International Conference on the Physics of Reactors "Nuclear Power: A Sustainable Resource"
Casino-Kursaal Conference Center, Interlaken, Switzerland, September 14-19, 2008

Production and processing of covariance data for nuclear applications by the Working Party on International Evaluation Nuclear Data Cooperation

M. E. Dunn[a,*] and M. Herman[b]

[a] *Oak Ridge National Laboratory, P.O. Box 2008, Bldg. 5700, Oak Ridge, TN 37831-6170, USA*
[b] *Brookhaven National Laboratory, Bldg 197D, Upton, NY 11973-5000, USA*

Abstract

The implementation of various nuclear technologies largely depends on computer simulations using nuclear data. The reliability of such calculations cannot be determined without precise knowledge of the uncertainties and related correlations associated with the basic nuclear data reported in the evaluated cross-section libraries. Scarcity of such information motivated establishment of the two international projects within the framework of the Working Party on International Nuclear Data Evaluation Cooperation (WPEC). The first project, WPEC Subgroup 24, is dedicated to the development of new methods for covariance data evaluation in the fast neutron region and the second project, WPEC Subgroup 28, on resonance region covariance processing methods to prepare covariance data libraries for sensitivity/uncertainty analyses. The goals and current achievements of both projects are reviewed.

1. Introduction

The implementation of safe, efficient, and optimized fissile material operations is increasingly dependent upon the use of radiation transport methods with accurate nuclear cross-section data. Moreover, covariance data that are provided in the evaluated nuclear data libraries are essential for assessing the impact of cross-section uncertainty data for nuclear fuel cycle analyses, reactor design, criticality safety analyses, etc. Within the framework of the Working Party on International Nuclear Data Evaluation Cooperation (WPEC), Subgroups (SGs) 20, 24, 26, and 28 have been working to address various covariance data issues. SG20 (now closed) and SG24 have been working to prepare covariance data for the resonance region and fast neutron energy regions, respectively. SG28 is focused on the development of covariance processing methods to prepare covariance data libraries for sensitivity/uncertainty analyses. SG26 efforts have identified nuclear data needs for advanced reactor systems. Because of the collective work of the WPEC subgroups, significant progress has been made to increase the availability of uncertainty data by developing new methods for covariance data evaluation and new evaluation formats to transmit and process the covariance data for use by nuclear analysts. Although a detailed discussion of all the efforts by the noted WPEC subgroups is beyond the scope of this paper, the objective of this paper is to summarize the efforts to produce and process covariance data by the active SGs 24 and 28 with appropriate references to SG20 and SG26.

---

[*] M. E. Dunn, dunnme@ornl.gov
Tel: (865) 574 5260; Fax: (865) 575 8481.

2. Overview of WPEC Subgroups 24 and 28

2.1. Subgroup 24

SG24 has been established to develop the methodology and tools for producing covariance data in the fast neutron region. Specific goals of the Subgroup are to

1. develop covariance generation capabilities in the nuclear reaction model codes EMPIRE (Herman et al., 2007), McGNASH (Young et al., 1996), and TALYS (Koning et al., 2004) using the Monte Carlo sensitivity method and KALMAN (Kawano and Shibata, 1997) Bayesian method;
2. compare results of these methods and validate the methodology against experimental covariance data;
3. address correlations between the fast neutron region and the neutron resonance region (low-priority goal); and
4. produce covariance data for a few selected materials.

2.2. Subgroup 28

Because of the efforts of SG20 (Kawano, 2006) and SG24, significant progress has been made to increase the availability of uncertainty data by developing new methods for covariance data evaluation and new evaluation formats to transmit the covariance data to the processing codes. The purpose of SG28 is to build upon the work completed by SG20 and SG24 and develop the requisite processing methods needed to process the resonance parameter covariance data, generate cross-section covariance data files, and demonstrate the use of covariance data in radiation transport analyses. The covariance evaluation work by SG20 provided much of the ground work needed to facilitate the work of SG28; however, resonance-region covariance evaluations for important uranium and plutonium isotopes were not prepared as part of the SG20 effort. As a result, the work scope for SG28 is organized into three phases with the following objectives:

1. The first phase of the project is performed concurrently with the second phase. Specifically, the objective of the first phase is to prepare a new evaluation with resonance-parameter covariance data for ^{235}U, which is the most difficult isotope to process in terms of the number of resonances and resulting covariance matrix size. This phase follows directly from the work of SG20, and the new evaluation is to be generated using the new methods and formats that were developed in SG20.

