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Final publishable summary report
SEVENTH FRAMEWORK PROGRAMME OF THE EUROPEAN ATOMIC ENERGY COMMUNITY

Nuclear Fission and Radiation Protection

Project acronym: ANDES
Project full title: Accurate Nuclear Data for nuclear Energy Sustainability
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ANDES Executive Summary

The ANDES FP7-EURATOM project has been designed to address the nuclear data needs associated to the new reactors and new fuel cycles supported by SNETP, in its strategic research agenda and in the ESNII proposal. ANDES has combined a reduced group of selected differential measurements, the improvement in uncertainties and covariance's within the evaluation process and the validation of present and new data libraries using integral experiments, to improve most critical nuclear data to approach the level of accuracies required by the new reactors and system promoted by ESNII and the SNETP. In addition, it has improved the prediction capabilities of high-energy transport codes for the design of ADS, developing better models and performing a few selected measurements. These activities have been coordinated with the main actors of nuclear data dissemination, the NEA/OECD and the IAEA.

In particular a huge amount of work has been performed within ANDES to perform and analyze differential measurements, producing a many new and good data for: inelastic scattering (of $^{238}\text{U}$ and others isotopes), capture of $^{238}\text{U}$ and $^{241}\text{Am}$, and fission of minor actinides. In addition, ANDES has conducted experiments reaching the limits of present techniques or present facilities helping to prepare for the next generation of experiments and identifying paths to skip with present capabilities. Furthermore, ANDES has prompted a reaction with similar measurement efforts in the USA and Asia. All together these campaigns will produce a very significant progress in nuclear data quality in few years.

In the field of uncertainties and covariance, ANDES has provided many innovative methodologies and code developments for: the evaluation of differential measurements; prediction, in a comprehensive way, of data not measured; how to assign uncertainties and covariance to basic data; evaluating the uncertainties in complex simulation results; and for including regularly uncertainties and covariances in the neutronic simulations. In addition, ANDES has contributed to extend all these tools both for reactors and for fuel cycles. De facto, ANDES has prepared for a new paradigm for reliable neutronic simulations.

For the interpretation of integral experiments, ANDES has contributed with the demonstration of different calculation routes and tools to identify present data deficiencies. In particular, the forward calculation routes including sensitivity evaluations and utilization of uncertainties were well evolved and provided first indications of needs for nuclear data corrections ($^{238}\text{U}$ inelastic). It has confirmed the difficulty of integral validation and getting feedback to basic nuclear data. Still, promising developments and test of methodologies to extract implications of integral experiments to nuclear data were made, in the form of precise identification of data probably needing improvements, precise identification of reaction channels and energy regions, and Identification of probably incorrect uncertainty assignments.

Finally the ANDES R&D in the high energy domain (100-600 MeV) has provided very reach and attractive data including Pb+p at GSI, with a new reverse kinematic, with full (A,Z, p) identification of both fragments and additional emissions from fission; the clarification of the total fission cross section puzzle; and very promising for fission yields and characterization of the spallation process. Additional new data was measured at TSL (UU) for high energy reactions on Bi & U, and integral validation data from radiochemistry analysis of irradiated spallation targets of ISOLDE & MEGAPIE was obtained at PSI. In addition, ANDES has prepared significant improvements and extensions on some of the most used high energy models: INCL and ABLA, including extension to lower energies ranges, and emission of clusters. Finally this progress has allowed making the first attempts to estimate uncertainties from the predictions of these high energy models.

ANDES has also made very large efforts to widely and efficiently disseminate its results and to use its intensive R&D activity for education and training of new nuclear scientists and engineers.
Project objectives and structure summary

The ANDES FP7-EURATOM project has been designed to address the nuclear data needs associated to the new reactors and new fuel cycles supported by SNETP, in its strategic research agenda and in the ESNII proposal, taking into account the priority lists for nuclear data from NEA/OECD, FP6-EURATOM projects EUROTRANS-NUDATRA and CANDIDE. The ANDES collaboration includes 20 research centres and universities and started its activities in May 2010.

ANDES combines within three work-packages (WP1-WP3) a reduced group of selected differential measurements, the improvement in uncertainties and covariance's within the evaluation process and the validation of present and new data libraries using integral experiments, to bring most critical nuclear data to the level of accuracies required by the new reactors and system promoted by ESNII and the SNETP. In addition, a specific work package (WP4) will improve the prediction capabilities of high-energy transport codes for the design of ADS, developing better models and performing a few selected measurements. All this activities has been coordinated with the main actors for nuclear data dissemination, the NEA/OECD and the IAEA.

For the measurements of low and medium energies for advanced reactor systems, a combination of the best world facilities has been used in ANDES, including: IRMM neutron sources, both the e- linear and the Van de Graaff accelerators, the n_TOF spallation facility at CERN, the Jyväskylä cyclotron and the IGISOL facility, the CNRS/Orsay accelerators, and the GANIL accelerator complex.
ANDES has concentrated the measurements of low and medium energies in:

1. High accuracy measurements of neutron inelastic scattering cross sections of $^{238}\text{U}$ and isotopes of structural materials and inert fuel matrix.

2. High accuracy measurements of neutron total and capture cross sections of $^{238}\text{U}$ and $^{241}\text{Am}$.

3. High accuracy measurements of fission cross sections several of Pu isotopes, and minor actinides, including the fission yields by surrogate neutrons and inverse kinematics.

4. Decay data measurements for reactor kinetics and decay heat of relevant fission fragments.

To improve and assess the absolute accuracy of the results from computer simulations the ANDES collaboration decided to improve the existing tools for nuclear data evaluation with estimation of the data uncertainties and correlations. A similar effort has been made to prepare simulation programs to use covariance information. Integral experiments provide very relevant information for evaluation and validation of nuclear data. For these purpose ANDES have selected data coming from the following facilities: MUSE, GUINEVERE, PROFIL, ZPPR10A, SNEAK-7A and -7B, and the collection of international criticality benchmarks. Each of these experiment provides specific complementary information. To provide directly useful data for the ESNII ADS demonstration facility, the main objective for ANDES in the high energy range is the model validation and optimization in the 150-600 MeV energy domain.

In parallel with these technical activities, ANDES has been used to improve the knowledge and training of young professionals in nuclear science and technology by promoting PhD work within ANDES and organizing a dedicated training school. Finally, to accelerate the dissemination of the new measured or evaluated nuclear data ANDES has setup a close cooperation with NEA and IAEA, the two agencies coordinating the distribution of nuclear data.

In the following chapters the main scientific and technical results produced in each work-package will be briefly summarized. A final chapter provides a summary of the potential impact of these results and the main dissemination actions.
Measurements for advanced reactor systems was undertaken by the ANDES "initiative. These new measurements include neutron inelastic scattering from $^{23}$Na, Mo, Zr, and $^{238}$U, neutron capture cross sections of $^{238}$U, $^{241}$Am, neutron induced fission cross sections of $^{240}$Pu, $^{242}$Pu, $^{241}$Am, $^{243}$Am and $^{245}$Cm, measurements exploring the limits of the surrogate technique for capture of Cm isotopes, measurements of fission yields of minor actinides by inverse kinematics, and measurements of the total gamma yield and delayed neutron emission probabilities of $^{88}$Br, $^{94}$Rb, $^{95}$Rb, $^{137}$I. The measurements which were performed at state-of-the-art European facilities have the ambition to achieve the lowest possible uncertainty, and to come as close as is reasonably achievable to the target uncertainties established by sensitivity studies.

A summary is presented of the main activities and achievements and an outlook is given.
**Introduction**

Advanced reactor systems are of interest for minimizing high level waste and maximizing utilization of resources while implementing the highest standards of safety and security. Sensitivity studies demonstrate the need for very tight nuclear data uncertainties to enable reliable and accurate estimates of key reactor and fuel cycle parameters. Such needs were prioritized and are advertised by the Nuclear Energy Agency [1] of the Organization for Economic Cooperation and Development. Many of these needs require a combination of accurate measurements and dedicated new nuclear data evaluations to take optimal advantage of this new experimental work. "Measurements for Advanced Reactors Systems" (MARS) is work package 1 (WP1) of the collaborative project "Accurate nuclear data for nuclear energy sustainability" (ANDES) that focusses on experiments for (equivalent) neutron energies less than 20 MeV. MARS took about 1/3 of the ANDES resources. The experiments are grouped in four tasks: inelastic scattering, capture cross sections, fission cross sections and yields and finally decay data for decay heat and reactor kinetics. The main achievements of these tasks and the outlook are described below. Further details may be found in the reports on the individual deliverables and in the references to papers and conference contributions provided here and in the deliverable reports.

The project deliverables were completed and submitted to the project coordinator for registration in the portal. The complete list of deliverables and the editors/authors of the reports are shown in Table 1.1.

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<td>Final report on measurements for non-actinide inelastic scattering cross sections</td>
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Task 1.1 High accuracy measurements of neutron inelastic scattering cross sections

Task 1.1 is responsible for deliverables D1.6, D1.7 and D1.11, which are concerned with the accuracy and covariances of \((n,n'\gamma)\) cross section measurements (D1.6), with new data for the \(^{238}\text{U}(n,n'\gamma)\) cross section (D1.7) and with new data for the \((n,n'\gamma)\) cross sections of \(^{23}\text{Na}\), and the isotopes of Zr and Mo (D1.11).

The measurements for \(^{238}\text{U}\) and \(^{23}\text{Na}\) directly respond to high priority requests on the OECD-NEA High Priority Request List for nuclear data. Measurements for Zr, Mo and also Mg and Si carried out at IRMM also respond to sensitivity studies for advanced reactor systems. In particular, these materials could become important fractions of reactor cores as inert fuel components of minor actinide bearing fuel. In such a scenario inelastic scattering on such elements will become an important process affecting the neutron spectrum. In view of the tight uncertainty requirements and the general call for covariance matrices to be supplied with new experimental data, an important component of the task is the establishment of a method to produce such covariance matrices.

Two independent setups were used for these measurements: GAINS (Gamma Array for Neutron Inelastic Scattering) and GRAPHEME (GeRmanium array for Actinides PrEcises MEasurements). GAINS is a ball of currently 12 large volume HPGe detectors located a 200 m flight path of GELINA. It is optimized for high neutron energy resolution and requires relatively thick samples. GRAPHEME consists of 4 planar HPGe detectors located at a 30 m flight path of GELINA. The higher intensity at 30 m and the better resolution for low energy gamma-rays makes it optimal for studies of deformed nuclides and, in particular, the actinides. Within ANDES, GAINS was employed to determine the neutron inelastic cross sections on Na, Zr and Mo while GRAPHEME was used for the investigation of \(^{238}\text{U}\). The data used for investigating the method of determination of covariances was optimized using data obtained with GAINS for \(^{28}\text{Si}\) and \(^{56}\text{Fe}\).

GAINS and GRAPHEME are shown in Figure 1.1.

![Figure 1.1](image1.jpg) **Figure 1.1.** The GAINS setup (left) consisting of 12 coaxial high purity germanium (HPGe) detectors of 8 cm length and 8 cm diameter and the GRAPHEME setup (right) consisting of 4 planar HPGe detectors.
Covariances for the \((n,n'\gamma)\) cross sections at GAINS (D1.6)

The limitations to the uncertainty of measurements of \((n,n'g)\) cross sections were investigated and documented in two publications and a report. With high resolution measurements statistics is an issue if cross sections are small (<50 mb) or if the neutron flux is low \((E_n>5\) MeV). For the important cross sections (>50 mb and between 100 keV and 5 MeV) statistics is not the main limiting factor, especially since the target uncertainties concern broad energy averages of the cross sections for which many high resolution points are summed together. The main limitations are therefore systematic and concern the detector efficiency calibration, the flux measurement, and for actinides also the target characterisation. In favourable cases which may more or less routinely be achieved for non-actinide samples this allows a lower limit due to systematic effects of 2-3% on the primary measured quantities: the gamma-production cross sections. For \(^{238}\text{U}\) the uncertainty is of the order of 5%.

In the case of the analysis of the GAINS data the data analysis is more or less automated allowing propagation of the input uncertainties (peak areas for gamma-rays, efficiencies, fission chamber counts, etc.) by a Monte Carlo method. The input quantities are randomized around their mean value with a Gaussian random variable with r.m.s. variation equal to the uncertainty of the input value. This procedure avoids approximations and errors in the propagation. It also allows cross correlations to be determined for instance for different gamma-rays and for derived cross sections (total inelastic and level inelastic cross sections). An example is shown in Figure 1.2 (see the deliverable report for details).

![Figure 1.2. Covariance matrix for the 846.8 keV transition in \(^{56}\text{Fe}\) (left) and the correlation matrix for the 2838 and 1779 keV transitions in \(^{28}\text{Si}\) (right).](image)

These investigations and the method development are final. They are documented in two papers, an EUR report, the contribution to the ND2013 conference and the report on the final deliverable.

Neutron inelastic scattering of \(^{238}\text{U}\) (D1.7)

A large number of measurements were made using the GRAPhEME setup with a natural uranium sample from Goodfellow of about 0.2 mm thickness. Covering about 1200 hours of GELINA beam time these
emphasized the investigation of systematic effects. Angle-integrated cross-sections of the \((n,x\gamma)\) process for 42 transitions have been extracted, including three and four transitions respectively for the \((n,2\gamma)\) and \((n,3\gamma)\) reaction channels. The results for six transitions, without internal conversion correction, are presented in Figure 1.3: the four lowest transitions in the main band, 44.9 keV \((2^+\rightarrow 0^+)\) (a), 103.5 keV \((4^+\rightarrow 2^+)\) (b), 159.3 keV \((6^+\rightarrow 4^+)\) (c), 211 keV \((8^+\rightarrow 6^+)\) (d), and two transitions from second-band levels, 635 keV \((1\rightarrow 2^+)\) (e) and 687 keV \((3\rightarrow 2^+)\) (f).

Figure 1.3. Cross-sections of six \((n,n'\gamma)\) reactions on \(^{238}\text{U}\) as a function of incident neutron energy. The data obtained for the ANDES project are marked "IPHC".

