-4 critical reference configuration are presented respectively in Figures 5.5 to 5.8, with comparisons of the results of the different simulations. Figures 5.9 to 5.12 show the comparisons as ratios of each calculated solution to a) the experimental value, or b) to the average value of a group of selected solutions when no experimental data is available. As in the COSMO case, in all these figures the solutions are ordered according to the principal database used in the simulation, starting on the left with the ENDF/B based results, followed by JENDL-3.2 results, and the JEF-2.2 based solutions on the right. The first three positions are very close, although the point in channel C7 is in the lead buffer. The fourth point, however, is slightly more distant from the centre resulting in a flux level of only 80% of that of the others, and a slightly harder spectrum (comparison of the ^{238}U and ^{241}Am fission rates). Apart from these differences, the comparison between different solutions presents the same pattern as in the COSMO case. The experimental data are affected by uncertainties ranging from 5% to more than 10%, sometimes larger than the difference between simulations. Most of the time the simulations are compatible with the experiment within errors, though some significant unexplained differences are observed on four C7 channel measurements, where data is about 10% larger than the simulations as compared with the COSMO and the other MUSE-4 critical positions.

Comparisons of the MUSE-4 subcritical configuration simulations

The results for the MUSE-4 critical reference configuration are presented in Figures 5.13 to 5.16, as ratios of the reaction rates of the different isotopes at the centre of the E-W and N-S horizontal channels and the C7 and C9 vertical channels. As already observed in the spatial distributions, the use of an external source introduces variations between close positions for the same solution and between solutions for the same position ranging between 10% and 30%, making the comparisons more difficult than in the critical cases. In addition, different participants have used different normalisation criterion. To avoid the effect of the flux level estimation each solution is normalised to the ^{235}U fission rate in the same position and from the same solution. The corrected results are shown in Figures 5.17 to 5.20. It can be observed that the comparison results once again partially display the tendencies observed in the critical cases. Figures 5.21 to 5.24 show these locally normalised data as a ratio of each simulation solution to the average of a group of selected solutions except in the cases of ^{238}U (N-S channel) and ^{239}Pu (E-W and N-S channels), for which experimental data are available. Note that in these graphs the order of the solutions has been changed, displacing to the right the results of solutions based on eigenvalue calculations.

Before any comparison, it should be noted that the results from KFKI, RRCK, UMM, PSIejf4 and PSIeral cannot be completely compared as their results are based on calculations with the hypothetical self-sustained fission source (transport equation eigenvalue), and the contributions from direct source and its multiplication by (n,xn) reactions are not included in the reaction rates. This effect is the largest in the centre of the C7 vertical channel, very close to the ^{3}H target, a little bit smaller in the centres of the two horizontal channels and significantly smaller in the centre of the C9 vertical channel at 33.9 cm from the ^{3}H target.

For ^{239}Pu and ^{241}Pu, with fission cross-sections (σ_f) which are rather similar to that of ^{235}U, most of the solutions agree within 2% and all results show an agreement better than 5% in the four positions. Compared with the experimental data, simulations agree better than 5% at the N-S channel but overestimate by 15% in the ^{239}Pu/^{235}U fission spectral index at the E-W channel.

For the fissions in ^{238}Pu, all solutions agree within 10% without observable dependency on the nuclear data library for the two horizontal channels and for C9. On the centre of C7, close to the source, the solutions with source calculation still agree within 10%, but the eigenvalue solutions systematically underestimate the fission rate between 10% and 20%.

For both ^{240}Pu and ^{242}Pu, with the thresholds in σ_f rather sensitive to fast fission, but non-negligible σ_f below threshold, the fluctuations between solutions with the same basic libraries are too large in the three positions close to the source, keeping in mind that a difference of 10% was observed in the critical cases. On the other hand, in the C7 channel, the eigenvalue calculations underestimate the fission rate by 35-40%. It should be noted that the spectral index deviations for each solution in these two isotopes are very similar, indicating that these deviations cannot be explained by large statistical uncertainties on the simulation. In the results for the C9 channel centre, the deviations are negligible and the coherence between solutions with the same basic library is shown, providing a difference of 7% in the predicted values based on ENDF/B and JEF-2.2.

For ^{241}Am and ^{243}Am, with a mixture of fast (> 400 keV) and epithermal (< 100 eV) fission, even larger fluctuations (20-25%) are observed for solutions based on the same basic data library, but with very similar results for the two isotopes and also similar to the ^{240}Pu and ^{242}Pu results. Near the source, C7 channel, it can be observed on the one hand that the eigenvalue calculations underestimate the spectral index by 40%, and on the other hand a 10% overestimation of the spectral index evaluations based on ENDF/B over JEF-2.2 solutions. As for the even Pu isotopes, the results for the C9 channel centre, these effects are negligible and the coherence between solutions with the same basic library is recovered, allowing to observe the 5-10% difference on the prediction based on ENDF/B and JEF-2.2 already observed in the critical cases.

For ^{238}U with thresholds in the σ_f around 1 MeV and mainly sensitive to fast fission (and negligible σ_f below threshold), the analysis is very similar to the previous four isotopes: large fluctuations (> 40%) are found in the centre of the horizontal channels, 60% underestimation of the fission rate for eigenvalue calculations and 5-10% difference between ENDF/B and JEF-2.2 based solutions in the centre of the C7 channel, and the recovery of the coherence at the C9 channel centre with negligible difference between ENDF/B and JEF-2.2 based solutions for the ^{238}U fission. Compared with the experimental point available, a group of simulations based on JEF-2.2 databases shows an agreement better than 10%.