2. The second phase of the project is focused on the development of the needed covariance processing methods and the implementation of the new processing methodology in widely used cross-section processing systems [e.g., NJOY (MacFarlane and Muir, 1999) and AMPX (Dunn and Greene, 2002)]. In addition, the cross-section checking codes must be updated to support the efforts of the nuclear data centers to check covariance data files for dissemination by the different data projects.

3. The third phase is focused on the generation of covariance data files for use in radiation transport analyses. As part of the third phase, sensitivity/uncertainty (S/U) analysis tools are used to demonstrate the propagation of the covariance data in specific radiation transport applications such as the SCALE/TSUNAMI (SCALE, 2006) and SUS3D (SUS3D, 2000) radiation transport packages.

3. Subgroup 24 accomplishments

The WPEC SG24 activities concentrated on the development of covariance capabilities within codes used for theoretical modelling of nuclear reactions and investigation of methods for including experimental data in the Monte Carlo sensitivity method. As the result, both EMPIRE and TALYS codes are currently capable of producing nuclear data covariances and storing them in the Evaluated Nuclear Data File Version 6 (ENDF-6) format (Herman, 2005). TALYS is using a Monte Carlo (MC) approach to drawing model parameters from uncorrelated distributions. A similar approach is also being used in EMPIRE by Capote and Trkov. A different approach is being used at Brookhaven National Laboratory where the EMPIRE code has been coupled to the KALMAN code written by Kawano and Shibata (1997).

The main characteristics of both methods are as follows:

- Monte Carlo Method
    - Error propagation by means of the random sampling technique
- Calculation is slow
    - Higher-order effects are included
    - Including experimental data is not straightforward—might be possible by random sampling in the data space
- KALMAN Method
    - Error propagation with the first-order Taylor expansion
    - Calculation is fast
    - Second-order effects are not taken into account
    - Experimental data are combined using Bayes theory

The numerical test, involving calculation of uncertainties and correlation matrices with both methods, produced very close results indicating that, in absence of experimental data, both methods are equivalent. However, special care should be taken of the non-linearity (higher-order) effects in the KALMAN approach. In order to minimize the impact of non-linearity, the sensitivity matrix should be calculated using model parameter variations that are equal to the parameter uncertainties.

Inclusion of experimental data into the covariance determination still appears to be a major issue. The KALMAN method accounts for them naturally but suffers from the general "deficiency" of all Bayesian approaches—uncertainties tend to reach values that are considered far too small if many experimental data are included in the analysis and the representation of experimental systematic errors and their correlations is missing or inadequate. So far, the only practical remedy to this problem is to prevent uncertainties on the model parameters to fall below some sensible limit (say 3%). While this procedure is simple and effective, it introduces a highly arbitrary component into the estimation of uncertainties.

The MC method, in its original formulation by D. Smith, has no explicit provision for experimental data. A conceptually simple way to work around this is to reject MC samplings that produce results lying outside a reasonable band defined by the experimental data. Alternatively, one may adjust parameter sampling intervals in a way to ensure that final results are within the above mentioned band. This procedure, successfully used by Koning in TALYS, provides useful results on parameter uncertainties, but lacks mathematical rigour and is affected by arbitrary judgement.

The MC plus Muir's GANDR formalism (Trkov, 2005) is more rigorous in merging model and experimental results than the two above mentioned approaches, but it represents a hybrid approach rather than a full MC treatment of the evaluation process.

An interesting method, called backward-forward MC, has been developed by Bauge (2006). This method determines the model parameter covariance matrix from the MC sampling, combined with a chi-squared approach (backward MC), and then propagates the covariances of the model parameters to obtain the cross section covariance matrix by MC sampling (forward MC). Application of this elegant method, however, is limited to relatively simple cases since more complex ones are difficult to handle.