The data obtained for the 45 keV transition are remarkably different from the evaluations by P. Romain of CEA Bruyères-le-Châtel and by M. Sin. In the remaining cases the agreement between model calculations and data is better but still indicates that improvements are in order. Experimentally it is expected that a 5% uncertainty is attainable below 9 MeV and about 20% above. The 45 keV transition is a special case owing to a conversion coefficient of about 605. Figure 1.4. illustrates the difficulty of extracting accurate data for this transition.

The final analysis requires an improved characterisation of the target. In particular its state of oxidation is severe and should be investigated further to better determine the mass fraction of uranium. Several routes for a chemical analysis were identified and the first is currently being pursued. A final result should then be available towards the end of 2014. Contacts with evaluators are developed and will be used to improve the evaluated data files (JEFF, CIELO).

It should be emphasized that these data are in high demand as U-238 inelastic scattering have been an important issue affecting reactor spectra and therefore criticality and reaction rate estimates in an important way. In fact, this was reaffirmed in the ANDES project in WP3 where new sensitivity analyses
confirmed the interest in this cross section also in the context of large PWR cores. Evidence for its relevance therefore continues to accumulate.

![Energy spectrum of gamma events](image)

**Figure 1.4.** Energy spectrum of gamma events below 220 keV as seen in one of our HPGe detectors, for a given time window. The analyzed \((n,n'\gamma)\) transitions are indicated.

**Measurements for non-actinide inelastic scattering cross sections (D1.11)**

The measurements with GAINS for \(^{23}\text{Na}, \text{Zr}, \text{Mo}\) were finalised. For \(^{23}\text{Na}\) and \(\text{Zr}\) the data analysis is also completed. The resulting data for \(^{23}\text{Na}\) are published and incorporated in the new version of the JEFF library (JEFF-3.2) which will be released February 2014. The cross section data for \(^{23}\text{Na}\) inelastic scattering meet the target uncertainties on the NEA High Priority Request List for this nuclide. The achieved uncertainties are 2-3\% while the target uncertainties for the sodium cooled fast reactor are 4\%. The primary driver for these uncertainties is the coolant void reactivity coefficient. The evaluation for Na based on the ANDES data is documented in a contribution to the ND2013 conference. It was made at CEA/Cadarache with the CONRAD/TALYS code system by P. Archier, G. Noguere and C. De Saint Jean and co-workers. The fact that this evaluation is adopted for JEFF-3.2 confirms the accuracy of the data and their consistency with reactor benchmarks.

The data for \(\text{Zr}\) and \(\text{Mo}\) are inherently less important than those for \(^{23}\text{Na}\) and \(^{238}\text{U}\). With a fraction of minor actinide bearing fuel pins of at most 20\% there will be considerably more sodium (iron) and uranium in a reactor core than there will be \(\text{Zr}\) or \(\text{Mo}\) (or \(\text{Si}\) and \(\text{Mg}\) for that matter). Therefore the present effort focussed on getting an impression of the status of evaluations by measurements on natural samples. From such a work and further impact studies it may then be decided whether \(\text{Zr}\) and \(\text{Mo}\) warrant further measurements. Given the large number of stable isotopes (\(^{90,92,93,94,96}\text{Zr}\) are stable with abundances 51.5, 11.22, 17.15, 17.38 and 2.80\% and similarly \(^{92,94,95,96,97,98,100}\text{Mo}\) with 14.77, 9.23, 15.90,16.68, 9.56, 24.19, 9.68\%), there are many overlapping gamma-rays allowing a rather limited number of gamma-production cross sections to be obtained reliably. Clearly improvements would require a chain of measurements for 11 of these 12 nuclides using enriched samples, something that is
well beyond the scope of the current project. The limited number of transitions that were determined here, do however point out the need for substantial additional work should it prove that either zirconium or molybdenum are is the material of choice for the inert fuel component in minor actinide fuel. The present work will be finalised in the coming two years and published subsequently. An example of the complications and need for improvement is shown in Figure 1.5.

![Figure 1.5. Gamma-ray spectrum for natural molybdenum inelastic scattering (left) and cross section for the 1510 keV transition of 92Mo (right).](image)

**Task 1.2 High accuracy measurements of neutron total and capture cross sections**

Task 1.2 is responsible for deliverables D1.3, D1.4 and D1.8, which are concerned with the capture cross section measurements for $^{238}$U (D1.8), for $^{241}$Am (D1.3), and for the feasibility study of using the surrogate technique for the determination of capture cross sections for Cm isotopes (D1.4).

The measurements for $^{238}$U and $^{241}$Am directly respond to the high priority requests on the OECD-NEA High priority request list for nuclear data. The surrogate measurements targeting Cm isotopes are of certain interest as is shown by additional sensitivity analyses (NUDATRA project, NEA-SG26) targeting the fuel cycle and minor actinide burner concepts (accelerator driven minor actinide burners). Direct measurements of the Cm capture cross sections were essentially non-existent at the time the project was started.

In view of the importance of the $^{238}$U and $^{241}$Am capture cross sections and the considerable work that was already carried out, it was decided to have several concurrent experiments for the two nuclides. In both cases measurements were performed at GELINA with C6D6 detectors and at the CERN n_TOF facility with both C6D6 detectors and with the BaF2 total absorption calorimeter. Thus, the experience from different experimental approaches could be discussed directly between the participants and for each case three new results could be obtained with considerable independence in terms of neutron source, time-of-flight facility, detectors and data analysis procedures. Of course certain commonalities
could not be avoided and in particular the measurements for $^{238}\text{U}$ shared a sample, while the employed $^{241}\text{Am}$ samples shared the same base material and were characterised for $^{241}\text{Am}$ content by the same method (calorimetry). A common understanding of the effects to be accounted for was of course the aim of having the projects run in parallel, however the implementation of the specific corrections varied by experiment. Combining results from two different detectors and independent measurement principles should result in a reduction of uncertainties due to systematic effects. This approach of having concurrent efforts is a unique feature of the ANDES project. In addition to the capture measurements total cross section measurements were made at IRMM for both $^{241}\text{Am}$ and $^{238}\text{U}$. Such total cross section data provide important complementary information allowing for instance to normalize the $^{241}\text{Am}(n,\gamma)$ data and to verify the resonance parameters proposed for $^{238}\text{U}$. Figure 1.6 shows the setups involved in the $^{241}\text{Am}$ and $^{238}\text{U}$ capture measurements.

![Figure 1.6. The setups which were employed in the ANDES project for radiative neutron capture measurements of $^{238}\text{U}$ and $^{241}\text{Am}$. Left 2 C6D6 detectors at the GELINA 12.5 m station viewing the $^{241}\text{Am}$ sample through a lead shield that blocks the 60 keV gamma from $^{241}\text{Am}$ decay. In the center two C6D6 detectors with beam tube and target ladder at the CERN n_TOF facility. On the right the BaF2 Total Absorption Calorimeter (TAC) at CERN n_TOF in open position.](image)

$^{238}\text{U}$ total and radiative neutron capture measurements at JRC and the radiative neutron capture measurements at n_TOF

The capture cross section in the unresolved resonance region is of special importance advanced (fast) reactors. Despite the importance inconsistencies of up to 15% are found amongst experimental data in the literature. The cross section between 22 eV and 25 keV is requested with an uncertainty between 1% and 2% on the OECD-NEA High Priority Request List for nuclear data. Such an accuracy level is difficult to obtain in a single measurement. As mentioned above, this led to complementary experiments at the GELINA and n_TOF facilities being part of the ANDES project.

Experimental data for the capture cross section of $^{238}\text{U}$ in the resonance region can be obtained by applying the total energy detection or total $\gamma$-ray absorption principle. The first principle is mostly implemented with C6D6 detectors using the pulse height weighting technique. An ideal detector for the total $\gamma$-ray absorption technique has a $4\pi$ geometry and a 100% absolute detection efficiency, like the total absorption spectrometer based on BaF2 detectors installed at n_TOF. Hence, these two principles are very different and have their advantages and disadvantages.
The experimental program consisted of measurements with C6D6 detectors at GELINA and measurements with a similar C6D6 detection system and a total γ-ray absorption detector at n_TOF. In addition, these capture cross section measurements were complemented with transmission measurements at GELINA. The final objective is to provide capture cross section data which can be used for a new evaluation of the capture cross section of $^{238}\text{U}$. The target uncertainty of the experimental data is less than 2% for the correlated component due to systematic effects such as the normalization and less than 2% for the uncorrelated component due to counting statistics. A similar approach has been followed to improve the status of the cross section for $^{241}\text{Am(n,}\gamma\text{)}$ (next section).

The measurements and data analysis at GELINA for the total and capture cross sections were completed and the results are summarized in the deliverable report. The data confirm the resonance parameters determined by Derrien et al. up to 150 eV incident neutron energy. Above this energy adjustments are needed to arrive at 1-2% uncertainty. The normalization uncertainty is 1% from 5 eV to 100 keV. Resonance shape analysis can be carried out up to 800 eV. In the Unresolved resonance range data can be obtained with 2.5% uncertainty between 5 and 100 keV. This is somewhat above the target uncertainty and is due to a sample that was not sufficiently optimized. An additional effort is being scheduled to support a successful finalization of this activity and to support the new CIELO project.

The capture measurements at n_TOF used one of the two targets used at IRMM, but in this case the target was encapsulated in 60 μm kapton. The measurements with both the C6D6 detectors and with the BaF2 TAC were completed and the primary data, the experimental capture yields were extracted. An internal normalization to the saturated 6.673 eV resonance allowed an overall normalization uncertainty better than 1%. Due to the energy dependence of the flux the uncertainty increases to 2% in the range from 1 to 2 keV. A SAMMY calculation comparing the parameters of Derrien et al. with the C6D6 data set confirm the conclusions obtained at IRMM. Furthermore these data sets agree up to 750 eV. Above 250 eV the n_TOF C6D6 data have better resolution allowing to extend the resonance analysis to 3 keV. A combined analysis with the TAC data should allow to reduce the impact of experimental bias on the final results. Figure 1.7 illustrates the results obtained in the resolved resonance region and which will require adjustments to the Derrien evaluation.

![Figure 1.7](image)  
**Figure 1.7.** Three capture yields obtained at GELINA (left), CERN n_TOF with C6D6 detectors (center) and with the BaF2 TAC (right)

The results presented in this report demonstrate the successful completion of subtask 1.2.a and 1.2.c of the ANDES project. The outcome of these subtasks, i.e. deliverable D1.8, provides important
experimental data to improve the capture cross section of $^{238}$U. The data will be submitted to the EXFOR data base and will be used as an input for the CIELO project (Collaborative International Evaluated Library Organization), which has the capture cross section of $^{238}$U in the resonance region as one of its priorities.

**Measurements of the neutron-induced capture and total cross section on $^{241}$Am measured at IRMM and n_TOF**

Accurate knowledge of cross sections for neutron induced reactions of major and minor actinides is essential for the operation of present reactors and the design of new advanced reactor systems. The minor actinide $^{241}$Am, which is mainly produced by the decay of the short-lived $^{241}$Pu, can play an important role in criticality and safety calculations in case of fuels with a high burn-up or with a high americium loading. In addition, $^{241}$Am, with a half-life of 432.2 y, is important for management of nuclear waste because of its large contribution to the radio-toxicity of spent fuel or reprocessed waste.

The present evaluated data libraries are based on a few available datasets showing quite important deviations from each other. New accurate measurements are therefore crucial input for new high quality evaluations. In the frame of this ANDES project a series of measurements was performed at the neutron time-of-flight facilities GELINA of the JRC-IRMM and n_TOF at CERN. The availability of suitable samples, manufactured prior to the ANDES project was an essential prerequisite.

Two measurements were performed at GELINA and two at CERN n_TOF. At GELINA, one measurement concerned capture (12.5 m Flight Path) with C6D6 detectors using the pulse height weighting technique and the other concerned transmission (26.5m Flight Path) used for obtaining accurate resonance parameters for the first three large resonances and allowing a normalization of the capture measurement. At CERN n_TOF one capture measurement was performed with C6D6 detectors using the pulse height weighting technique, while the other used the BaF2 TAC.

All measurements were completed and reaction yields were extracted. In addition, the GELINA measurements were analysed in terms of resonance parameters and the results were published. Furthermore the results were incorporated in a new evaluation of $^{241}$Am for the JEFF-3.2 library (to be released February 2014). In particular, this work passed the reactor benchmark testing that is required for releases of the JEFF library. For the C6D6 measurement from CERN n_TOF the data were analysed as well and a publication is being finalised. All technical details and further references may be obtained from these papers. The extracted yield from the BaF2 data obtained at n_TOF is currently being analysed and final results will be published later.

The results obtained at GELINA are illustrated in Figure 1.8. The transmission factors are described very well by a resonance shape analysis with the REFIT code. It was shown that the special samples used for this work did not suffer of the particle-size effect. The accurately extracted resonance parameters of the three main resonances perfectly describe the capture yields for these resonances allowing a precise normalization of the latter. Also shown is that the capture yields are useful over a much wider energy range. In particular, an accurate (5% uncertainty) thermal cross section and thermal range energy
dependence could be obtained. The cross section is somewhat higher but essentially consistent (2s) with a set of recent thermal cross section determinations. The thermal range energy dependence was shown to be of interest for the interpretation of reactor based measurements of the thermal cross section through a correction to the Westcott g-factor. In the resonance range the resonance strengths are found to be 15% higher than found in the literature before this work. This might well be caused by particle-size effects in these earlier works.

Figure 1.8. The GELINA transmission factors (bottom left) and capture yields (top right) for the three main resonances of $^{241}$Am and the capture yield from 10 meV to 100 eV (left).

The resolved range capture yields and the unresolved range capture cross sections obtained at CERN n_TOF using the C6D6 detectors are shown in Figure 1.9. The data were normalized using a separate run with a gold target by a saturated resonance at 4.9 eV. The normalization was verified to 0.7% by comparison with the thermal cross section of the $^{197}$Au(n,g) reaction. The latter is a neutron standard.