The interpretation of the last three groups of isotopes can be related to a different contribution from the fast neutrons, in particular those reaching to the detector directly from the source, with a possible (n,xn) multiplication. This fact explains discrepancies due to the fast neutron transport between different codes and libraries.

For ^{197}Au, with a capture cross-section (σ_c) strongly dominated by a resonance close to 5 eV and a non-negligible σ_c between 100 and 1 000 eV, the results do not show any clear tendency on the basis of source-eigenvalue or data libraries, but do present nearly 30% fluctuations between solutions. With very few exceptions, the fluctuations cannot be explained as statistical fluctuations of the simulations because there is a good agreement between the simulations of the two horizontal channels.

For ^{115}In, with a σ_c strongly dominated by a resonance close to 1.5 eV, there are large fluctuations between results obtained with the same data libraries, but it is still possible to observe the 30% overestimation of the simulations based on ENDF/B with respect to those from JEF-2.2. In addition, in the closest position to the sample, C7 channel, the eigenvalue simulations tend to overestimate the spectral index by 10%.

Finally, for ^{55}Mn, with a 1/v σ_c and large resonances between 0.1 and 10 keV, as in the ^{115}In case, large differences (typically 25%) are shown between the simulations based on ENDF/B and JEF-2.2.

Comparisons of the neutron fluence spectra

Figures 5.25 and 5.26 show the normalised neutron fluence energy spectra in 172 groups at the centre of the horizontal and vertical channels of the COSMO experiment. The spectra are normalised to make the sum of all channels equal to 1. Figures 5.27 to 5.30 present the normalised neutron fluence spectra at the centre of the two horizontal and the two vertical channels of the MUSE reference critical configuration. The corresponding spectra for the MUSE reference subcritical configuration are presented in Figures 5.31 to 5.34.

Very similar neutron spectra are found by all the solutions at all positions of COSMO, MUSE critical configuration and at the centre of the C9 vertical channel of the subcritical MUSE configuration (far from the source). However, the spectrum in C9 is harder than in C7 or the horizontal channels for the critical MUSE configuration. The apparent difference of the JAERI results is only the effect of a different binning method interpretation, as can be confirmed in Figure 5.26, where CIEMAT used this alternative interpretation of the benchmark specification to evaluate the difference with the JAERI solution. The ENEA solution provided the results with bins incompatible with the comparison figures.

For the closest position of the subcritical MUSE configuration, C7 channel, the source calculations have a dispersion on the direct 14 MeV peak of more than a factor 2. The relative order of the codes (by intensity) gets reversed when the energy decreases from 14 MeV to 1 MeV and remains stable from that point to at least 1 keV. The order at 14 MeV is compatible with the order of the results for the spectral indexes in this position for the fast fissions on ^{238}U, ^{240}Pu, ^{242}Pu, ^{241}Am and ^{243}Am, confirming the hypothesis made in the previous subsection. Note that although the RIT spatial distribution and spectral indexes calculations in the subcritical MUSE configuration were performed in source mode, the spectra were calculated in eigenfunction mode.

In the energy spectra at the C9 channel the 14 MeV peak has essentially disappeared (< 0.4%). At the centre of the N-S horizontal channel of the subcritical MUSE configuration, the amplitude of the 14 MeV direct peak is only 40% of the peak in the C7 channel. At the centre of the E-W channel the peak amplitude is only 30% of the values in the C7 channel. In both cases the order (by intensity in the peak) of the solution is approximately the same but not exactly as in the C7 channel, resulting in an intermediate situation between the C9 and the C7 channels, in agreement with the spectral index results.

Conclusions

Discrepancies between simulations performed with different nuclear databases in the critical configurations are observed, indicating significant differences among the cross-sections of these libraries. For the fission in ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am and the capture in ^{197}Au the discrepancies are smaller than 10%, but for the capture in ^{55}Mn and ^{115}In the differences range between 30-40%.

For the subcritical MUSE configuration, there are two kinds of solutions: source driven and eigenvalue calculations. Close to the source, the two types of calculations present large discrepancies that can be attributed to a different evaluation of the fast and high-energy fraction in the neutron fluence. The effect is most pronounced at the closest point to the source (C7 channel), inside the lead buffer. In addition, the solutions with source and with the same basic library show significant discrepancies that are consistent when different isotopes and different positions are compared and cannot be justified by statistical or computation uncertainties. For the time being these differences are attributed to differences in the transport (including multiplication) of the high-energy (14 MeV) neutrons from the source, and it will be very interesting to compare the different source simulations with additional experimental results. All these effects essentially disappeared at 34 cm from the source (C9 channel), where results very similar to those in the critical case are produced.

The large fluctuations in the subcritical simulations do not allow confirming the smaller differences induced by the choice of nuclear data library, but the large effects for the ^{55}Mn and ^{115}In spectral indexes are still observable.

The uncertainties concerning the experimental results are in most cases too large to allow indicating a preference between simulation solutions. Further, the very limited experimental data collected on the subcritical configurations is not sufficient to indicate the source of the differences between simulation solutions.

Chapter 6

K_{eff} AND GLOBAL PARAMETERS

Requested results

A small number of global parameters are requested for each configuration. These parameters should allow testing the code and nuclear data effects on the reactivity, kinetics and neutron multiplication and should also allow explaining some of the differences observed in the local parameters.