Recently, the new and quite rigorous Unified Monte Carlo (UMC) method has been proposed by Smith (2008). It is based on application of the Bayes theorem and the principle of maximum entropy and makes use of the MC sampling in the multivariate space. It combines model-based and experimental covariances into a consistent approach. The popular Generalized Least-Squares (GLS) method can be derived from the UMC under some simplifying assumption (e.g., linear dependence on the model parameters). The results of preliminary studies are very promising. Calculations of simple test cases show that UMC and GLS yield very similar results if linearity assumption holds. In non-linear cases, however, the differences between the two methods might be significant. So far, application of the UMC method has been limited to relatively straightforward problems. More realistic calculations are very time-consuming, but implementation of more advanced sampling algorithms, such as the one by Metropolis et al. (1953), can make the UMC approach practicable.

The intriguing issue is why the formally correct Bayesian approaches tend to produce too low uncertainties. Neglect of the intrinsic model uncertainties is considered a possible explanation.

Hopefully, the work by Pigni and Leeb (2006) will shed light on this problem.

We also note the search for the invariants (general measures) in covariances has been performed by Gai and Pronyaev (2007). These authors concluded that the uncertainties obtained in the course of the international evaluation of the neutron cross section standards are realistic, while the CSEWG estimate of the corridor of errors based on the "modern day experimental possibilities" is pessimistic. Any estimation considering uncertainties assigned to the individual experiments should give lower uncertainties.

SG24 efforts resulted in the considerable amount of covariances produced in support of the two major projects – ENDF/B.VII.0 and SG26. For ENDF/B-VII.0, 12 evaluations of covariances were produced with EMPIRE/KALMAN and three with EMPIRE/MC/GANDR methodology. The numbers are even more impressive in the case of SG26 for which preliminary covariances for 36 materials were produced with the EMPIRE/ KALMAN method and three with TALYS/MC. Finally, pure model-based covariances were generated by Pigni (2008) for 307 nuclei from ^{19}F to ^{209}Bi. These results were supplemented by estimates of covariances on actinides by Kawano. This large-scale project was initiated by the U.S. Nuclear Criticality Safety Program to provide a low-fidelity but complete set of covariances that could be used to exercise processing methodologies and tools.

4. Subgroup 28 accomplishments

4.1. ^{235}U resonance parameter covariance evaluation

The initial subgroup activity focused on the development of a resonance parameter covariance evaluation for ^{235}U using the SAMMY R-matrix computer code (Larson, 2003). SAMMY calculates various cross sections via R-matrix theory (Reich-Moore approximation), includes corrections for experimental conditions (Doppler and resolution broadening and multiple scattering corrections, backgrounds, etc.), and determines the best fit of the theoretical calculation to experimental data by means of the generalized least-squares fitting procedure. Experimental uncertainties are incorporated directly into the evaluation process in order to propagate those uncertainties into the resonance parameter results. Uranium-235 is an evaluation for which resonance parameters were prepared for ENDF/B-VI Release 5 and is the current resonance evaluation in ENDF/B-VII.0. The objective of the current evaluation work is to preserve the existing resonance parameters but provide a resonance parameter covariance data file that corresponds to the existing resonance parameters. In the traditional resonance evaluation approach, the evaluator prepares the resonance parameter covariance matrix (RPCM) as part of the resonance analysis. Historically, the RPCM was discarded once the resonance parameters were prepared for the cross-section evaluation. For ^{235}U, the resonance evaluation was prepared in the mid 1990s; however, the RPCM was not preserved. With the advent of robust sensitivity/uncertainty analysis methods in recent years, there is a demand for cross-section uncertainty data. In an effort to avoid a complete re-evaluation of existing cross-section data files, ORNL developed a “retroactive” covariance analysis method to prepare covariance matrices while preserving the existing resonance parameters. For ^{235}U, SAMMY was used to retroactively generate the resonance parameter covariance data (Arbanas et al., 2006).