Figure 1.9. Capture yields for the resolved resonance region (left) and the unresolved resonance range cross section (right) obtained from the C6D6 experiment at the CERN n_TOF facility.
A resonance shape analysis with the SAMMY code was made and compared with the present data. In previous analyses the resolved range extended to 150 eV while in this work the range was extended to 320 eV. Thus parameters were obtained for 172 additional resonances, 15 of which with energies below 150 eV. The data and this analysis demonstrate the excellent TOF resolution of the new data. The cross sections in the unresolved range were corrected for multiple scattering effects and fitted using the FITACS code to obtain the average resonance parameters needed to describe the cross section in this energy range.

The data taken with the TAC were completed and reduced to capture yields. Given the large number of channels, the high count rate due to the high efficiency, the need to investigate the proper sum-energy and multiplicity criteria to determine the background carefully this data reduction was completed just prior to the end of the ANDES project. A resonance shape analysis still has to be performed. This resonance shape analysis will need transmission data for the normalization of the capture yield since an internal normalization by saturated resonance was not afforded by the sample used and because the gold response differs too strongly from that of $^{241}$Am. The steps to arrive at final results will be completed in the near future. Figure 1.10 shows some of the capture yields that were obtained along with the unresolved energy region capture cross section.

![Figure 1.10. Examples of capture yields (left and center) and the unresolved range capture cross section (right) obtained with the BaF$_2$ TAC. The data are preliminary.](image)

The feasibility of determining surrogate neutron-capture cross sections for Cm isotopes.

Neutron-induced radiative-capture cross sections of short-lived nuclei are crucial in reactor physics. In particular, these data are important for nuclear-waste transmutation using fast neutrons. However, often the high radioactivity of the samples makes the direct measurement of these cross sections extremely difficult or even impossible. For the important Cm isotopes no reliable neutron-induced capture cross sections were measured up to now. The surrogate method is an indirect way of determining neutron-induced cross sections for compound-nucleus reactions. A transfer reaction is used to populate the same compound nucleus as for the targeted neutron-induced reaction. By detecting the light outgoing particle the excitation energy is fixed. By measuring the ratio of reaction products with and without coincidence on the outgoing particle the probability for the desired exit channel is determined. The technique is well-established for fission cross sections. In particular, with the use of the $(^3$He,d) ($^3$He,t) and $(^3$He,$^4$He) reactions agreement of better than 10% can be obtained for cases with a well-known (n,f) cross section. The $(^3$He,p) reaction may suffer from a spurious proton yield so that only the shape of the reaction probability can be determined, but not its normalization.
For capture reactions the validation of the method is the goal of the ANDES contribution. For the validation well-known neutron-induced capture cross sections were compared with capture cross sections deduced from a surrogate measurement. As reference reactions $^{172,173}$Yb(n,$\gamma$)$^{173,175}$Yb, $^{236}$U(n,$\gamma$)$^{237}$U, $^{238}$U(n,$\gamma$)$^{239}$U and $^{237}$Np(n,$\gamma$)$^{238}$Np were chosen. The associated transfer-reactions were $^{174}$Yb($^3$He,$^4$He$\gamma$)$^{173}$Yb, $^{174}$Yb($^3$He,p$\gamma$)$^{176}$Lu, $^{238}$U($^3$He,$^4$He$\gamma$)$^{237}$U, $^{238}$U(d,p$\gamma$)$^{239}$U and $^{238}$U($^3$He,t$\gamma$)$^{238}$Np. The cases targeting $^{172}$Yb and $^{175}$Lu were studied first as they offer the advantage of stable targets. The data were obtained at IPN Orsay, they were analysed and published. The results illustrated in Figure 1.11 show large differences in the direct and surrogate cross sections for capture. Using model calculations this difference can be understood as being due to a difference in the spin distribution of the populated compound nuclear states. The higher spin states populated by the transfer reaction have suppressed neutron widths and therefore a high probability for emitting gamma-rays. This results in a cross section that is larger than the neutron-induced cross section by a considerable factor.

![Figure 1.11](image-url)  
Figure 1.11. The neutron-induced capture cross sections for $^{172}$Yb and $^{175}$Lu obtained by the surrogate method (this work) in comparison with data and evaluations for the direct method (top row). Preliminary neutron-induced fission (bottom left) and capture (bottom right) cross sections of $^{238}$U measured at three angles with the $^{238}$U(d, p) reaction. Experimental neutron-induced data, a TALYS calculation and several evaluations are also shown for comparison.
Since the spin states populated in a reaction may differ for a heavier target the next test case involved a depleted uranium target (99.5% $^{238}$U). The data were taken at the Oslo Cyclotron Laboratory. The results for the (d,p) reaction are shown for fission and for capture in Figure 1.11. A similar effect is found for capture. The result for fission shows a problem with the normalization of the data. Again this is due to a spurious proton yield that may be due to excess protons from the break-up of deuterium and/or to impurities in the target. An improved normalization would increase the difference between the capture data further, and therefore does not change the main outcome.

The work performed clearly meets the objectives of the ANDES project. Important data were obtained that address the suitability of the surrogate technique for inferring capture cross sections. It was found that the simple Bohr hypothesis cannot be applied as a result of the differences in the population of the compound states and the possible occurrence of other reaction mechanisms. The results do indicate that considerable high quality data can be obtained for low-energy nuclear reactions by transfer reactions. These can still lead to improved knowledge of neutron-induced capture reactions provided these data are used for optimizing the physical parameters describing the reaction and the compound nucleus decay. A close collaboration with theoretical groups is therefore pursued.

**Task 1.3 High accuracy measurements for fission**

Task 1.3 is responsible for deliverables D1.1, D1.5, D1.9 and D1.10, which are concerned with neutron-induced fission cross sections for $^{241}$Am, $^{243}$Am and $^{245}$Cm (D1.1), neutron-induced fission cross-sections for $^{240}$Pu and $^{242}$Pu (D1.5), measurements to infer the $^{238}$Pu(n,f) cross section by the surrogate method (D1.9), and inverse kinematics transfer reactions to determine fission yields for isotopes of neptunium, plutonium and americium (surrogate method).

The measurements for $^{238}$Pu, $^{240}$Pu, $^{242}$Pu, $^{241}$Am, $^{243}$Am and $^{245}$Cm directly respond to the high priority requests on the OECD-NEA High Priority Request List for nuclear data. While the need for improved accuracy Pu fission cross sections emerges from any scenario involving fast reactors, the need for Am and Cm fission cross sections derives more specifically from fuel cycles where minor actinides are recycled or burned. The fission yield measurements for minor actinides are of imminent importance to the safety of the fuel cycle with fast reactors designed for recycling high level actinide waste or to accelerator driven minor actinide burners. So Task 1.3 clearly addresses high priority nuclear data issues in support of minimization of high level waste and nuclear safety.

**The Fission Cross-Section of $^{241}$Am, $^{243}$Am, and $^{245}$Cm from the n_TOF Facility at CERN**

The measurements of the fission cross section of $^{241}$Am, $^{243}$Am and $^{245}$Cm were performed at the neutron time-of-flight facility n_TOF at CERN in the first experimental campaign, together with several other minor actinides of interest for advanced nuclear technologies for energy production and nuclear waste transmutation. The data sets considered here were obtained with the Fast Ionization Chambers (FIC) of CERN which had two $^{235}$U deposits for normalization to the standard fission cross section of this nuclide. While for most measured isotopes the data analysis presented no major problems, for the three
mentioned isotopes the measurement was heavily affected by the high radioactivity of the samples or by the presence of unexpected levels of contaminants.

Figure 1.12. The results obtained for the ANDES project from the data taken at n_TOF in the first measurement campaign: the fission of $^{241}$Am (top row, this work), $^{243}$Am (center row, this work) and $^{245}$Cm (bottom row, n_TOF).
Such problems led to a data analysis much more cumbersome than expected, requiring some additional work and alternative methods for determining the absolute cross sections. This was the aim of Task 1.3.e of the project ANDES. The primary result is an un-normalized ratio of the fission cross section of the nuclide concerned to that of $^{235}$U. In particular, using this ratio the energy dependence of the cross section had already been determined with an accuracy of 3-5% for all isotopes, so that for the ANDES project we proposed to determine the absolute cross section by combining the n_TOF results with other, possibly recent, measurements, for example at thermal neutron energy. The proposed task has been achieved, and the obtained results are the subject of three recent publications. The final results have either been or are being uploaded in the EXFOR database.

In Figure 1.12 some of the results for these three nuclides are shown. The results are compared to data in the literature, to evaluated files and to model calculations.

**Fission cross section measurements for $^{240}$Pu and $^{242}$Pu**

In view of the importance of the fission cross section for $^{240}$Pu and $^{242}$Pu and the very tight target uncertainties of about 2% on the High Priority Request List three subtasks were committed to the measurement of the cross section (1.3b, 1.3c and 1.3d). Each subtask concerned a different measurement. These measurements differ by measurement principle, flux normalization and neutron source. Moreover in the measurement principles applied they differ from what was done before for these reactions. In this way ANDES aimed to make a substantial new contribution to the knowledge of the neutron-induced fission cross section for these two isotopes. In doing so it reacted to the observations that 1) despite numerous earlier measurements the spread in the data is larger than the target uncertainty established by sensitivity analyses, 2) a large number of earlier measurements relies on parallel plate fission ionization chambers in which the Pu samples are back-to-back with $^{235}$U for normalization. For a summary of the status prior to the ANDES measurements see Ref. [7].

Important enablers for this task were the targets of very high purity $^{240}$Pu and $^{242}$Pu prepared, characterized and delivered to the partners by the Target Preparation Laboratory of the IRMM. These targets were available after the first year of the ANDES project. The method of preparation and characterisation is described in a paper and the details concerning activity and mass were made available to the partners. The mass determination was based on defined solid-angle alpha counting in combination with new measurements of the isotope ratios. The latter were needed since prior to preparation a chemical separation of $^{241}$Am from the Pu material was carried out ($^{241}$Pu has a short half-life and decays to $^{241}$Am). In addition, the total alpha activity is more accurately determined than the isotopic alpha activity as the latter requires fitting of peaks with considerable width and tails. The accuracy of the mass is limited to about 1% as a result of the uncertainty of the half-lifes.

Subtask 1.3.b concerns measurements with double Frisch-grid ionization chambers in which the fission cross section of $^{240}$Pu or $^{242}$Pu is measured relative to a flux monitor which is either the fission rate from $^{237}$Np or from $^{238}$U. The neutrons are produced by binary reactions at the IRMM Van de Graaff accelerator. The use of digitizers for data-acquisition allowed a careful elimination of alpha-particle pile-up. The grid and anode signals were combined to analyse the effective efficiency (loss below threshold and in the deposit) of the chamber by looking at pulse heights versus the cosine of the scattering angle.
for spontaneous fission. Accurate new data were obtained for the spontaneous fission half lives of both isotopes. Cross sections were extracted from the ratio to the $^{237}$Np cross section (below 2 MeV) and from the ratio to the $^{238}$U cross section above. $^{237}$Np was used as it was considered to be a derived standard and because it has a threshold below that of the two plutonium isotopes. Nevertheless the cross sections extracted from this work show a jump going from the $^{237}$Np to the $^{238}$U normalized data. This indicates an issue with the $^{237}$Np cross section. Measurements are planned to investigate this problem further through a direct determination of the $^{237}$Np to $^{238}$U cross section ratio and through the use of $^{235}$U as a standard.

Subtask 1.3.d concerns measurements of INFN, NTUA and CERN with Micromegas detectors and the time-of-flight technique at the CERN n_TOF facility. The setup consists of four detectors for $^{240}$Pu, four for $^{242}$Pu and two for $^{235}$U. The latter two are used for the determination of the neutron fluence rate. It was the first time that Micromegas detectors were used for fission cross section measurements. The measurements ran in parallel with other experiments at the CERN n_TOF facility in the 2012 and 2013 measurement campaigns. In view of the large data set and an involved data analysis the results obtained are still preliminary as only a subset of the full data set was analysed. A rather high sample activity for in particular $^{240}$Pu led to a first example of radiation damage to Micromegas detectors. Detectors suffered from coloration and obvious damage and the pulse height response degraded over time. Therefore results will only be obtained for $^{242}$Pu.

Subtask 1.3.c concerns measurements with photovoltaic cells to determine the fission rate of $^{240}$Pu and $^{242}$Pu, with back-to-back samples and the neutron fluence rate by means of a proton recoil telescope. This setup was developed and used by the group from CENBG employing quasi mono-energetic neutrons at the Van de Graaff accelerator of CEA/Bruyères-le-Châtel. Previous experience with this arrangement was obtained while measuring the fission cross section of $^{243}$Am. This led to interesting high quality new results that were published recently. The measurements for $^{240,242}$Pu suffered from an unfortunate delay as a result of radiation protection and licence limitations for the laboratory at CENBG. Therefore an alternative measurement was scheduled at CEA/Bruyères-le-Châtel to make progress with a first check of the experimental equipment. These measurements showed the principal feasibility of the experimental arrangement for $^{242}$Pu, demonstrating excellent separation of alpha particles and fission fragments in the spectrum. However, they also showed for the first time a limitation of the photovoltaic cells. As a result of the high activity of the $^{240}$Pu target the pulse height spectrum was not stable with time and degraded steadily. As this was a first test no preliminary results are available. Further experiments are anticipated and will be reported in due course.

In Figure 1.13 the preliminary results are shown that were obtained for the $^{240,242}$Pu(n,f) cross section at IRMM and Figure 1.14 shows the preliminary results for the $^{242}$Pu(n,f) cross section from CERN n_TOF.
Figure 1.13. Neutron-induced fission cross section of $^{240}\text{Pu}$ (left) and $^{242}\text{Pu}$ (right). The triangles represent our data taken relative to the ENDF/B-VII.1 $^{237}\text{Np}$ evaluation; while the bullets are data taken relative to the ENDF/B-VII.1 $^{238}\text{U}$ evaluation.