The neutron multiplication constant K_{eff}, obtained as the eigenvalue of the time-independent transport equation, is requested for every configuration. In addition the kinetic parameters *l* (mean neutron lifetime birth to birth) and β_{eff} are requested for both the critical and subcritical configurations of MUSE. Finally, for the subcritical configuration, the difference between the eigenvalue and the source (D-T at centre) neutron multiplication constants, K_{eff} and K_{source}, and the total power for a fixed source intensity are also requested.

Results and discussions

Many solutions (up to 34) are provided for K_{eff} for the critical configurations, a few less (30) for the K_{eff} of the subcritical configuration, and still fewer (28) for the K_{source}. These solutions include some variants allowing to check sensitivity to methods or nuclear data. The results are presented in Table 6.1 grouped by nuclear data library and in Table 6.2 grouped by simulation method. Globally the absolute value of K_{eff} can be simulated with an uncertainty of approximately 600 pcm, with a dispersion between solutions of approximately 2 000 pcm (2%). On the other hand, the change between two configurations can be better estimated, typically within 250 pcm. In this global comparison the difference between K_{source} and K_{eff} also has a large uncertainty (-1 400 ± 1 300 pcm). Comparing different data libraries, there is a tendency to produce higher K_{eff} values with ENDF/B-6 than with JENDL-3.2 or JEF-2.2. The difference between ENDF/B-6 and JEF-2.2 may be estimated as 500-600 pcm, but the exceptions make it very difficult to reach clearer conclusions.

Not all solutions, however, are equally representative. For a more significant analysis, we selected a group of the most realistic results for each code-library combination. In this selection, a clear and simple library (not necessarily the best) selection, and complete, well-described simulation methods were requested. In addition, cases showing large deviations from the mean value were discarded. The resulting selection is shown in Table 6.3, and the average values and variation range for the solutions in this selection are shown in Table 6.4.

For the COSMO configuration, Tables 6.1 and 6.2 show the average difference between the experimental value and the average simulation result of each code-library combination. A small difference of 67 pcm is observed between MCNP (stochastic) and ERANOS (deterministic) simulations, much smaller than the variation range of the measurements within each of these groups. On the other hand, a clear difference of about 600 pcm is observed between the solutions based on ENDF/B-6 and

Table 6.1. Results for K_{eff} and K_{source} of the different solutions, grouped by nuclear data library

1. Criticality constant			Cosmo			MUSE critical ref.			MUSE subcritical ref.				
Laboratory	Code	Library	Value	Diff pcm	Err pcm	Value	Diff pcm	Err pcm	DKeff	Diff pcm	Err pcm	Keff-Ksrc	KSubc
Experimental value			0,99870			0,99920			-0,03000				0,97000
ANLb5m	MC2-Eranos	ENDFB5	1,00216	346	0	1,00026	106	0	-0,0323	-230	0	-1853	0,96796
ANLb6m	MC2-Eranos	ENDFB6	1,00921	1051	0	1,00817	897	0	-0,03253	-253	0	-1450	0,97564
RRCK	LOOP2	ENDFB6	0,99770	-100	0	0,99393	-527	0	-0,03276	-276	0	-858	0,96117
ANLVIM	VIM	ENDFB6				1,00477	557	41					
UPM	MCNP4b	ENDFB601	1,00166	296	27	1,00064	144	17	-0,03200	-200	52	-567	0,96864
CNRS	MCNP4c	ENDFB6.0	1,00819	949	25	1,00691	771	24	-0,03250	-250	48	-1323	0,97441
SCKendf	MCNP4c3	ENDFB6	1,00718	848	11	1,00687	767	7	-0,03231	-231	7	-1353	0,97456
PSIb6	MCNP4c	ENDFB6	1,00836	966	18	1,00731	811	18	-0,03274	-274	35	-1357	0,97457
PSIb6ures	MCNP4c	ENDFB6+Unr. Res	1,00934	1064	18	1,00815	895	18	-0,03288	-288	36	-1330	0,97527
FZJ	MCNP4c3	ENDFB6+B5+				1,00760	840	7	-0,03224	-224	14	-1343	0,97536
VTTjjdl	MCNP4c	JENDL3.2+ENDFB6	1,00612	742	19	1,00428	508	18	-0,03102	-102	25	-738	0,97326
JAERI	MVP	JENDL3.2+197Au(EN	1,00351	481	642	1,00411	491	592					
CEA	ERANOS2.0	ERALIB1 JEF2.2	0,99892	22	0	0,99828	-92	0	-0,03678	-678	0	-1835	0,96150
ENEA	ECCO-Eranos	JEF2.2	0,99914	44	0	1,00026	106	0	-0,03234	-234	0	-1651	0,96792
ANLjefe	ECCO-Eranos	JEF2.2	1,00190	320	0	1,00071	151	0	-0,032084	-208	0	-1865	0,96863
ANLjefm	MC2-Eranos	JEF2.2	1,00478	608	0	1,00360	440	0	-0,03172	-172	0	-1596	0,97188
PSIeral	ERANOS-1.2-33	ERALIB1	1,00340	470	0	1,00389	469	0	-0,03220	-220	0	0	0,00000
PSIejf4	ERANOS-1.2-33	JEF2.2+NewPu9tot	1,00273	403	0	1,00312	392	0	-0,03166	-166	0	0	0,00000
KFKI	TORT Sn	JEF2.2 (172gr)	1,01168	1298	0	1,01634	1714	0	-0,03282	-282	0	-1130	0,98352
KFKI (4gr)	TORT Sn	JEF2.2	1,03444	3574	4								
CIEMAT	MCNP4c3	JEF2.2+Pu9CEA	1,00270	400	21	1,00058	138	7	-0,03132	-132	13	-1534	0,96926
NRG	MCNP4c3	JEF2.2/(B6.2+J3.2)	1,00069	199	5	0,99816	-104	5	-0,03145	-145	6	-1657	0,96671
RIT	MCNP4c3	JEF2.2	1,00453	583	32	1,00481	561	40	-0,03161	-161	47	-1404	0,97320
SCKjef	MCNP4c3	JEF2.2+Pu9CEA	1,00792	922	12	0,00000	0	0	-0,0314	-140	8	-1595	-0,03140
UMM	MCNP4c2	JEF2.2/ENDFB6.2	1,00701	831	23	1,00651	731	89	-0,03346	-346	128	-1116	0,97305
PSIjef2	MCNP4c	JEF2.2+Pu9parXs	1,00624	754	18	1,00498	578	18	-0,03141	-141	36	-1396	0,97357
PSIjef3	MCNP4c	JEF2.2+Pu9totXsJ	1,00881	1011	18	1,00780	860	18	-0,03166	-166	36	-1285	0,97614
PSIjef4	MCNP4c	JEF2.2+Pu9totXsF	1,00201	331	18	1,00029	109	18	-0,03143	-143	36	-1721	0,96886
Average Calculation			1,00464	594	pcm	1,00394			-0,03208	pcm		-1389	pcm
Max -Min				1398	pcm		2241	pcm	244	pcm		1298	pcm
Average absolute difference				601	pcm		486	pcm					