The ^{235}U resonance evaluation extends from 10^{-5} eV to 2250 eV and has 3193 resonances. With five resonance parameters per resonance, there are 15,965 resonance parameters needed to describe the energy-dependent cross-section data. Based on the number of resonance parameters, the number of elements required to represent the upper triangular RPCM exceeds 127 million matrix elements, thereby requiring ~2 GB of memory to store the RPCM. In order to reduce the size of the covariance data while preserving the important uncertainty information, a procedure was developed to convert the ENDF File 32 RPCM representation into the ENDF File 33 cross-section covariance matrix (CSCM). A study was performed to determine the number of energy group boundaries needed to preserve the resonance region cross-section uncertainty information, and 580 energy boundaries are needed to represent the CSCM (Leal et al., 2008). As a result, the File 33 CSCM representation for ^{235}U is reduced from ~2 GB to ~30 MB and the File 33 CSCM is more suitable for distribution by the international data centers. Users needing the detailed ^{235}U RPCM data can obtain the RPCM data directly from ORNL.

Although SG28 work efforts have focused on the resonance region, concurrent SG20 and SG24 work efforts by Los Alamos National Laboratory (LANL) participants resulted in a "high-energy" (i.e., above the resonance region) covariance evaluation for ^{235}U. As a result, the ^{235}U RPCM has been merged with the high-energy covariance evaluation. Therefore, the combined efforts of SG20, SG24, and SG28 have resulted in a complete covariance evaluation for ^{235}U. During the SG24 and SG28 work time frame, additional work efforts by the SG participants also resulted in the development of full-energy-range covariance data files for ^{233}U, ^{238}U, and ^{239}Pu.

4.2. Covariance processing enhancements

With the complete ^{235}U covariance file available for processing and testing, SG28 efforts focused on making improvements to the existing cross-section processing software to enable production of covariance libraries for sensitivity/uncertainty analysis tools. As part of the international work activities, SG28 participants have developed new covariance processing methods for preparing covariance data libraries. In particular, the PUFF-IV module (Wiarda and Dunn, 2006) and the ERRORJ module (Chiba, 2007) of the AMPX and NJOY cross-section processing systems, respectively, have been updated for processing the latest ENDF/B-formatted covariance data files.

Prior to the start of SG 28, the AMPX covariance processing module PUFF-III (Dunn, 2000) was used at ORNL for processing covariance information in ENDF Files 31, 32, and 33. The SG28 work activities resulted in the development of a new version of the PUFF module (PUFF-IV) with expanded File 32 resonance parameter covariance processing capabilities. The processing code PUFF-IV is based on PUFF-III, but the original Fortran 77 code was rewritten in Fortran 90 to allow for a more modular design. PUFF-III had the capability to perform limited sensitivity analyses for select File 32 formats [i.e., restricted to Single-Level Breit-Wigner (SLBW) resonance format]. PUFF-IV can perform full processing of the following ENDF/B resonance formats: SLBW, Multi-level Breit-Wigner (MLBW), Reich-Moore, Adler-Adler, and R-Matrix Limited format (ENDF/B LRF=7). PUFF-IV processes the RPCM covariance matrices specified by the following ENDF/B compatibility flag (LCOMP) options: 0—only diagonal elements of matrix are provided; 1—full covariance matrix is provided; and 2—Compact Covariance Matrix format. Note that PUFF-IV does not process long-range covariance information as defined by the ENDF-102 manual. The user input for PUFF-IV is identical except for additional processing options. Test cases verify that PUFF-IV produces the same results as PUFF-III for File 31 and 33 processing and for File 32 processing where supported in PUFF-III. Additional comparisons have been performed with SAMMY to verify the processing results from PUFF-IV. The amount of covariance information that can be processed by PUFF-IV is limited only by available computer memory. Additional details concerning the PUFF-IV processing capabilities were published at the PHYSOR-2006 meeting (Wiarda et al., 2006). Although PUFF-IV is part of the AMPX cross-section processing system, a stand-alone PUFF-IV package has been developed and is available for distribution from the Radiation Safety Information Computational Center (RSICC) and OECD/NEA Data Bank. The stand-alone PUFF-IV package also includes utility modules to facilitate the data interface with the NJOY code system.