Figure 1.14. The first $^{242}\text{Pu}$ resonance at 2.7 eV (top left panel) and resolved resonances between 750 and 800 eV (top right) and around 1800 eV (bottom left). Data above the fission threshold (bottom right). Above 2 MeV, data are treated with a special method to eliminate the effect of an electrical interference due to the 20 GeV/c proton pulse and/or its prompt off-spring. The use of this CPU-intensive method means only a subset of the available statistics has been processed, hence the larger uncertainties pictured here.
The surrogate method for the fission cross section of $^{238}$Pu

The determination of the $^{238}$Pu neutron-induced fission cross section is very important but very difficult for the direct method as a result of the conflicting needs of sufficient target material and an acceptable alpha activity ($T_{1/2} = 87.7$ years) to limit alpha pile-up. The available direct measurements scatter importantly even between recent measurements (up to 40%). It therefore seems natural to investigate what may be contributed by the surrogate method and this was the objective of subtask 1.3a of the ANDES project. The preferred transfer reaction for such a study is the $^{237}$Np($^3$He,p)$^{239}$Pu reaction since it uses a $^3$He beam for which a lot of experience exists. However it has protons in the exit channel for which it is well-known that target impurities may easily present spurious yields and therefore an un-normalized final result. Considerable time and effort was spent to find targets of adequate chemical purity. However, this was unsuccessful. A second alternative was therefore investigated: the $^{240}$Pu($^3$He,$^4$He)$^{242}$Pu reaction. Good experience with this reaction channel was already obtained for $^{241}$Am and $^{236}$U (n,f) reactions. The issue of chemical impurities is now shifted to avoiding spurious sources of alpha particles. In the separation chemistry of $^{240}$Pu employed to remove $^{241}$Am, Cl and Fe are involved. These may result in spurious yields and should therefore be limited to low concentrations (0.02% mol/mol). It appears that this is now feasible and target production at IPN Orsay will be part of the follow-up CHANDA project.

Fission yield measurements with the transfer technique for isotopes of Np, Pu and Cm

The aim of this larger program is to combine the surrogate method and the inverse kinematics technique to obtain isotopic fission-fragment yields for heavy-actinide (Np, Pu, Cm, Cf) low-energy fission. In addition, fission probabilities can be extracted. Such fission yields would be unique, and contribute substantially to improving decay heat and delayed neutron estimates for advanced fast reactors (spent) fuel. The contribution of this task of the ANDES project was to study the feasibility of the isotopic separation of the fissioning system. This was successfully achieved as demonstrated below.

At GANIL multi-nucleon transfer reactions are used to produce heavy actinides for which the fission fragments are detected. The inverse kinematics allows a complete isotopic identification of the fission fragments. The range of excitation energies overlaps that of the compound nuclei produced by fast neutron induced fission so that the technique is a surrogate method for studying fission yields and probabilities for important (n,f) reactions.

Two experiments were made. The first in April 2008 and an improved second experiment in July 2011. The initial experiment performed at GANIL relied on transfer reactions between a $^{238}$U beam at 6.09A MeV and a $^{12}$C target. The isotopic identification of the fission fragments was performed by the VAMOS spectrometer while a segmented annular silicon ΔE-E telescope, SPIDER, identified the produced actinides by tagging the target-recoil nuclei, providing as well a measurement of the excitation energy induced in the fissioning nuclei. This experiment was limited by the lack of isotopic identification of the fissioning systems: SPIDER only provided identification in atomic number.
The SPIDER response had suffered from high counting rates (up to 40 kHz) of high-energy elastically scattered $^{12}$C target nuclei (up to 200 MeV). The consequence was an important increase of the leakage current in the detector (up to several μA), which caused a reduction of the applied high voltage. Therefore, SPIDER was not permanently fully depleted and the response dropped as a function of time for a given particle and energy. In addition, the high counting rate increased the detector temperature, which deteriorated the resolution in energy. Moreover, the detector side facing the target was submitted to a high electromagnetic flux, δ electrons in particular, from the interaction of the highly-charged $^{238}$U beam with the target. This side remained thus unusable, complicating the reconstruction of the trajectories of the particles through the different stages of SPIDER and the multi-hit analysis.

A number of technical solutions were tested and finally implemented to improve the SPIDER resolution and to validate the sources of the problems. A new SPIDER telescope was bought and a frame with a cooling system was built at GANIL (Copper frame with alcohol circulation at -10°C). The cooling limited the heating by the energy-loss of the scattered target nuclei and also the leakage current. Strong magnets were placed around the target (around 185G at the target position) and a mylar foil polarized at 500 V was placed on the target to protect the detector from δ electrons. Some SPIDER channels were wired with a new preamplifier, which aimed to limit the drop of the applied voltage with increasing leakage current. The guard resistance against the noise from the high voltage units was lowered to maintain the voltage above the depletion value for a greater range in leakage current. The best compromise between increasing noise and maintaining complete depletion was chosen. These new experimental conditions showed a sufficient resolution of the detector to give an isotopic separation of the different transfer channels.

These experimental results fulfilled the objectives defined for the ANDES programme, as we demonstrated the feasibility to measure the isotopic distribution of fission fragments of isotopically identified fissioning systems. This encouraging result lead us to run in July 2011 a second and complete experiment, where a successful identification of the target-like particles and hence, of the fissioning systems was achieved. The analysis is in progress, and gave rise to a conference publication on the validity of the surrogate method for heavy target fission yields and probabilities. These results are about to be submitted for publication. The fission probabilities of the compound nuclei ($^{238}$U, $^{239}$Np, $^{240}$Pu and $^{241}$Pu) were derived as a function of the excitation energy. The fission-fragment distributions for the different systems $^{236,238}$U, $^{239}$Np, $^{240,241,242}$Pu, $^{244}$Cm are the subject of an on-going PhD work.

The improvement of isotopic separation obtained in the ANDES project is illustrated in Figure 1.15. Also shown are preliminary fission yields for the $^{240}$Pu fissioning system at an excitation energy of 10 MeV.
Figure 1.15. Energy-loss versus total energy identification matrix measured with the initial experimental conditions (top left, 2008 experiment) and with the developments performed within the ANDES programme (top right, 2011 experiment). Preliminary fission yields for $^{240}$Pu at an excitation energy of 10 MeV are also shown (bottom row, 2011 experiment).

Task 1.4 High accuracy β-decay measurements for $^{88}$Br, $^{94}$Rb, $^{95}$Rb and $^{137}$I

Task 1.4 is responsible for deliverable D1.2 which is concerned with high accuracy β-decay measurements for $^{88}$Br, $^{94}$Rb, $^{95}$Rb and $^{137}$I and includes technical developments for improving such studies for a wide range of fission products. Two types of studies are targeted for these fission products: beta-delayed total gamma-ray emission yields and β-delayed neutron emission probabilities.

The interest in these measurements was established by Subgroup 25 of the OECD Nuclear Energy Agency’s Working Party on Evaluation Cooperation for nuclear data. For reactor safety and safety of the back-end of the fuel cycle it is of key importance to know precisely the heat released through the radioactive decay of fission products. For reactor operation the beta-delayed neutron fraction is a key parameter governing reactor kinetics and therefore the ability to control criticality, a crucial aspect of safety of operation. It was established that there is a discrepancy between so-called summing calculations based on the available nuclear structure and decay data of the important fission products and the total gamma yields and neutron probabilities deduced from more integral measurements. This so-called pandemonium effect needs to be addressed by the evaluated nuclear data files used in nuclear
energy applications. The present work therefore targets four of the nuclides identified by Subgroup 25 as being critical for making substantial progress.

Unique samples of these nuclides were prepared with the IGISOL-3 ion trap at the University of Jyväskylä Physics Laboratory (JYFL) and subjected to either Total Absorption Gamma-ray Spectroscopy measurements (TAGS-measurements) using a BaF2 Total Absorption Spectrometer (TAS) or to neutron-emission probability measurements using the BELEN neutron counter. In addition, IGISOL-3 was dismantled and IGISOL-4 was established over the course of the project.

The IGISOL facility utilizes the ion guide based mass separation of fission products and subsequent online source preparation with the JYFLTRAP Penning trap. With these devices a sample of a single isotope or even an isomeric state of any fission product can be formed. The use of mono isotopic samples significantly simplifies the analysis of the measurements with the TAS and the BELEN detectors.

The TAS detector is a compact cylindrical arrangement of 12 independently operated BaF2 detectors. For the measurements of the isotopes of interest it was installed at the IGISOL-3 trap together with a Si(Li) detector to measure coincidences with β-decay. The measurements were the first of this kind employing BaF2 and therefore also served to commission the detector. High quality results were obtained that have been shown at several conferences and workshops. The statistics obtained did not allow to fully reach the targeted uncertainty and a follow-up measurement with IGISOL-4 is planned for 2014. Figure 1.16 shows the spectra obtained during the experiment.

The BELEN-20 neutron counter is a 90 × 90 × 80 cm matrix of polyethylene, with 20 cylindrical $^3$He proportional counters arranged in two concentric rings, an inner ring with 8 tubes and an outer ring with 12 tubes. It has an estimated efficiency of 40% for neutrons of 10 keV. It was installed and commissioned at IGISOL-3 for the required measurements together with a Si(Li) detector for the coincidence with the β-particles and a Ge detector to allow a verification of the purity of the isotopic sample. The preliminary results obtained for the neutron emission probabilities are in good agreement with the literature (Table 1.2).

![Figure 1.16](image-url) Online total absorption γ-ray spectra obtained with the BaF2 TAS detector at IGISOL-3.
### Table 1.2

<table>
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<th>THIS WORK</th>
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<td>33.0±3.6 %</td>
<td>39.89±0.86 %</td>
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<td>88 Br</td>
<td>6.75±0.18 %</td>
<td>6.72±0.27%</td>
<td>0.5071±0.0153</td>
</tr>
<tr>
<td>90 Br</td>
<td>31.3±6.0 %</td>
<td>22±10%</td>
<td>31.27±0.67 %</td>
</tr>
<tr>
<td>85 Rb</td>
<td>10.24±0.21 %</td>
<td>10.9±0.7 %</td>
<td>11.1±0.9 %</td>
</tr>
<tr>
<td>89 Rb</td>
<td>8.87±0.29 %</td>
<td>9.7±0.4%</td>
<td>8.2±0.8 %</td>
</tr>
<tr>
<td>137 I</td>
<td>7.33±0.38 %</td>
<td>7.02±0.54 %</td>
<td>7.46±0.30%</td>
</tr>
</tbody>
</table>

| Calculated values of the neutron-emission probability \( P_n \) compared with previous measurements. |

The upgrade from IGISOL-3 to IGISOL-4 was a very significant one involving a new cyclotron, a new experimental hall, the installation of new beamlines, the reinstallation and upgrade of the experimental facilities and the commissioning of the facility. In view of the delays suffered during this work improved TAS and BELEN experiments were rescheduled to 2014, after the end of the ANDES project. The promising new capabilities are illustrated in Figure 1.17 showing the excellent resolving power (200 000). This may be further improved when Ramsey cleaning is commissioned. IGISOL-4 also promises significantly greater yields of mass separated nuclides and isomers than were obtained with IGISOL-3.
Figure 1.17. Mass spectrum for the isobar $A = 96$ resolved with JYFLTRAP.
Conclusions

The above summary emphasizes the main achievements of the four tasks of the Work Package 1 of ANDES. A considerable number of new data measurements were initiated and advanced considerably. These are accompanied and complemented by technical and method developments that significantly improve the capability for high level nuclear data measurements. It was clearly shown that these measurements target improvements in predictive capabilities for the safety and sustainability of advanced solutions in nuclear energy. They do so by directly addressing identified high priority needs.

The list of completed activities includes the $^{23}$Na inelastic scattering data (published and adopted in JEFF-3.2), the new method for covariance generation of $(n,n'\gamma)$ data, the $^{241}$Am$(n,\gamma)$ data (published and adopted in JEFF-3.2), method qualification papers for the surrogate technique as a replacement of $(n,\gamma)$ measurements ($^{172}$Yb, $^{175}$Lu), new data for the fission cross sections of $^{241}$Am, $^{243}$Am and $^{245}$Cm, new spontaneous half-life data for $^{240}$Pu and $^{242}$Pu, the proof of feasibility of isotopic fission yield measurements for trans-uranium actinides by inverse kinematics, new data for the total gamma-ray yield and for the fission neutron probability of $^{88}$Br, $^{94}$Rb, $^{95}$Rb, $^{137}$I, and finally commissioning results for IGISOL-4.

Ongoing work that has advanced considerably over the course of the project and will be completed in the near future includes the inelastic scattering data for $^{238}$U, the capture data for $^{238}$U from GELINA and the two n_TOF experiments, the $^{241}$Am data from the n_TOF experiments, the fission cross section data for $^{240}$Pu and $^{242}$Pu, and method qualification data for the surrogate technique for $(n,\gamma)$ data in the actinide range.

Through the developments made in the project we may expect future nuclear data measurements to benefit from the experience gained and technical improvements made in the course of the three years of the ANDES project. It also became clear that the challenges in nuclear data accuracy posed by nuclear energy applications is such that significant additional technical developments are needed to meet these needs. It is therefore particularly encouraging that a follow-up project could be defined and funded by the European Commission that exactly targets these technical improvements. This new project CHANDA (Challenges in Nuclear Data) began 1 December 2013 and will cover 4 years.
ANDES Work Package 2, Uncertainties and covariances of nuclear data


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5. Nuclear Physics Department, Bucharest University, Bucharest-Magurele, Romania
6. CIEMAT, Avenida Complutense 40, 28040 Madrid, Spain
7. National Nuclear Laboratory, B170 Sellafield Works, Seascale, Cumbria, CA20 1PG, UK
8. Dpto. de Ingeniería Nuclear, Escuela Técnica Superior de Ingenieros Industriales, Universidad Politécnica de Madrid UPM, José Guitierrez Abascal 2, 28006 Madrid, Spain

An adequate determination of safety and economical margins of nuclear systems relies directly on the uncertainties of nuclear data. Therefore, an objective is to enhance the European capability to produce covariance data for isotopes which are important for advanced reactors, as identified from recent sensitivity studies on GEN-IV reactors and ADS. The emphasis has been put on the thermal, resonance and fast neutron energy ranges.

Three different aspects of nuclear data evaluation have come together to accomplish this:

1. Uncertainty/covariance evaluation of experimental data
2. Uncertainty/covariance evaluation of data from nuclear reaction models
3. A proper theoretical treatment and evaluation of nuclear reactions on actinides (especially fission models) and its relation with 1. and 2.