Table 6.2. Results for K_{eff} and K_{source} of the different solutions, grouped by simulation method

1. Criticality constant			Cosmo			MUSE critical ref.			MUSE subcritical ref.				
Laboratory	Code	Library	Value	Diff pcm	Err pcm	Value	Diff pcm	Err pcm	DKeff	Diff pcm	Err pcm	Keff-Ksrc	KSubc
Experimental value			0,99870			0,99920			-0,03000				0,97000
ANLb5m	MC2-Eranos	ENDFB5	1,00216	346	0	1,00026	106	0	-0,0323	-230	0	-1853	0,96796
ANLb6m	MC2-Eranos	ENDFB6	1,00921	1051	0	1,00817	897	0	-0,03253	-253	0	-1450	0,97564
ANLjefm	MC2-Eranos	JEF2.2	1,00478	608	0	1,00360	440	0	-0,03172	-172	0	-1596	0,97188
ANLjefe	ECCO-Eranos	JEF2.2	1,00190	320	0	1,00071	151	0	-0,032084	-208	0	-1865	0,96863
ENEA	ECCO-Eranos	JEF2.2	0,99914	44	0	1,00026	106	0	-0,03234	-234	0	-1651	0,96792
CEA	ERANOS2.0	ERALIB1 JEF2.2	0,99892	22	0	0,99828	-92	0	-0,03678	-678	0	-1835	0,96150
PSIeral	ERANOS-1.2-33	ERALIB1	1,00340	470	0	1,00389	469	0	-0,0322	-220	0	0	0,00000
PSIejf4	ERANOS-1.2-33	JEF2.2+NewPu9tot	1,00273	403	0	1,00312	392	0	-0,03166	-166	0	0	0,00000
KFKI	TORT Sn	JEF2.2 (172gr)	1,01168	1298	0	1,01634	1714	0	-0,03282	-282	0	-1130	0,98352
KFKI (4gr)	TORT Sn	JEF2.2	1,03444	3574	4								
RRCK	LOOP2	ENDFB6	0,99770	-100	0	0,99393	-527	0	-0,03276	-276	0	-858	0,96117
UPM	MCNP4b	ENDFB601	1,00166	296	27	1,00064	144	17	-0,032	-200	52	-567	0,96864
CNRS	MCNP4c	ENDFB6.0	1,00819	949	25	1,00691	771	24	-0,0325	-250	48	-1323	0,97441
SCKendf	MCNP4c3	ENDFB6	1,00718	848	11	1,00687	767	7	-0,03231	-231	7	-1353	0,97456
PSIb6	MCNP4c	ENDFB6	1,00836	966	18	1,00731	811	18	-0,03274	-274	35	-1357	0,97457
PSIb6ures	MCNP4c	ENDFB6+Unr. Res	1,00934	1064	18	1,00815	895	18	-0,03288	-288	36	-1330	0,97527
FZJ	MCNP4c3	ENDFB6+B5+				1,00760	840	7	-0,03224	-224	14	-1343	0,97536
VTTjjdl	MCNP4c	JENDL3.2+ENDFB6	1,00612	742	19	1,00428	508	18	-0,03102	-102	25	-738	0,97326
PSIjef2	MCNP4c	JEF2.2+Pu9parXs	1,00624	754	18	1,00498	578	18	-0,03141	-141	36	-1396	0,97357
PSIjef3	MCNP4c	JEF2.2+Pu9totXsJ	1,00881	1011	18	1,00780	860	18	-0,03166	-166	36	-1285	0,97614
PSIjef4	MCNP4c	JEF2.2+Pu9totXsF	1,00201	331	18	1,00029	109	18	-0,03143	-143	36	-1721	0,96886
CIEMAT	MCNP4c3	JEF2.2+Pu9CEA	1,00270	400	21	1,00058	138	7	-0,03132	-132	13	-1534	0,96926
NRG	MCNP4c3	JEF2.2/(B6.2+J3.2)	1,00069	199	5	0,99816	-104	5	-0,03145	-145	6	-1657	0,96671
RIT	MCNP4c3	JEF2.2	1,00453	583	32	1,00481	561	40	-0,03161	-161	47	-1404	0,97320
SCKjef	MCNP4c3	JEF2.2+Pu9CEA	1,00792	922	12	0,00000	0	0	-0,0314	-140	8	-1595	-0,03140
UMM	MCNP4c2	JEF2.2/ENDFB6.2	1,00701	831	23	1,00651	731	89	-0,03346	-346	128	-1116	0,97305
ANLVIM	VIM	ENDFB6				1,00477	557	41					
JAERI	MVP	JENDL3.2+197Au(EN	1,00351	481	642	1,00411	491	592					
Average Calculation			1,00464	594	pcm	1,00394			-0,03208	pcm		-1389	pcm
Max -Min				1398	pcm		2241	pcm	244	pcm		1298	pcm
Average absolute difference				601	pcm		486	pcm					