As part of SG activities, the ERRORJ module was updated to process the ENDF/B resonance parameter covariance formats. The ERRORJ module is based on the ERRORR module that has been distributed with NJOY. Prior to SG28, ERRORJ was a stand-alone module that was not part of NJOY. Recently, work by JAEA and LANL has resulted in the development of a new ERRORJ module that can be used as part of the NJOY code system. In addition, covariance data can be processed at all energies that include the resonance region and high-energy region. Comparison studies have been performed by SG28 participants to verify results from PUFF-IV and ERRORJ. The comparison studies have resulted in computational improvements in both code systems. As a result, versions of PUFF-IV and ERRORJ have been developed that will permit users to process existing ENDF/B covariance formats. Additional ERRORJ improvements have been made in the area of computational efficiency, resulting in faster covariance calculations. In some cases, a factor of 2 to 3 speed-up has been observed with the updated version of ERRORJ. The ERRORJ module will be distributed with the next NJOY release currently scheduled for 2008 (Oblozinsky, 2007).

4.3. Demonstration of covariance data use in sensitivity/uncertainty calculations

One of the important SG28 tasks is to demonstrate the use of the ^{235}U covariance data in S/U calculations. Two papers at this conference provide detailed demonstrations of the use of the covariance data with SCALE/TSUNAMI-3D and SUS3D (Leal et al., 2008; Gil and Leal, 2008).

In the work with SCALE (Leal et al., 2008), the TSUNAMI sequence uses the KENO V.a Monte Carlo neutron transport code to produce the sensitivity of multiplication factor (k_{eff}) to the cross-section data on an energy-dependent, nuclide-reaction-specific basis. In this calculation, the sensitivities of k_{eff} to the problem-dependent multigroup cross-section data are produced with adjoint-based perturbation theory. S/U calculations were performed using TSUNAMI for thermal, intermediate, and fast systems, and the calculations examined the impact of the ^{235}U uncertainty data. The calculations included ten thermal systems, and the average uncertainty in k_{eff} due to ^{235}U is ~0.7%. Results that demonstrate the propagation of ^{235}U covariance data for a thermal benchmark problem involving highly-enriched uranium solution are provided in Table 1. The benchmark problem modeled in Table 1 is the International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP) benchmark HEU-SOL-THERM-001-01 (International, 2006). Five intermediate benchmarks were calculated, and the uncertainty in k_{eff} due to ^{235}U ranged between 1% and 2.9% with the highest uncertainty occurring for the ZEUS series of benchmark problems. For fast-energy benchmark systems, the uncertainty in k_{eff} due to ^{235}U ranged between 1% and 3% as observed with the intermediate systems.

Table 1
Relative percent standard deviation of k_{eff} due to ^{235}U uncertainty data for the HEU-SOL-THERM-001-01 benchmark system (Leal et al., 2008)

	(n,γ)	(n,f)	(n,n)	(n,n')	(n,2n)	ν-bar
(n,γ)	$2.0057 \times 10^{-1} \pm 6.7745 \times 10^{-5}$					
(n,f)	$1.1572 \times 10^{-1} \pm 8.3693 \times 10^{-5}$	$8.5765 \times 10^{-2} \pm 9.1514 \times 10^{-5}$				
(n,n)	$1.4599 \times 10^{-2} \pm 3.8936 \times 10^{-6}$	$-6.4656 \times 10^{-3} \pm 2.9765 \times 10^{-6}$	$3.2326 \times 10^{-3} \pm 3.7405 \times 10^{-6}$			
(n,n')			$-6.1170\ 10^{-3} \pm 1.0276 \times 10^{-5}$	$1.0497 \times 10^{-2} \pm 1.2372 \times 10^{-5}$		
(n,2n)			$-6.4745\ 10^{-5} \pm 1.1040 \times 10^{-7}$		$5.6611 \times 10^{-4} \pm 5.2855 \times 10^{-7}$	
ν-bar						$6.7756 \times 10^{-1} \pm 5.2886 \times 10^{-5}$