In addition to nuclear reaction data, radioactive decay and fission yield data need to be accompanied with associated covariance data, and this has been developed as well. Finally, the new covariance data for nuclear reactions, radioactive decay and fission yields has been used in adapted processing and reactor/fuel cycle codes to calculate the impact on advanced reactor parameters.
Introduction

The assessment of uncertainties in nuclear reaction data is important for both basic physics and technological applications. First, it defines the current quality of both experimental and theoretical nuclear reaction physics. Experimental uncertainties represent a sort of limit of the current-day precision with which we can measure a particular observable (the fact that these uncertainties have a systematic and a statistical component requires a discussion on its own). Theoretical uncertainties would represent the extent to which we are (un)able to cast nature into models and their associated parameters. Second, nuclear reaction data, such as cross sections, resonance parameters, energy spectra and angular distributions are of prime importance to the computational simulation of nuclear installations. A reliable assessment of the uncertainties in calculated integral reactor parameters depends directly on the uncertainties of the underlying nuclear data. To make the most impact for design calculations, nuclear data libraries should include uncertainty information. Starting from the covariance matrices of the basic nuclear data, error propagation in transport, reactor, activation, etc. codes enables to estimate the uncertainties of calculated design parameters, which has a profound impact on issues of general concern such as safety and economy.

Since the last decade or so, covariance estimation has (again) played an important role in nuclear data evaluation. Generally, this was restricted to the general purpose libraries of e.g. ENDFB-VII, JENDL and JEFF. In ANDES, this has been extended to all nuclear data libraries of relevance. This means that not only uncertainties of cross sections have been considered, but also those of thermal scattering, fission yields and decay data.

The project deliverables were completed and submitted to the project coordinator for registration in the portal. The complete list of deliverables and the editors/authors of the reports are shown in Table 2.1.

<table>
<thead>
<tr>
<th>Number</th>
<th>Editor/author</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2.1</td>
<td>O. Cabellos, UPM</td>
<td>Activation data libraries for Monte Carlo uncertainty propagation in fuel cycle code ACAB</td>
</tr>
<tr>
<td>D2.2</td>
<td>A. Koning, NRG</td>
<td>Report on evaluation of $^{239}\text{Pu}/^{238}\text{U}$ and $^{241}\text{Am}$</td>
</tr>
<tr>
<td>D2.3</td>
<td>H. Leeb, TU Wien</td>
<td>Software package for experimental covariance matrix</td>
</tr>
<tr>
<td>D2.4</td>
<td>A. Koning, NRG</td>
<td>Evaluated ENDF formatted file for $^{239}\text{Pu}/^{238}\text{U}$ and $^{241}\text{Am}$</td>
</tr>
<tr>
<td>D2.5</td>
<td>R. Mills, NNL</td>
<td>Report with transmutation calculations for advanced reactors with new covariance data + updated sensitivity tables</td>
</tr>
<tr>
<td>D2.6</td>
<td>O. Cabellos, UPM</td>
<td>Report on the impact of uncertainties of the fission product nuclear data on the inventory of the irradiated fuel for ACAB</td>
</tr>
</tbody>
</table>
Task 2.1 Covariance tool development

Three specific covariance-oriented computer tools have been developed.

A computer tool has been built by CEA-DAM to assist the evaluator in the construction of an experimental covariance matrix based on the information available in the original papers describing the measurements. Statistical and systematic errors are treated separately, with all types of systematic correlations (stemming from sample, experimental geometry, beam normalization reaction for example) being treated properly. The code, including manual and tutorial, has been released as an ANDES deliverable.

The general evaluation tool GENEUS has been extended by TUW to include fission observables. The code is based on the concepts of Bayesian statistics, which provides a complete evaluation including mean values of observables and cross section covariance matrices. As before, the package is connected to the TALYS code, but now also makes use of its new fission capabilities. Bayesian statistics offers a well-defined formalism to combine experimental and prior knowledge. The prior knowledge consists of cross sections given by nuclear models and associated covariance matrices. The latter contain uncertainties stemming from the limited knowledge of the parameters and model deficiencies. While parameter uncertainties are accounted for in many modern Nuclear Data evaluation techniques, uncertainties from model defects were first implemented in the Full Bayesian Evaluation Technique. It turned out that considering model defect uncertainties can visibly improve the evaluated output in the case of a deficient model. In addition, great emphasis was given to estimate experimental uncertainties and to include correlations between different experimental data points of single and different experiments. It could be shown that considering experimental correlations leads to evaluated uncertainties in agreement with the correlated systematic uncertainties of the experiments contrary to the too small evaluated uncertainties of some other modern evaluation techniques.

The CONRAD code has been extended by CEA/DEN to include a more general experimental covariance treatment. CONRAD is developed in C++ at CEA-Cadarache and designed for the nuclear data evaluation (analysis of microscopic, semi-integral and integral measurements). It is based on a Bayesian parameters estimation (Generalized Least Squares), it estimates and/or propagates uncertainties (with Monte-Carlo or Analytical methods) and establishes a link with reactor physicists (from pointwise to multigroup cross-sections). Many methods to properly treat uncertainties coming from microscopic and integral measurements were introduced in the CONRAD framework. Figure 2.1 gives an idea of the adjustment possibilities of differential and integral data.
Figure 2.1: Different methods in CONRAD to calculate a derivative matrix.

**Task 2.2 Covariance data evaluation**

Methods have been developed that provide the best possible covariance data in nuclear data libraries. Activities required to accomplish this have included:

- Assessing uncertainty ranges for nuclear model parameters, especially for actinides.
- Investigation and implementation of Unified Monte Carlo: i.e. a method for the precise determination of both theoretical and experimental based covariance data.
- ENDF-6 formatting: the results should be ready to store in ENDF-6 data libraries and should be successfully processed for application.

The size of the project has restricted us to apply these developments on $^{239}$Pu and $^{241}$Am. The TALYS code system, which has provided already many evaluations for the European JEFF library, is the central tool to provide the covariance data. However, it is important to use independent software for confirmation. Therefore, the EMPIRE-II code has been used as complementary tools both for theoretical modelling. Figure 2.2 shows an example of an EMPIRE calculation done for ANDES.
A TALYS-based method which was further developed during ANDES is the so-called Total Monte Carlo approach of uncertainty propagation. The essence is given in Figure 2.3. 20 to 30 theoretical parameters are all varied together within pre-determined ranges to create TALYS inputs. With the addition of a large number of random resonance parameters, nuclear reactions from thermal energy up to 20 MeV are covered. The TALYS system creates hundreds of random ENDF nuclear data files based on these random inputs. For each random input file, a reactor (e.g. MCNP) calculation is done so that all statistical information for the required quantity, such as k-eff, is available at the end.

Figure 2.2: $^{238}\text{U}(n,n')$ evaluation by EMPIRE-II compared with experimental data and other libraries

Figure 2.3: TALYS system for Total Monte Carlo uncertainty propagation
Task 2.3 Covariances for activation, radioactive decay and fission yields

For a number of important nuclides, complete activation data libraries with covariance data have been produced, so that uncertainty propagation in fuel cycle codes, in this case ACAB, could be further developed and tested. Thanks to this, these fuel inventory codes are now able to handle the complete set of uncertainty data, i.e. those of nuclear reactions (cross sections, etc.), radioactive decay and fission yield data. For this, capabilities have been developed both to produce covariance data and to propagate the uncertainties through the inventory calculations. All results are available in publications and reports. As one example, Figure 2.4 shows a Pu-burnup case, comparing the Total Monte Carlo method with a method (CUP) which considers sampling from available covariance matrices. This is just one example of many quantities which can now be accompanied by uncertainty estimates. This ranges from inventories, to decay heat, to radiotoxicity etc.

![Figure 2.4: Number of atoms during the burn-up of 239Pu as a function of number of histories in the time step 23 of the burn-up](image)

Task 2.4 Application of covariance methodologies to representative advanced nuclear systems (reactors and fuel cycles)

Uncertainty propagation has also been tested in reactor and fuel cycle codes, to determine the uncertainty of the most important reactor and fuel cycle parameters in selected systems and fuel cycles. One of the models is for the European Facility for Industrial Transmutation (EFIT), which is a fast-epithermal reactor with the aim of transmuting minor actinides for the reduction of spent fuel
inventory. Uncertainties for fuel depletion have been calculated with various methods. As an example, Table 2.2 shows the uncertainty for the various isotopes at the end of burn-up of EFIT.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Decay FYs</th>
<th>Cross-section</th>
<th>Uncertainty (as rel. std. dev. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JEFF-3.1.1</td>
<td>EAF-2007</td>
<td>SCALE</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>0</td>
<td>-</td>
<td>13.2</td>
</tr>
<tr>
<td>$^{237}$Np</td>
<td>0</td>
<td>-</td>
<td>6.1</td>
</tr>
<tr>
<td>$^{240}$Pu</td>
<td>0</td>
<td>-</td>
<td>1.9</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>0</td>
<td>-</td>
<td>8.3</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>0</td>
<td>-</td>
<td>7.0</td>
</tr>
<tr>
<td>$^{243}$Am</td>
<td>0</td>
<td>-</td>
<td>6.1</td>
</tr>
<tr>
<td>$^{242}$Cm</td>
<td>0.1</td>
<td>-</td>
<td>10.4</td>
</tr>
<tr>
<td>$^{244}$Cm</td>
<td>0.2</td>
<td>-</td>
<td>23.4</td>
</tr>
<tr>
<td>$^{245}$Cm</td>
<td>0</td>
<td>-</td>
<td>13.2</td>
</tr>
<tr>
<td>$^{247}$Cm</td>
<td>0</td>
<td>-</td>
<td>15.7</td>
</tr>
<tr>
<td>$^{246}$Bk</td>
<td>1</td>
<td>-</td>
<td>20.2</td>
</tr>
<tr>
<td>$^{252}$Cf</td>
<td>0.3</td>
<td>-</td>
<td>56.4</td>
</tr>
<tr>
<td>$^{94}$Nb</td>
<td>0.03</td>
<td>5.9</td>
<td>17.6</td>
</tr>
<tr>
<td>$^{93}$Mo</td>
<td>0.01</td>
<td>2.7</td>
<td>82.6</td>
</tr>
<tr>
<td>$^{126}$Sb</td>
<td>5.21</td>
<td>9.2</td>
<td>9.0</td>
</tr>
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<td>$^{126}$Sb</td>
<td>1.05</td>
<td>7.5</td>
<td>16.4</td>
</tr>
<tr>
<td>$^{156}$Sm</td>
<td>0.01</td>
<td>3.0</td>
<td>11.0</td>
</tr>
<tr>
<td>$^{151}$Sm</td>
<td>0.05</td>
<td>4.2</td>
<td>10.9</td>
</tr>
</tbody>
</table>

**Table 2.2:** Uncertainties in the number of atoms for the most relevant variations due to the usage of EAF-2010 instead of EAF-2007, at the end of the burn-up (150 GWd/tHM) in EFIT.

**Conclusions**

A major step forward in nuclear data uncertainty methodology has been accomplished in ANDES. While retaining the usual method of using covariance matrices for uncertainty propagation, an entirely new way, called Total Monte Carlo, is now also used for all aspects of nuclear data uncertainty propagation: transport libraries, thermal scattering, fission yield and activation libraries. The theoretical development for this, mainly revolving around the TALYS code, is now merged with more robust ways to account for experimental covariance data and retrieval and development tools for this have been produced. Finally, nuclear data uncertainties can now be applied in activation codes and fuel cycle calculations.

The list of dissemination activities of this work package of ANDES is given below. It consists of full papers, and conference and workshop contributions. It is complemented by the deliverable reports listed in Table 2.1.
ANDES Work Package 3, Integral experiments for validation of nuclear data and constraints on uncertainties

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3. NRG, PO Box 25 1755 ZG Petten, The Netherlands.
4. Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia.
5. CIEMAT, Avenida Complutense 40, 28040 Madrid, Spain.

The first goal of this work package was to agree on a common methodology to use the integral experiments to improve and validate nuclear data and to constrain their uncertainties. To reach this goal, it was necessary to define and share the methodology between the participants, and apply it to different kinds of integral experiments of the public domain, to be able to estimate the impact of the new evaluations with covariances (provided in WP2) to the knowledge of the neutronic behaviour as measured in the analysed integral experiments.

The project deliverables were completed and submitted to the project coordinator for registration in the portal. The complete list of deliverables and the editors/authors of the reports are shown in Table 3.1.

<table>
<thead>
<tr>
<th>Number</th>
<th>Editor/author</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3.1</td>
<td>D. Bernard, CEA</td>
<td>Definition of a generic strategy for the integral validation of nuclear data</td>
</tr>
<tr>
<td>D3.2</td>
<td>D. Villamarin, CIEMAT</td>
<td>Report on analysis of MUSE experiment and C/E + sensitivity vectors</td>
</tr>
<tr>
<td>D3.3</td>
<td>I. Kodeli, JSI</td>
<td>Analysis of the IRPhE experiments and C/E + sensitivity vectors</td>
</tr>
<tr>
<td>D3.4_1</td>
<td>A. Trkov, JSI</td>
<td>Analysis of selected ICSBEP criticality benchmarks</td>
</tr>
<tr>
<td>D3.5</td>
<td>D. Bernard, CEA</td>
<td>Analysis of the PROFIL calculation benchmark and the PROFIL experiments</td>
</tr>
<tr>
<td>D3.6</td>
<td>A. Kochetkov, W. Uyttenhove, J. Wagemans (All -SCK•CEN)</td>
<td>Analysis of VENUS-F core (GUINEVERE) experiment and C/E</td>
</tr>
<tr>
<td>D3.7+D3.8</td>
<td>D. Bernard, CEA</td>
<td>Report analysis of the impact of the new evaluations (with covariances) coming from WP1 (and WP2) + resulting trends on actual nuclear data</td>
</tr>
</tbody>
</table>

Main conclusions detailed in previous deliverables will be reported in this document.
Task 3.1 Generic strategy
The objectives of the so-called V&V&Q&UQ process are to provide a validated (i.e., reliable) code package, qualified on integral experiments for the users. The final aim is to check that the average discrepancies on given integral parameters (such as critical masses or pin-by-pin power distributions) «calibrated» in a specified range of problems are lower than the target accuracy. The strength of this approach is to use a complete library/code package including nuclear data evaluation tools, library generation tool and continuous energy Monte Carlo codes.