Table 6.3. Selection of solutions for the detailed criticality constant simulation analysis

	COSMO K_{eff}	MUSE critical	MUSE subritical	MUSE K_{source}-K_{eff}
MCNP4C ENDF/B6	CNRS, SCKendf PSIb6, PSIb6ures	CNRS, SCKendf, PSIb6, PSIb6ures	CNRS, SCKendf, PSIb6, PSIb6ures	CNRS, SCKendf, PSIb6, PSIb6ures
MCNP4C JEF-2.2	PSIjef4, CIEMAT, NRG, RIT	PSIjef4, CIEMAT, NRG, RIT	PSIjef4, CIEMAT, NRG, RIT	PSIjef4, CIEMAT, NRG
ERANOS JEF-2.2	ANLjefm, ANLjefe, ENEA, CEA, PSIeral, PSIejf4	ANLjefm, ANLjefe, ENEA, CEA, PSIeral, PSIejf4	ANLjefm, ANLjefe, ENEA, PSIeral, PSIejf4	ANLjefm, ANLjefe

Table 6.4. Average and variation of the results from the selection for the detailed criticality analysis

Units = pcm	COSMO K_{eff} sim-exp		MUSE critical K_{eff} sim-nominal		MUSE subritical-critical		MUSE K_{source}-K_{eff}	
	Max-min	Average	Max-min	Average	Max-min	Average	Max-min	Average
MCNP4C ENDF/B6	216	957	128	811	57	3 261	34	1 341
MCNP4C JEF-2.2	384	378	665	176	29	3 145	317	1 579
ERANOS JEF-2.2	586	311	561	244	68	3 200	269	1 730

JEF-2.2. Both solutions seem to overestimate the reactivity. The same difference of about 600 pcm between these two libraries is observed in the MUSE critical K_{eff} calculations, despite the lead buffer and the evacuated accelerator pipe penetration. In this case the table presents the averages and scatter within each group of the simulated K_{eff} minus the nominal value.

Two neutron multiplication constants are requested for the subcritical MUSE configuration: the eigenvalue solution, K_{eff}, and the K_{source} for the D-T source placed on the centre of the reactor. Tables 6.1 and 6.2 show that the change in K_{eff} from the critical to the subcritical MUSE configurations is evaluated with a much better agreement than the absolute K_{eff} values. For a code/library combination, the dispersion is reduced to less than 70 pcm, and the difference between ENDF/B-6 and JEF-2.2 is less than 100 pcm over a predicted change of 3 200 pcm. The evaluation of the neutron multiplication in the source-driven subcritical configuration shows larger variations within a group, a small difference between MCNP and ERANOS calculations of 150 pcm, and a difference of 300 pcm between the ENDF/B-6 and JEF-2.2 based simulations. These last effects might be partially related to the different treatment of the neutron transport and multiplication in the lead buffer.

These results confirm that there are some small systematic effects on the absolute K_{eff} estimation due to the data and the methodology, but these effects are systematic and compensate in evaluations of the reactivity change between two close configurations.

Table 6.5 presents the results for the mean neutron fission lifetime (birth to birth), *l*, the β_{eff} for the critical and subcritical MUSE configurations and the time-averaged power produced in the MUSE subcritical core for an average pulse intensity of 10^7 neutrons per pulse and a frequency of 1 KHz. Misunderstandings concerning the definition of the *l* parameter, have limited the number of solutions compatible with the definition (five). All the solutions agree within 20%, with slightly smaller values

Table 6.5. Results for the mean neutron fission lifetime, *l*, the β_{eff} and the power for a given source

2. Kinetic parameters + Power			MUSE critical ref.				MUSE subcritical ref.					
Laboratory	Code	Library	ℓ	Error	β_{eff}	Err pcm	ℓ	Error	β_{eff}	Err pcm	P (W)	Err
Experiment			5,87E-07	1,08E-08	334,0	4,0						
ANLb5m	MC2-Eranos	ENDFB5	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	7,15	0,00
ANLb6m	MC2-Eranos	ENDFB6	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	9,61	0,00
RRCK	LOOP2	ENDFB6	5,15E-07	0,00E+00	330,0	0,0	5,54E-07	0,00E+00	324,0	0,0	23,50	0,00
ANLVIM	VIM	ENDFB6	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	0	0
UPM	MCNP4b	ENDFB601	2,77E-06	< 0,00001	0,0	0,0	2,97E-06	1,30E-09	288,0	0,0	6,97	0,18
CNRS	MCNP4c	ENDFB6.0	7,50E-06	6,77E-08	350,0	30,0	7,64E-06	6,52E-08	357,0	0,0	7,51	0,07
SCKendf	MCNP4c3	ENDFB6	5,95E-07	0,00E+00	355,8	0,0	6,08E-07	0	320,2	7,0	8,42	0,56
PSIb6	MCNP4c	ENDFB6	3,24E-06	3,18E-09	365,0	54,0	3,47E-06	2,63E-09	345,0	44,0	8,37	0,17
PSIb6ures	MCNP4c	ENDFB6+Unr. Res	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	8,69	0,17
FZJ	MCNP4c3	ENDFB6+B5+	3,59E-06	0,0	347,5	3,50E+01	0	0	349,0	35,0	7,59	0,08
VTTjjdl	MCNP4c	JENDL3.2+ENDFB6	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	0,00	0,00
JAERI	MVP	JENDL3.2+197Au(E	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	0	0
CEA	ERANOS2.0	ERALIB1 JEF2.2	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	0	0
ENEA	ECCO-Eranos	JEF2.2	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	0	0
ANLjefe	ECCO-Eranos	JEF2.2	4,99E-07	0,00E+00	366,5	0,0	5,19E-07	0,00E+00	372,6	0,0	7,68	0,00
ANLjefm	MC2-Eranos	JEF2.2	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	8,27	0,00
PSIeral	ERANOS-1.2-3:	ERALIB1	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	7,78	0,00
PSIejf4	ERANOS-1.2-3:	JEF2.2+NewPu9tot	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	7,71	0,00
Kfki	TORT Sn	JEF2.2 (172gr)	2,50E-07	0,00E+00	225,0	0,0	2,48E-07	0,00E+00	224,0	0,0	4,20	0,00
KFKI (4gr)	TORT Sn	JEF2.2 (4gr)	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	0	0
CIEMAT	MCNP4c3	JEF2.2+Pu9CEA	5,84E-07	0,00E+00	343,0	3,0	5,98E-07	0,00E+00	0,0	0,0	7,45	0,06
NRG	MCNP4c3	JEF2.2/(B6.2+J3.2)	3,16E-06	5,06E-10	341,8	1,6	3,39E-06	5,17E-10	372,2	0,6	6,55	0,08
RIT	MCNP4c3	JEF2.2	5,86E-07	0,00E+00	348,0	32,0	6,00E-07	0,00E+00	372,0	35,0	7,80	0,08
SCKjef	MCNP4c3	JEF2.2+Pu9CEA	0,00E+00	0,00E+00	0,0	0,0	6,01E-07	0	0	0	6,95	0,52
UMM	MCNP4c2	JEF2.2/ENDFB6.2	3,24E-06	8,05E-09	340,9	131,0	3,51E-06	9,13E-09	269,0	142,0	6,59	0,13
PSIjef2	MCNP4c	JEF2.2+Pu9parXs	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	7,96	0,02
PSIjef3	MCNP4c	JEF2.2+Pu9totXsJ	0,00E+00	0,00E+00	0,0	0,0	0	0	0	0	9,05	0,18
PSIjef4	MCNP4c	JEF2.2+Pu9totXsF	3,23E-06	3,62E-09	291,0	52,0	3,37E-06	2,80E-09	458,0	41,0	7,10	0,14
Average Calculation			2,29E-06		348,9		2,41E-06		347,9		7,76	
Max -Min			7,25E-06		36,5		7,39E-06		189,0		3,06	

for ERANOS than for MCNP both with the JEF-2.2 library, and smaller value for the only ENDF/B-6 simulation, based on LOOP2. In all these cases, higher values are obtained for the mean neutron fission lifetime of the subcritical system, with increments ranging from 3% to 8% with respect to the critical configuration.

The β_{eff} parameter was computed in nearly half of the solutions, however with very different precisions. In general, the uncertainty quoted is between 10-40% and the scatter of results is close to 20% for MUSE critical and 55% for the MUSE subcritical configurations. The large uncertainty does not allow identifying a general tendency for the evolution of β_{eff} with the reactivity. However two MUSE critical solutions quote a much smaller uncertainty for β_{eff}, 1 pcm or about 0.3%. Indeed both solutions, based on MCNP and JEF-2.2 but using different methods to compute β_{eff}, agree within the indicated precision. Only one solution, NRG, provides a high precision estimation of β_{eff} for critical and subcritical configurations. In this solution β_{eff} increases by 9% in the subcritical configuration. The experimental value agrees with these high precision simulations to less than 10 pcm.

Most solutions provide a result for the average power with a pulsed source. Even after discarding the largest and smallest values (very different from the others), the dispersion of results is close to 40% of the mean value. Part of these differences can be attributed to the different source multiplication, but after correction for this effect mainly related to the nuclear data library, a 21% difference is still observed between the largest positive and negative deviation from the mean value (after removing the anomalous points). Two groups are however more coherent between themselves. The four ERANOS calculations of ANL have a maximum-minimum spread of 6% and the PSI MCNP calculations with source have a spread of 1%. The ERANOS simulation predicts 4% lower values than MCNP for the reactivity compensated power (Power*(1 – Ksrc)). These remaining discrepancies show the differences in the central DT source efficiency and in the average mean energy per fission of ERANOS and MCNP, and between different solutions using each code.

Conclusions

Important difficulties were found in the definition and understanding of the requested global parameters. The very different methods used to evaluate the requested parameters further led to very different calculation uncertainties. Both effects introduced severe difficulties for the comparisons and identification of code and nuclear data libraries effects on these global parameters.