Task 3.2 MUSE Experiment
Next figure shows a radial cut of the MUSE-4 reference configuration at core mid plane where the main element can be observed. The experimental program covered both critical and sub critical configurations, but for the ANDES project, only the critical configuration experiments are considered.

Sensitivity analysis was performed using MCNPX code and a minimization process was successfully tested to improve nuclear data by comparing calculation to experiment in a very complex system and by using Monte Carlo codes for reaction rate sensitivity. The main conclusion is that the discrepancies between calculation and experiment observed in the lead region could not be explain by uncertainties on the considered cross sections.

Task 3.3 Analysis of the IRPhE Experiments
The experiments were selected from openly available databases ICSBEP (International Handbook of Evaluated Criticality Safety Benchmark Experiments) and IRPhE (International Reactor Physics Benchmark Experiments) maintained by the OECD/NEA.
Different approaches developed at JSI and CEA, using different computer codes, cross-section libraries, energy group structures and modelisation of the geometry were applied. They gave roughly the same results as shown in the next figure for the SNEAK-7A experiment.

![Sensitivity Plot](image)

This study confirmed the good agreement between the sensitivities, both of integral values and profiles, calculated using the two approaches and contributes in this way to their validation.

**Task 3.4 Criticality benchmark experiments**

The calculations of the sensitivity coefficients using full Monte Carlo models of integral benchmarks can be performed, but it is computationally very intensive. This way is investigated for many years by NRG Petten. It gives adjusted results on $^{239}$Pu and provided better C/E results for a selection of 14 fast and intermediate benchmarks. The quality of each file is plotted in the next figure.

![Comparison Plot](image)
The second involves a more classical perturbation theory as available in deterministic codes. Overall, the agreement between the Monte Carlo sensitivities and the simple deterministic approach through adjoint calculations is reasonable and can be applied for practical calculations since the determination of the sensitivities by the Monte Carlo approach is rather cumbersome and extremely computationally intensive. Next figure show the $k_{\text{eff}}$ sensitivities to Pu elastic cross section calculated by a Monte Carlo (MC) approach and by classical approach.

![Sensitivity Profile for the Flattop-Pu benchmark](image)

**Task 3.5 PROFIL Experiment**

The first step was to define a calculation benchmark to allow each participant to use their own code to perform depletion calculations and associated sensitivity studies. A first milestone was achieved: Description of the PROFIL Calculation Benchmark.

The simplified RZ description of the PHENIX will be used for this benchmark is as following:

![Diagram](image)

Hence, each participant had to describe his own way of calculating the benchmark realizing so new milestones. Finally, comparisons were done between calculation results. It as been shown an overall
good agreement on depleted isotopic compositions. Nevertheless, Monte Carlo approach looks like logically suffering from stochastic convergence for very low reaction rates.

The second step was the interpretation of PROFIL and PROFIL2 experiments. PROFIL experiments concerned two Post Irradiation Analysis of doped samples (2 sets of experiments: PROFIL and PROFIL-2) irradiated in the FBR-PHENIX reactor in France. The goal of such experiments is to validate neutron cross sections (radiative or \((n,2n)\) capture) of nuclides (actinides and fission product) involved in cycle studies for Fast Breeder Reactors.

**Task 3.6 GUINEVERE@VENUS-F**

A first milestone describes the layout of the VENUS-F reactor in the framework of its first experimental programme within the GUINEVERE project. The minor actinide fission rate ratio measurements campaign was fulfilled and the results were analysed. The results of this measurements could be recommended as a benchmark for the nuclear data improvement and licensing for the fast lead cooled core designs.

The results of this experiment as well as the criticality of the core were compared with calculations and reported in the associated deliverable. As an example, the calculated \(k_{\text{eff}}\) is \(1.00546\pm0.00006\) for the critical CR0 configuration.
Task 3.7+3.8: Impact of the new evaluations (with covariances) coming from WP1 (and WP2) + resulting trends on actual nuclear data

The aim of this deliverable was to emphasize the nuclear data improvement performed through Work Package 1 (“differential” measurements for advanced reactor systems) by comparing calculation results and measurements of so-called integral values.

The second objective of this report was to estimate the a priori uncertainty of these calculated integral values due to nuclear data knowledge by propagating covariances coming from Work Package 2. The comparison of this a priori uncertainty to actual experimental uncertainties stressed the need of integral measurements for the nuclear data experimental validation or for the assimilation process.

Total Monte Carlo (Deliverable 3.4) such as proposed by NRG answers a third objective (for non-depleted cases for the time being), i.e. estimating nuclear data (and associated uncertainties) to reproduce the targeted measured value as accurately as (integral) experimental uncertainties. This methodology needs at first an accurate nuclear data uncertainty to find the better set of adjusted (or a posteriori) nuclear data and of experimentally constraint covariances.

To answer to the first two objectives, the published report assesses the need of nuclear data files (ENDF format and so the need of evaluation work) coming from WP1&2 to be used for nuclear data qualification and propagation of a priori uncertainty. Nevertheless, in spite of the absence of evaluated nuclear data files, it was stressed some improvement needed for available JEFF-3.1.1 nuclear data and identified main contributors to the global uncertainty of integral parameters.
The goal of this work package was to provide reliable simulation tools for the design of a future ADS demonstration facility as the MYRRHA project, which consists of a proton accelerator delivering a 600 MeV proton beam to a liquid Pb-Bi spallation target. The optimization of the spallation target for such a facility, the assessment of the radioprotection and material damage problems related to high-energy reactions, the reduction of the safety margins require simulation tools validated in the energy domain of the demonstration facility and a quantitative estimation of their predicting capabilities. While there has been of lot of work in the past years devoted to the collection of high-quality data and improvement of high-energy models around 1 GeV (among which the work performed within HINDAS and NUDATRA), much less has been done between 150 and 600 MeV. Therefore, this work package has focussed on the improvement of the models in this energy range with validation on the appropriate experimental data. Two experiments dedicated to the measurements of key experimental data for constraining the models and solving former inconsistencies were conducted. Analyses of samples from irradiated thick targets were also performed in view of the validation of the models.
Introduction

This Work Package was devoted to the improvement and validation of the high-energy models, which are implemented into Monte Carlo transport codes used for the design of ADS, in the 150-600 MeV energy domain. The goal was to be able to assess the uncertainty with which quantities related to high-energy reactions can be predicted.

During the NUDATRA project, new versions of the INCL4 intranuclear cascade and ABLA de-excitation models were developed in view of improving the prediction capabilities of the simulation codes used for the design of ADS spallation targets. However, most of the work done up to recently was focused on reactions around 1 GeV, mainly because this was the energy foreseen for the final ADS transmuter. Much less had been done concerning the 150-600 MeV energy domain, which, actually, is of interest for demonstrator facilities and in particular the MYRRHA facility to be built in Mol, Belgium. The first task (Task 4.1) was to establish the state-of-the-art regarding the prediction capabilities of the nuclear models used in standard transport codes in this domain and identify the remaining deficiencies that should be tackled, in Task 4.4. The goal is to further improve the predicting capabilities of the simulation tools for MYRRHA design, with emphasis on key parameters of the spallation target i.e. the total activity and major contributors to the activity of the target and structure materials, the production rate of helium (mostly for material damage assessment) and of radioactive gases, in particular tritium and volatile elements from the liquid target. Because experimental data are scarce and sometimes discrepant in the 150-600 MeV domain, Task 4.2 and 4.3 were devoted to two specific experiments able to bring high-quality elementary data in order to help understand the physics mechanism and consequently solve the deficiencies in the models. In view of the validation of the models, experimental samples from the ISOLDE and MEGAPIE already irradiated thick targets irradiated were analysed.

The project deliverables were completed and submitted to the project coordinator for registration in the portal. The complete list of deliverables and the editors/authors of the reports are shown in Table 4.1.

<table>
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<tr>
<th>Number</th>
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</thead>
<tbody>
<tr>
<td>D4.1</td>
<td>J.C. David (CEA/DSM)</td>
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Task 4.1 State-of-the-art of high-energy model predicting capability in the 150-600 MeV domain

In this Task, the results from the recent IAEA benchmark together with additional experimental data sets were used to evaluate the quality of the predictions of INCL4.5-ABLA07 combination of models in the 150-600 MeV range and, when possible, compared to other models. Details can be found in Deliverable D4.1. Globally, the predicting capability of the model was found as rather good and, generally, better than other models available in high-energy transport codes. However, a few specific deficiencies have been pointed out, which generally tend to increase as the incident energy decreases. They concern:

1) forward angle double-differential cross sections whatever the type of considered particle, and, in particular the prediction of quasi-elastic peaks
2) the appearance of a spurious hole around 10 MeV in neutron energy spectra, which becomes more and more important as the incident energy decreases
3) a less good agreement of the models for composite particle double-differential cross sections
4) a clear overestimation of the production of intermediate mass fragments through our coalescence mechanism
5) a significant underprediction of some residues close to the target nucleus
6) a difficulty to properly predict fission fragment all along the energy range (illustrated in Fig.4.1).

![Image](image_url)

**Figure 4.1.** Measured excitation functions (points) for the production of $^{127}$Xe (left) and $^{85}$Kr (right) from a $^{nat}$Pb target bombarded by protons compared to INCL4.5-ABLA07 (red) and INCL4.2-ABLA (blue).

The goal ascribed to Task 4.4 was therefore to cure these deficiencies without, as far as possible, degrading the good results obtained in other observables. It should be recalled that in the used models, parameters are not adjusted for each different set of data, but fixed once for all based on physics considerations and comparison with the whole bulk of data.
The other point that was identified as unsatisfactory concerns composite particle-induced reactions. Indeed, composite particle double-differential cross sections exhibit a significant high-energy tail. In a thick target, these particles will undergo secondary reactions that could lead to the production of isotopes with two additional charge compared to the target nucleus. In the case of Pb-Bi, this means the production of polonium and astatine isotopes, which are a major concern for radioprotection. Although INCL4.5 was able to treat reactions with projectiles up to helium, it was not really tested and the first attempts to calculate these isotope productions did not give satisfying results. This led to addressing this issue in Task 4.4 and improving the treatment of composite particle reactions.

**Task 4.2 p+Pb at 500 MeV: measurement of fission fragments and light evaporation residues in coincidence with light ions**

Lead or liquid lead-bismuth eutectic are considered as optimum materials for spallation targets. Therefore, a good knowledge on the interaction of relativistic protons with these materials is mandatory. In particular, the production of residual nuclei in spallation reactions is of outmost importance for the radiological characterization of the target after an irradiation period.

In order to develop reliable model calculations of the radiological inventory in spallation blankets a dedicated experimental program to measure the production of residual nuclei in this reactions was initiated a decade ago at GSI (Germany) under the FP6 project HINDAS. These experiments took advantage of the inverse kinematics technique and the use of the magnetic spectrometer FRS at GSI. This technique made it possible to unambiguously identify in atomic and mass number all fragments produced in the reaction, as well as their production cross sections with typical uncertainties around 10%. Among others, reactions induced by protons at 500 and 1000 MeV on $^{208}$Pb were investigated.

Despite the quality of the measurements performed at GSI, the limited acceptance of the magnetic spectrometer used in these experiments was considered as a possible limitation to accurately determine the production cross sections of fission residues. Indeed, the total fission cross sections measured at GSI for the reaction $^{208}$Pb+p at 500 A MeV was in conflict with a direct kinematics measurement. In order to solve this discrepancy, a new dedicated experiment, also in inverse kinematics, was performed at GSI using a detection setup with full acceptance for both fission fragments but with limited identification capabilities. This experiment, supported by the FP7 EUROTRANS project, yielded a total fission cross section for the reaction $^{208}$Pb+p at 500 A MeV close to the direct kinematics experiment.

The remaining ambiguities in the measured total fission cross sections and the need of new observables to constraint the role of dissipative effects in fission justified a new experiment, named SOFIA, combining the inverse kinematics and the excellent resolution of the FRS spectrometer with a large acceptance setup. Such a detection setup should allow for almost complete kinematic measurements where all reactions products could be characterized. Details of the experiment performed in September...
2012 at GSI, the results obtained, and their implications in the understanding of the fission of $^{208}$Pb induced by relativistic protons are described in Deliverable D4.4.

Figure 4.2. Schematic representation of the experimental set-up used in the SOFIA experiment.

In this experiment, the proton-induced fission of $^{208}$Pb was investigated in inverse kinematics at 370, 500 and 650 A MeV. The combination of the inverse kinematics technique with a highly efficient detection set-up made it possible to determine the total fission cross sections with high accuracy. The results obtained made it possible to solve the inconsistencies observed in previous measurements. With the new measurements it was possible to establish a complete excitation function of the total fission cross section from 60 up to 1000 MeV.

Figure 4.3. Total fission cross sections measured in this work (red squares) compared to other measurements of the same reaction at different beam energies and using direct kinematics with $^{nat}$Pb and inverse kinematics with $^{208}$Pb.
The challenging detector setup used in this experiment made it possible to identify for the first time in atomic and mass number the two fission fragments produced in the reaction in an event-by-event basis. The used of the large-acceptance dipole magnet Aladin together with tracking and timing detectors at the frontier of present technologies were the key aspects for the isotopic identification of the fission fragments.

Moreover, the setup also provided the identification of the light-charged particles and neutrons emitted during the fission process. This information, together with the complete identification of the fission fragments will contribute to fully characterize the fission process at high excitation energy and improved present physical models describing this process.

![Figure 4.4](image)

**Figure 4.4.** Left panel: Scattered plot showing the correlation between the atomic numbers of the two fission fragments identified in coincidence. Right panel: Identification of light-charged particles using the energy-loss of events.