The only clear parameter was the neutron multiplication or criticality constant, though even for this parameter large differences are found between different solutions, up to 2% for the K_{eff} value. When a selection of more reliable nuclear data choices and simulation methods is analysed, it is possible to identify a clear difference, close to +600 pcm, on the absolute evaluation of K_{eff} using ENDF/B-6 versus JEF-2.2. However, no or negligible effect is detected between stochastic and deterministic codes with the same data library. Finally, a strong reduction on the difference between the nuclear data libraries is observed when computing the change of reactivity between two configurations (100 pcm on 3 200 pcm).

The total power shows a large discrepancy that can be explained as a combination of the different neutron source multiplication with different data libraries and a small difference in neutron source efficiency for ERANOS versus MCNP calculations (4%).

Chapter 7

TIME EVOLUTION OF THE ENEUTRON FLUX AFTER A SHORT NEUTRON PULSE

Requested results

The decay of the neutron flux, global fission rate and detector specific reaction rates are probably the most characteristic aspects of the subcritical systems. Furthermore, several proposals inspired by the point kinetics model have suggested the time evolution of the detector reaction rates as the method to measure and control the reactivity of subcritical systems, without the need to use the reference for a critical configuration.

In the benchmark, the time evolution of the ^{235}U fission detectors placed in the nine monitoring positions is requested. The detector position is specified and the participants are requested to indicate the approximations used for the detector description.

The experimental neutron source has a width smaller than 1 μs but not completely negligible, which has been modelled for the benchmark as a 1 μs gate. These pulses are repeated in the experiment with different frequencies, but 1 kHz was selected for the benchmark. As the experiment progresses, after each pulse the detectors observe the prompt neutrons of that pulse plus the delayed neutrons of all the preceding pulses. After a few minutes, the population of delayed neutron precursors reaches equilibrium. For this reason, two time evolutions, one corresponding to the first pulse (without accumulated delayed neutrons) and the time evolution after the equilibrium level has been reached by the delayed neutrons, have been requested. Normally the second one is not directly computed by the simulation, but evaluated as the sum of a calculated delayed neutron constant level (in the ms time scale) plus the response without delayed neutrons.

Simulations for the first pulse

Only 11 solutions, nine based on MCNP with various libraries, and two deterministic (e.g. one based on ERANOS and another on LOOP) were submitted. These simulations are particularly demanding for the Monte Carlo solutions, where large statistics and correspondingly huge computing time are required to reduce the fluctuations. Indeed, all solutions present large statistical uncertainties at long times after the pulse and for detector placed in the reflector. Figures 7.1 to 7.4 display the results for detectors I and F in the fuel core, A in the reflector and G in the shield, respectively. The other detectors present shapes compatible within errors with the results plotted for the detector in the same region (core, reflector or shield) of the reactor.

The comparisons of the results for the detectors I and F show that the general behaviour is similar for all the solutions, but that the logarithmic slope is different for each simulation. These differences can mostly be explained by the different reactivity estimated for each simulation.

Table 7.1 shows the expected α values for the different solutions, assuming β_{eff} = 349 pcm and $\Lambda = 7.4 \times 10^{-7}$ s. The results are similar to the values fitted in the range between 50 and 120 μs after

Table 7.1. Analysis of the time evolution simulations for detector positions I and F (core), A (reflector) and G (shield)*

Time evolution analysis				MUSE subcritical ref.								
Laboratory	Code	Library	KSubc	α (s^{-1})	TI - α	TI - Λ	TF - α	TF - Λ	TA - α	TA - Λ	TG - α	TG - Λ
Experimental value			0,97000	46308								
ANLb5m	MC2-Eranos	ENDFB5	0,96796	49244								
ANLb6m	MC2-Eranos	ENDFB6	0,97564	38254								
RRCK	LOOP2	ENDFB6	0,96117	59106	51613	8,5E-07	51609	8,5E-07	43934	1,0E-06	42648	1,0E-06
ANLVIM	VIM	ENDFB6	0,00000									
UPM	MCNP4b	ENDFB601	0,96864	48264	49050	7,3E-07	48695	7,3E-07	41924	8,5E-07	38854	9,2E-07
CNRS	MCNP4c	ENDFB6.0	0,97441	40003	42672	6,9E-07	42825	6,9E-07	37590	7,9E-07	33096	8,9E-07
SCKendf	MCNP4c3	ENDFB6	0,97456									
PSIb6	MCNP4c	ENDFB6	0,97457	39775	37140	7,9E-07	39048	7,5E-07	35838	8,2E-07		
PSIb6ures	MCNP4c	ENDFB6+Unr. Res	0,97527	38780								
FZJ	MCNP4c3	ENDFB6+B5+	0,97536	38652	39686	7,2E-07	39846	7,2E-07	34877	8,2E-07	39657	7,2E-07
VTTjjdl	MCNP4c	JENDL3.2+ENDFB6	0,97326	41641								
JAERI	MVP	JENDL3.2+197Au(EN	0,00000									
CEA	ERANOS2.0	ERALIB1 JEF2.2	0,96150									
ENEA	ECCO-Eranos	JEF2.2	0,96792	49302								
ANLjefe	ECCO-Eranos	JEF2.2	0,96863	48284	49288	7,2E-07	49289	7,2E-07	45265	7,9E-07	45066	7,9E-07
ANLjefm	MC2-Eranos	JEF2.2	0,97188	43613								
PSIeral	ERANOS-1.2-33	ERALIB1	0,00000									
PSIejf4	ERANOS-1.2-33	JEF2.2+NewPu9tot	0,00000									
KFKI	TORT Sn	JEF2.2 (172gr)	0,98352	27157								
KFKI (4gr)	TORT Sn	JEF2.2	0,00000									
CIEMAT	MCNP4c3	JEF2.2+Pu9CEA	0,96926	47372	47721	7,3E-07	45983	7,6E-07	41072	8,5E-07	33998	1,0E-06
NRG	MCNP4c3	JEF2.2/(B6.2+J3.2)	0,96671	51049	50226	7,5E-07	51074	7,4E-07	52948	7,1E-07		
RIT	MCNP4c3	JEF2.2	0,97320	41727	42859	7,2E-07	43865	7,0E-07	38373	8,0E-07	36138	8,5E-07
SCKjef	MCNP4c3	JEF2.2+Pu9CEA	-0,03140									
UMM	MCNP4c2	JEF2.2/ENDFB6.2	0,97305	41941	43850	7,1E-07	46041	6,7E-07	54777	5,7E-07	55695	5,6E-07
PSIjef2	MCNP4c	JEF2.2+Pu9parXs	0,97357	41199								
PSIjef3	MCNP4c	JEF2.2+Pu9totXsJ	0,97614	37545								
PSIjef4	MCNP4c	JEF2.2+Pu9totXsF	0,96886	47947	47833	7,4E-07	45771	7,8E-07	36011	9,9E-07		
			βeff	**0,00334**								
			Λ (s)	**7,40E-07**	Fit on times from 50 to 120 μs							