**Task 4.3 Measurement of neutron-induced light ion cross-sections at 175 MeV on Fe, Bi and U**

Especially important for the design of ADS are double-differential cross sections (DDXS) of light-ion production in neutron-induced reactions since they are related to the production of helium and tritium in the target and surrounding materials. To satisfy these needs a series of measurements around 96 MeV has earlier been performed at The Svedberg Laboratory (TSL), Uppsala. Above 100 MeV, however, experimental data are extremely scarce. In Task 4.3, DDXs for light ions (p, d, t, $^3$He, and $^α$) from Fe, Bi, and U induced by 175 MeV quasi mono-energetic neutrons were measured using the Medley setup. Results are provided in Deliverable D4.5. DDXS for light ion (p, d, t, $^3$He and $^α$) from Fe and Bi are already available on the EXFOR database.
The MEDLEY setup (Spectrometer system for detection of light ions) at the Svedberg Laboratory, Uppsala.

Figure 4.6. Double-differential cross section data for Bi(n,px) (left) and Bi(n,tx) (right). Experimental results (black symbols) are compared with INCL4.5-ABLA calculations for both monoenergetic 175 MeV neutrons (green symbols) and the true experimentally accepted neutron spectrum (red symbols). Data for four different angles are shown: 20° (circles), 40° (upward triangles, scaled by $10^{-2}$), 80° (squares, scaled by $10^{-4}$), and 160° (downward triangles, scaled by $10^{-6}$).

The measurements were performed at the quasi-monoenergetic neutron beam available at The Svedberg Laboratory (TSL), Uppsala, Sweden. The neutrons were produced from the $^7$Li ($p,n$). The pulsed proton beam with 45 ns repetition time had an energy of 179 MeV, and the Li target thickness was 23.5 mm. This yielded a neutron beam with peak energy of (175±3) MeV and comprising 40% of the
produced neutrons. The remaining 60% form the neutron tail which was, partly, suppressed by time off-light methods. The neutron energy spectrum is obtained from measurement of elastic np scattering from a CH2 target of similar size than the other targets in the measurement campaign. The relative neutron fluence for the various targets was derived from several standard beam monitors available at TSL; the beam dump monitor, a thin-film breakdown counter and the ionization chamber monitor. The energy loss was corrected for in the analysis procedure by means of an iterative procedure.

![Figure 4.7](image)

*Figure 4.7. Same as Fig.4.5 but for Bi(n,αx) (left) and Fe(n,αx) (right).*

Experimental results have been compared with model calculations obtained with TALYS, a modified version of JQMD [9], and MCNP6. It was found that the models generally manage to reproduce observed trends and in some cases describe the data rather well. Nevertheless, none of the models is able to give a completely satisfactory description of all the experimental data, with composite particles being especially problematic. As an example, comparisons of the revised Bi data with model calculations from the INCL4 intra-nuclear cascade code (version 4.5) combined with the ABLA de-excitation code are show in Fig.4.6. Model calculations for both a true monoenergetic neutron beam with energy 175 MeV and for the accepted neutron energy spectrum are also displayed. The differences of the resulting “washing out” are clearly seen at the high energy end of the 20° data. Comparing the model calculations in the (n,tx) and (n,αx) cases with the experimental data, an overall, good agreement, especially at the low energy end is found. This agreement in especially the (n,αx) case increases the confidence that the thick target correction has been made in a correct way. A systematic difference is, however, observed at the high-energy end, especially at 20°. There, triton and alpha production are overpredicted by the INCL4
calculations. The seemingly large discrepancy at 160° is due to the fact that the experimental data here are exposed to large background which is reflected in the very large uncertainties.

In the (n,αx) cases, shown in Fig.4.7, similar trends can be observed. Unfortunately, due to the identification cutoff and the thick-target correction, the experimental data in the Bi case do, so far, not extend far down enough to clearly see the top of the evaporation peak, as seen in the Fe data.

For the (n,px) data, as can be seen in Fig.4.6, a good agreement with the model calculation at both the low and high energy end at 20° is found. In the intermediate range (50-120 MeV), however, the INCL4 calculations underpredict the experimental data. At 40° a better agreement in shape is observed but the model calculations underestimate the experimental results. At 80° they overpredict the experimental data at both ends of the energy spectrum.

Task 4.4 Improving of the predicting capabilities of the simulation tools in the 150-600 MeV in order to reduce the uncertainties on key parameters of the demonstration facility spallation target

At high incident energies the number of open reaction channels is large and difficult to handle in evaluated nuclear data libraries, in particular, correlations between the produced particles and nuclei are lost using libraries. Also, these libraries are limited to 150 or 200 MeV and not available for all target nuclei. Therefore, high-energy transport codes that are used to simulate ADS generally rely on physics models to provide the production cross sections and characteristics of the particles and nuclei produced in nuclear reactions occurring inside the irradiated materials. Evaluated nuclear data libraries are used systematically for neutron-induced reactions below 20 MeV and when files exist for neutron and proton-induced interactions up to 150 or 200 MeV.

Task 4.4 has led to two kinds of simulation tools (for nuclear reactions). The first one (subtask 4.4.1) is the improved version of the Liège cascade model (INCL) and the improved version of the ABLA model, following the prescriptions of Task 4.1. The second one rests on the extension of evaluated data files above 150 MeV, generated by the TALYS code system, which is developed in WP2.

Sub-Task 4.4.1: Improving the high-energy models
In Task 4.4.1, efforts have been devoted to cure the deficiencies identified in Task 4.1. A new version of the INCL model, INCL4.6, have been developed, which, coupled to the last version of the ABLA model, brings significant improvements to most of the points above listed. In addition, the model was extended towards lower incident energies in order to be able to better treat reactions induced by secondary particles in thick targets. The details of the modifications done in the model and comparisons with experimental data can be found in a published paper, which is included in the Deliverable 4.2 report.

The INCL4.6-ABLA07 code is available on request at http://irfu.cea.fr/Sphn/Spallation/incl.html.
It should be stressed that the simulation tools developed in the frame of Task 4.4 are now implemented into several high-energy transport codes that can be used for simulations of ADS. The latest official version of the Fortran code (INCL4.6 coupled to ABLA07) is included in a private version of MCNPX. A patch is available for authorized users of MCNPX. Moreover, INCL was recently included in the Japanese PHITS code and it is the default option for the simulation of reactions induced by nucleons, pions and light charged particles up to 3 GeV. Finally, the C++ version of the model (INCL++) is part of the last release of the Geant4 particle-transport toolkit and can be used through appropriate “physicists”.

In the frame of Task 4.4, the INCL model has evolved from version INCL4.5 to the (improved) INCL4.6 version and embodied in a stable numerical code of the same name. The ABLA07 de-excitation model and code was already available at the beginning of ANDES. The model has subsequently been improved on several points, regarding the emission of light charged particles (LCPs) and intermediate mass fragments (IMFs) and the mass and charge distribution of fission fragments, even if GSI colleagues have withdrawn from the project before its end. The new features of INCL4.6+ABLA07 are described in Deliverable 4.2 and in the attached paper. The performances (at least those which are important for the evaluation of the key parameters of spallation sources) have been compared with those of INCL4.5 coupled to the former version of ABLA07.

Fig. 4.8 shows that the hole identified in Task 4.1 as point 2) has been cured. Examples of improvements brought by the last improvements of the models on residue production are shown in Figs. 4.9 and 4.10.

**Figure 4.8:** Neutron double differential cross sections for incident neutrons of 65 MeV on iron (left) and incident protons of 63 MeV on lead (right), as functions of the emitted neutron kinetic energy T. The red (respectively blue) histograms give the predictions of INCL4.6 (resp. INCL4.5) –ABLA07.
It has to be underlined also that the improvement of the INCL+ABLA tool carried out during the ANDES project is much broader than what was required by the conclusion of Task 4.1. The reason is that in the process of improving a simulation tool to alleviate some specific deficiencies, one is often led to consider other improvements dedicated to enhance the coherence of the physics models or in other energy regimes than the one which was explicitly considered when the models are to be benchmarked in global conditions. To be specific, it is not sufficient to have good reaction models in the 150-600 MeV range for simulations of the spallation target of the future demonstrator facility, MYRRHA. Indeed, secondary reactions in the spallation targets, initiated by low energy particles (and/or clusters) may be of importance. Therefore the improvements brought in the INCL+ABLA tool are much more numerous than those required in the report Deliverable 4.1. They bear essentially on the treatment of the reaction mechanism at low energy, on the production of clusters and on the emission of intermediate mass fragments (IMF). These improvements allowed for instance a significant improvement of the prediction of astatine in liquid lead-bismuth targets as shown by Fig. 4.11 right.

The goal of this WP was the reduction of uncertainties for evaluating key parameters of spallation targets, in particular the targets envisaged for ADS with a special emphasis on the MYRRHA project. The relation of the observables studied during this project to key parameters is given below:

- Neutron multiplicities and spectra: characterization of the neutron source in terms of neutron emission patterns.
• Production of (light) gaseous elements: emission rates of volatiles from the spallation source, contribution to radiotoxicity. The example of tritium production in lead is shown in Fig. 4.11 left.

• Production of (heavy) volatile isotopes: idem

• Residues close to the target nucleus produced with large cross sections: evaluation of radiotoxicity

• Recoil energy of residues: calculation of radiation damages in (solid) targets

• Nucleon-induced reactions at low-energy: importance for secondary reactions

• Reactions induced by light clusters, especially at low energy: idem.

Figure 4.11. Left: Ratio between tritium production cross-section in $^{nat}$Pb calculated with the new version INCL4.6-ABLA07 and experimental data measured by different groups. Right: Astatine production rates (in atoms per $\mu$C of charge of the incident beam) measured at ISOLDE, as a function of the mass number. Data (black symbols) are compared with the predictions of INCL4.6-ABLA07 (red lines) and CEM (blue lines) implemented in MCNPX.

In all cases, the new version INCL4.6+ABLA07 gives better results than the version (INCL4.5+ABLA07) available at the beginning of ANDES, when benchmarked against thin target data. In many cases, a very good agreement is obtained. Since the simulation tools developed in the frame of Task 4.4 are now included into several high-energy transport codes thick target calculations using the new version implemented into MCNPX have been performed, especially concerning the Pb-Bi eutectic target of the IS419 experiment at ISOLDE, as shown in Fig.4.11 right.

Globally, it was shown that the predictive power for residue production has been increased with the improvement brought during this project. It is not possible to quantify this improvement in terms of uncertainties, but it can be said that globally, the uncertainty has been reduced by a factor 2 or so. Of course, this improvement does not mean that all local deficiencies have been eliminated.
Sub-task 4.4.2: Investigating the possibility to use Evaluated Data Files above 150 MeV

Many nuclear data evaluations and related validation methods revolve around TALYS, which up to recently was limited to 200 MeV incident energy. This subtask was devoted to a study of a possible extension to higher energies. The Koning-Delaroche optical model potential from 2003 has been extended by two simple terms for the volume real and imaginary potentials. The resulting predictions have been tested against available experimental data above 200 MeV and now seem to provide reasonable results up to about 1 GeV. By means of logarithmic binning of the multiple decay scheme in TALYS it is now also possible to calculate non-elastic channels at higher energies. Emission spectra have not yet been validated, but preliminary results for residual production cross sections for protons incident on Al, Fe and Zr have been investigated and promising results obtained. Examples are presented in Fig 4.12.

![Excitation functions](image)

**Figure 4.12.** Top-left panel: Excitation functions for non-elastic cross section of p+Al; other panels: excitation functions for the production of a particular isotope in p+Al (top) or p+Fe (bottom)

This means that it is possible to produced nuclear data libraries above 200MeV, especially since the ENDF format allows such an extension.
Task 4.5 Validation on the results from the post irradiation analysis of MEGAPIE samples

In the frame of the ANDES Project, WP4.5, the radionuclide inventory of proton-irradiated LBE samples was studied. The obtained experimental data shall serve as benchmarks for theoretical predictions based on models and calculation codes, especially for future facilities like MYRRHA/XT-ADS, planned to work in a similar energy range like MEGAPIE at PSI.

Two types of samples were available for the work:

- LBE samples from the test experiments at ISOLDE (1-1.4 GeV, evaporation experiments as preparation for MEGAPIE)
- Samples from the MEGAPIE target (590 MeV, pilot experiment at PSI demonstrating the feasibility of a high-power liquid metal target)

The ISOLDE samples were used for test studies, especially for the development of the chemical separation systems. Nevertheless, values for isotopes of non-volatile elements like Bi, Ba or Rh can also serve as benchmarks for the isotope production in the energy region above 1 GeV. Moreover, we have found indications for accumulation of certain radionuclides at exposed positions, e.g. free surfaces or steel/LBE interfaces.

![Figure 4.13](image)

Figure 4.13. Left panel: ISOLDE target; proton beam enters from the target bottom. Right panel: Absorber foils (left) were located around the central rod in the expansion tank (right).

More than 70 LBE samples were taken from the MEGAPIE target. These works are extremely complicated and time consuming, because they have – due to the high activity level - to be carried out remote controlled in a Hotcell. After extended \(\gamma\)-mapping, representative samples underwent several chemical procedures in order to determine radionuclides, which are not detectable by \(\gamma\)-spectrometry. Special efforts were undertaken to investigate the phase interfaces because in the case of isotope accumulation these information are essential for quantifying the production rates. For this reason, also the absorber device was dismounted and examined.

In the following, the results are summarized:
• $^{207}_{\text{Bi}}$ – the component with the highest activity - is an isotope of the matrix material bismuth and, therefore, expected to be homogeneously distributed. Its amount has been quantified.
• Isotopes of noble metals could be detected in all LBE samples. Since they are soluble in LBE they are equally distributed and could be quantified.
• The content of the $\alpha$-emitting polonium nuclides $^{208-210}_{\text{Po}}$ has been quantified as well. In contrary to the findings from the ISOLDE target, Po is homogenously distributed within the target.
• $^{194}_{\text{Hg/Au}}$ is rather homogeneously distributed within the target, but its activity concentration shows a larger scatter, compared to that of $^{207}_{\text{Bi}}$. Samples taken from the LBE/steel interface showed a significant enrichment of $^{194}_{\text{Hg/Au}}$ in the LBE located near to the steel wall of the target container. The reason for this enrichment remains unclear.

<table>
<thead>
<tr>
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<th>$A_{\text{total}}$ [GBq]</th>
<th>$A_{\text{total}}$ [GBq]</th>
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<tr>
<td></td>
<td>$^{207}_{\text{Bi}}$</td>
<td>$^{194}_{\text{Hg/Au}}$</td>
</tr>
<tr>
<td></td>
<td>chem. anal. bulk</td>
<td>61.70 ± 3.13</td>
</tr>
<tr>
<td></td>
<td>FLUKA</td>
<td>93.7</td>
</tr>
<tr>
<td></td>
<td>MCNPX</td>
<td>71.2</td>
</tr>
<tr>
<td></td>
<td>chem. anal. steel wall</td>
<td>2.5 ± 1 /16m$^2$</td>
</tr>
<tr>
<td></td>
<td>chem. anal. LBE/wall</td>
<td>65.3 ± 4 /16m$^2$</td>
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Figure 4.14. Total $^{207}_{\text{Bi}}$ (left) and $^{194}_{\text{Hg/Au}}$ (right) concentration in MEGAPIE target at EOB (21.12.2006) compared to FLUKA and MCNPX simulations assuming an homogeneous distribution.

• Lanthanides like $^{172/173}_{\text{Lu}}$ or $^{143}_{\text{Gd}}$ are not detectable in the bulk, but are strongly accumulated on the steel/LBE interface and the free surface. The total amount of produced radionuclides has been estimated by relating it to the total inner surface of the loop, without considering the free surface to the expansion tank, which is negligible in comparison to the surface of the steel tubes.
• There is strong evidence that iodine as also accumulated on the steel/LBE interface. The bulk concentrations are below the detection limits and yield less than 10% of the total amount calculated for the tube surface.
• The absorber foils positioned in the expansion tank showed only slight contamination, caused by several radionuclides. None of them contributes more than 1% to the total inventory, and are, therefore, neglected.
• Most of the results agree more or less fairly with theoretical predictions from FLUKA and MCNPX. At least, they are all in the right order of magnitude.
The Deliverable D4.7 consists of a written report, describing the methods and results in detail, and a excel file comprising the obtained data. Since the MEGAPIE data were also taken to validate the models, results concerning Po production have been compared to the last version incorporating all the new features developed during the ANDES project. The results are compared, in Table 4.2, with two calculations performed with MCNPX, using either the default model (i.e. Bertini-Dresner) or the INCL4.6+ABLA07 cascade/de-excitation model. Both calculations take care of the 2-year irradiation and the ten-year cooling, owing to an MCNPX-CINDER90 simulation. Despite of the preliminary status of the data, there is no doubt that there is a great improvement thanks to INCL4.6-ABLA07. As for the case of the astatine production shown above, the improvement is largely due a proper description of the production of light composites and of the re-interaction of the latter with either Pb or Bi nuclei.

<table>
<thead>
<tr>
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<th>Exp/Bertini-Dresner</th>
<th>Exp/INCL4.6+ABLA07</th>
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<tbody>
<tr>
<td>$^{208}$Po</td>
<td>6.2</td>
<td>0.52</td>
</tr>
<tr>
<td>$^{209}$Po</td>
<td>36.2</td>
<td>0.72</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>3.6*10^4</td>
<td>5.46</td>
</tr>
</tbody>
</table>

Table 4.2: Production of Polonium isotopes in the Pb-Bi MEGAPIE. The numbers give the values of the ratio between the (preliminary) data and the predictions using the default model (i.e. Bertini-Dresner) or the INCL4.6+ABLA07 cascade/de-excitation model. The second calculation has been performed in a simplified geometry.

**Conclusion**

This work-package has allowed the improvement and validation of the INCL4.6-ABLA combination of models with emphasis on the 100-600 MeV energy domain of relevance for ADS demonstrators such as MYRRHA. The models are now available for simulations using high-energy transport codes. An attempt to produce evaluated data files up to 600 MeV has been done but a full benchmarking is yet to be done. Two specific experiments, at Uppsala and GSI, have been conducted which have provided very high quality data helping to constrain the models and relevant for the production of gases and radioactivity assessment, respectively, in spallation targets of ADS. The analysis of samples from the ISOLDE and MEGAPIE irradiated targets have led to important findings concerning the behavior of radioactive species in liquid metals and are useful for the global validation of the models.

The evaluation of the uncertainty brought in thick target transport calculations by the high-energy models model remains to be done, especially if this uncertainty is to be expressed in terms of covariances matrices. This will be an important part of the activity in the forthcoming CHANDA project.
ANDES WP5 & 6: Potential impact and Dissemination activities

Impact and Dissemination
The ANDES project has produced output that will have impact on very different communities, ranging from fundamental science, international agencies, and nationally funded nuclear research programs to nuclear industry. Generally there are two main classes of nuclear data users: nuclear industry and large, usually government-funded, research infrastructures for the development of innovative technological designs (GEN-IV, ITER, ADS, etc.). In the case of ANDES, the results are directly impacting on the development of the ESNII demonstration plant conception, safety analysis and optimization and indirectly on most projects related to ESNII and SNETP strategic research agenda.

The interface of such users with nuclear data is depicted in the Figure below. Nuclear data needs are specified and prioritized and through a combination of differential measurements, nuclear modelling, data evaluation, library production, processing and validation with integral measurements, ready-to-use qualified nuclear data libraries are returned. Depending on the complexity, the total time of such a cycle may take several months to several years, especially if in the latter stages of nuclear data validation (the inner circle of the figure) new needs for differential data improvement emerge (bringing us in the outer circle again).

![Figure 5.1: Life cycle of nuclear data development, using the JEFF file as an example.](image)

Distribution of the nuclear data is done by their incorporation into one of the nuclear data bases distributed by international centers, particularly NEA/OECD or IAEA. Special links with the NEA/OECD and the IAEA have been established by members of the project who are also participating in the nuclear data expert groups of both institutions. Various joint meetings of the NEA JEFF project and ANDES have been held during the time span of ANDES. These connections have facilitated the transfer of the results of the project to the international nuclear data libraries managed by the corresponding central distribution centers of the NEA/OECD and IAEA. This mechanism has also provided control to the access of the results. In fact, new data libraries modified according to the new measurements and evaluations
of ANDES, and distributed by NEA and IAEA are now being routinely used by scientist and engineers all over the world.

These dissemination activities include very large distributions of:

- Dissemination of experimental data, using the EXFOR format and the databases of NEA and IAEA.
- Dissemination of nuclear model codes including TALYS-1.6, EMPIRE, CONRAD and GENEUS, by websites specific for each code.
- Dissemination of evaluated nuclear data libraries via the JEFF project (ANDES data is part of the release JEFF-3.2)
- Dissemination of integral data to related research networks. In particular including: the OECD/NEA Expert Group on "Uncertainty Analysis in Modelling", the European Sodium Fast Reactor projects (EISOFAR, CP-ESFR), the task force on Shielding Aspects of Accelerators, Targets and Irradiation Facilities (SATIF), and the MYRRHA related projects (CDT).

The dissemination of knowledge and results of the ANDES project have used the following methods depending on the nature of the results:

* Differential experimental data:* All final reports on measurements are publicly available. Progress has been reported in workshops and conferences as appropriate and the final work is or will be submitted for publication in international journals (a list of dissemination activities for these measurements is included at the end of this chapter). Numerical results have been submitted for adoption by project participants when possible and required. In addition, the numerical values have been sent to the OECD/NEA Data Bank for inclusion in the EXFOR database, ensuring a worldwide use.

* Nuclear model codes:* Developments on nuclear model codes TALYS, EMPIRE, CONRAD and GENEUS have been reported at various workshops, conferences and journal publications. In addition, websites are being maintained from which users can obtain the software. Also, nuclear model codes can be sent to the OECD/NEA Computer Program Services for adoption in the software database. High-energy codes such as INCL automatically find application by a lot of users though their inclusion in standard simulation codes such as MCNP and possibly GEANT.

* Nuclear data libraries:* These are the result of the combined use of experimental data and nuclear model codes and have been made available for general use in reactor physics and burn-up calculations through their adoption in the European JEFF and (TALYS-based) TENDL data libraries. All reports on development of covariance data have been made public as well, also in associated publications in international journals.

* Integral experiments and uncertainty propagation methods:* As uncertainty quantification is an essential part of any safety-related nuclear analysis, nuclear covariance data from ANDES have found their way in several applied nuclear communities, such as JEFF and UAM. Independently from the ANDES project, uncertainty propagation from nuclear data to reactor design is now also undertaken by industry (AREVA). While the first contacts between the two communities have already been set, future
developments of uncertainty techniques developed in ANDES will also find their way into this direction. The summary report on impact of new evaluations of the ANDES project of these experiment analyses will be open for common publication. The impact on nuclear data trends and accuracy on neutronics performance will also be disseminated in open publications.

**Innovative systems:** European initiatives such as MYRRHA and the ESFR may base their design calculations, especially when uncertainty quantification is concerned, on nuclear data libraries and high-energy model codes developed during ANDES. Projects for the preparatory studies of those demonstrators are already using data and codes from ANDES.

*ANDES has been exposed at various meetings, workshops and conferences:* One example is the JEFF meeting, with which ANDES meetings in conjunction have been organized. Another one is the International Conference on Nuclear Data for Science and Technology in 2013 in New York, where an overall project review was presented by the coordinator. The main achievements of the project was also presented at the Technology and Components of Accelerator Driven Systems (TCADS-2), organized by NEA/OECD at Nantes in May 2013. Finally, all public information produced by the project will be available from the dedicated webpage that will be maintained several years beyond the project.

**Education and training**

Competence management is a cause of general concern in the nuclear data field. The age structure of the field is not favorable, with retirements being more frequent than the new recruitments. The CANDIDE project (2007-2008) has made one modest attempt to remedy this situation by launching the EXTEND course (European course on Experiments, Theory and Evaluation of Nuclear Data), and ANDES has followed up on this by coordinating the preparation of another specific school dedicated to the nuclear data research for sustainable nuclear energy in 2012 in Budapest. Specific financial resources had been reserved to support the access of European young scientist to this school.

Indeed, the European school on EXperiments, Theory and Evaluation of Nuclear Data (EXTEND) was held during September 17 - 28, 2012 in Budapest, Hungary under the organization of the ANDES project. The school was held under the local organization of Szabolcs Czifrus at the Institute of Nuclear Techniques (INT), located centrally downtown Budapest, Hungary. During the course use was made of, e.g., the local training reactor.

The school was highly appreciated by both teachers and participants. A summary of the evaluation results and comments from the participants is given in the final report (D5.2). The overall rating for the course was between “really good” and “excellent”. Furthermore, the number of applicants exceeded the number of available seats. Hence it can be concluded that there is space for further editions of the course. In order to make this course an established institution in the nuclear data community, it needs to be available to students from all EC member states. For this it is important to allocate enough financial contribution, from either the EC or other sponsors, to keep participants fees at a low and acceptable level for PhD students. Without contribution from the EC via ANDES, EXTEND 2012 would not have been possible.
Transfer of the know-how to future generations is also considered by the Executive Committee by making sure that the research performed within the technical work packages has also resulted in the preparation of PhD and Master Theses, with the same high output as obtained in previous nuclear data projects of FP5 and FP6.

**List of dissemination activities**

A partial list of dissemination activities of ANDES is given below. It consists of full papers, and conference and workshop contributions. It is complemented by the deliverable reports listed in the previous chapters.


22. T. Wright, C. Guerrero, J. Billowes, T. Ware, D. Cano-Ott, E. Mendoza and the n_TOF collaboration, "High-precision measurement of the $^{238}$U(n,\gamma) cross section with the Total Absorption Calorimeter"

23. F. Mingrone, C. Massimi, G. Vannini and the n_TOF collaboration, \[^{238}\text{U}(n,\gamma)\] reaction cross section measurement with C6D6 detectors at the n_TOF CERN facility", International Nuclear Physics Conference, Firenze, Italy 2 – 7 June 2013, to be published in European Physics Journal Web of Conferences


34. F. Belloni, M. Calviani, N. Colonna, et al. (n_TOF collaboration), Measurement of the neutron-induced fission cross-section of \(^{241}\text{Am}\) relative to \(^{235}\text{U}\) from 0.5 to 20 MeV. Eur. Phys. J. A 47: 160, 2011.


38. G. Sibbens, A. Moens, R. Eykens, D. Vanleeuw, F. Kehoe, H. Kühn, R. Wynants, J. Heyse, A. Plompen, R. Jakopić, S. Richter, and Y. Aregbe. Preparation of \(^{240}\text{Pu}\) and \(^{242}\text{Pu}\) targets to improve cross section


40. A. Tsinganis, M. Calviani, E. Chiaveri, N. Colonna et al. (n_TOF collaboration), Measurement of the $^{240,242}$Pu(n,f) Cross Section at the CERN n_TOF Facility, Nuclear Data Sheets 115, to be published, 2014.


45. X. Derkx et al., Minor actinide fission induced by multi-nucleon transfer reaction in inverse kinematics –5th ASRC International Workshop "Perspectives in Nuclear Fission" - Tokai, Japan 2012


53. A. Algora et al., Total absorption gamma-ray spectroscopy (TAS) applications to the decay heat problem: Present and future perspectives. IOP Nuclear Physics Conference. Brighton, UK, 2-4 April, 2012

54. Gamma-neutron competition above the neutron separation energy in delayed neutron emitters:
A. Algora et al., 4th International Workshop on Level Density and Gamma Strength. Oslo, Norway, 27-31 May, 2013


75. D. Rochman and A.J. Koning, "Evaluating and adjusting 239Pu, 56Fe, 28Si and 95Mo nuclear data with a Monte Carlo technique", PHYSOR2012 Advances in Reactor Physics, Knoxville Tennessee, USA, April 15-20 2012.
78. M. Sin, R. Capote, and A. Trkov, Evaluation of fast neutron reaction data for $^{238}$U and $^{241}$Am, ANDES report, unpublished.
**ANDES website**

The information on the ANDES project can be consulted at the ANDES website at:

http://www.andes-nd.eu/

In addition, after the agreements with the CHANDA EURATOM-FP7-2013, that project will also provide a link to the ANDES web repository from the final CHANDA website (http://www.chanda-nd.eu/ in preparation).

The website includes public and private parts. Most of the private content is open to everybody interested after getting a free account, used to monitor and control the use of the ANDES results.