the pulse for the I and F detectors, shown in the same table. Conversely the value for the neutron generation time, Λ, obtained from the fitted α values and a β_{eff} = 334 pcm show a maximum-minimum spread of less than 15%, including the nine MCNP and the ERANOS simulations. The LOOP simulation gives a slightly higher Λ value, while the ERANOS simulation shows higher counting rate values than all the other simulations for longer time periods (> 175 μs).

The statistical fluctuations in the simulations of detectors A and G are too large to allow the interpretation of the fitted α and Λ values.

The difference in the reactivity of the experimental and simulated configurations makes a direct comparison impossible; thus, a high statistic simulation of the actual experimental configuration was undertaken using the same code, libraries and approximations as for the CIEMAT solution for the benchmark configuration. Figures 7.5 and 7.6 show the comparison between the experiment and the simulation of the time evolution of the ^{235}U fission rate in a detector in the core and in the shield, respectively, after the first DT pulse in the subcritical MUSE configuration. The simulated fission rate was normalised to the experimental values at t = 0. An excellent agreement is found for the detector in the core. The simulation, however, underestimates the experimental response in the shield detector for long time periods (t > 70 μs). After several simulations [13], a better agreement was found for the shield detector by reducing 20% of the Fe capture cross-section from 0 to 1 eV (see Figure 7.7).

* T*d*-α shows the fitted α, logarithmic slope for the range from 50 to 120 μs, for detector *d* in s^{-1}. T*d*-Λ the value, in s, of the equivalent mean neutron generation time computed from that α, the K_{eff} from the same simulation and a value of β_{eff} = 334 ppm. The α column shows the expected point kinetic value of the logarithmic derivative, from the K_{eff} obtained in the simulation, β_{eff} = 334 pcm and $\Lambda = 7.4 \times 10^{-7}$ s.

Simulations for the equilibrium pulse

Only five solutions were provided for the time evolution at the equilibrium pulse; they are plotted in Figure 7.8.

All four Monte Carlo solutions provide the same general trend, and the NRG and CIEMAT solutions show essentially the same results; FZJ and UMM are also quite close. RRCK's deterministic solution apparently does not include the delayed neutron contribution.

The figure includes two "Experiment" series representing the values of detector F in the actual SC2 configuration ($\rho \cong 8.5\$$) normalised to both the CIEMAT and UMM simulations at t = 50 μs. The agreement is good in both cases despite the different configurations simulated, because the reactivity difference is not that great. The result is closer to the UMM simulation as expected by its reactivity $\rho = 8.3\$$, whereas the CIEMAT/NRG/FZJ simulations, corresponding to $\rho = 9.5\$/10.3\$/7.6\$$, show slightly larger deviations.

Conclusions

A clear correlation is observed between the K_{eff} value and the logarithmic slope of the counting rate decay of the ^{235}U fission detectors located in the fuel core at medium times, 50-120 μs, after the source pulse. A similar decay rate is observed in the reflector and shield in this time interval, although the large uncertainties do not allow drawing clear conclusions. At shorter times the time evolution is very different at different locations.

These correlations between K_{eff} and the logarithmic slope could be used to evaluate the reactivity of the system. The simulation dispersion in the logarithmic slope for a given reactivity (with the present limited statistics) can be estimated close to 15% from the evaluation of the equivalent neutron generation time, Λ, of different simulations. No difference is observed between the MCNP and ERANOS time evolutions until 150 μs, though a slightly equivalent Λ value is predicted by LOOP.

Chapter 8

GENERAL BENCHMARK CONCLUSIONS AND RECOMMENDATIONS

The simulation of fast neutron sources (14 MeV) inside a subcritical reactor introduces greater uncertainties as concerns the reactor behaviour. This is related to a number of factors, including: uncertainties on the nuclear data in the region between 0.5 and 20 MeV, model deficiencies on some codes and lack of experience on the application of the codes to these kinds of problems.

The exercise has been very helpful in identifying the points of the different simulation methodologies that should be improved, and sensitive nuclear data.

MUSE does not provide the answer to all the discrepancies, and additional exercises of comparisons between simulation and data, paying particular attention to the external fast neutron source propagation within the multiplier media and transport of thermal neutrons in large and nearly transparent reflectors, would certainly be of interest.

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