Relative standard deviation % $\Delta k/k$ in k_{eff}
0.7213 ± 0.0002

S/U calculations have been performed using recently generated covariance data for ^{235}U, ^{238}U, and ^{239}Pu [Gil and Leal, 2008]. Moreover, SUS3D and TSUNAMI were used to calculate fast and thermal benchmark systems and determine the impact of the primary fissile isotope uncertainty on the system in k_{eff}. In the case of ^{235}U, the uncertainty in k_{eff} for select thermal and fast systems is ~0.7% and ~1%, respectively. The results of these benchmark calculations demonstrate the successful processing of the ^{235}U covariance data with PUFF-IV and ERRORJ followed by use of the covariance data in S/U calculations.

5. Conclusions

SG24 successfully applied covariance capabilities developed in the two main reaction codes—TALYS and EMPIRE. This effort resulted in a considerable amount of covariance data produced in support of ENDF/B.VII.0, SG26 and criticality safety.

In spite of the fact that many covariances were produced using the EMPIRE and TALYS codes, one should keep in mind that, still, there are issues to be resolved. The most pressing one is the treatment of experimental data in both KALMAN and MC methods. There is a hope that the new concept of Unified Monte Carlo turns out a viable approach.

Determination of covariances for materials without experimental data will necessarily rely on model calculations. To this end, we need reliable estimates of uncertainties and correlations for model parameters. This issue is addressed with the International Atomic Energy Agency (IAEA) coordinated research project RIPL-3. Finally, there is urgent need to clean the Exchange Format (EXFOR) data base of experimental data from mistakes, misprints, and obviously wrong data so that it can be safely used as a reference in large-scale, automated model calculations aiming at the determination of covariances for cross sections and model parameters. This important activity is being carried out within the WPEC Subgroup 30.

SG28 work activities have resulted in the development of full-energy-range cross-section covariance data for ^{235}U. Additional work efforts by the WPEC SG participants have resulted in the development of full-energy-range covariance data files for ^{233}U, ^{238}U, and ^{239}Pu. As part of the international work activities, SG28 participants have developed new covariance processing methods for preparing covariance data libraries. In particular, the PUFF-IV module and the ERRORJ module of the AMPX and NJOY cross-section processing systems, respectively, have been updated for processing the latest ENDF/B-formatted covariance data files. Using the new covariance processing tools, the cross-section covariance data files have been processed into covariance data library files for use in S/U radiation transport tools. In particular, ENDF/B-VII.0, SG24, and SG28 covariance files have been processed into multigroup covariance data files for use in S/U calculations. Furthermore, the processed covariance data files have been successfully used in SCALE/TSUNAMI and SUS3D sensitivity/uncertainty analysis tools, and the cross-section data uncertainty information has been propagated to system-calculated k_{eff} values for critical benchmark problems. In summary, the technical contributions of WPEC SG24 and SG28 have advanced the state of the art for covariance data evaluation and processing methods that will benefit the international nuclear community.

Acknowledgement

The work has been performed under the auspices of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) WPEC framework. The authors' leadership of the international subgroups on covariance data has been sponsored by the U.S. Department of Energy Nuclear Criticality Safety Program (NCSP) and the U.S. Nuclear Data Program (USNDP).

References

Arbanas, G., Leal, L.C., Larson, N.M., Derrien H., 2006. Retroactive Covariance Matrix for ^{235}U in the Resolved Resonance Region, American Nuclear Society, PHYSOR-2006 Topical Meeting, Vancouver, BC, Canada.

Bauge, E., 2006. Assessment of the covariance matrix of neutronic cross sections using the Backward-Forward Monte-Carlo Method. 11th International Conference on Nuclear Reaction Mechanisms, Varenna, June 12-16.

Chiba, G., 2007. ERRORJ: A code to Process Neutron-nuclide Reaction Cross-Section Covariance, Version 2.3, JAEA-Data/Code 2007-007.

Dunn, M.E., 2000. PUFF-III: A Code for Processing ENDF Uncertainty Data into Multigroup Covariance Matrices, NUREG/CR-6650 ORNL/TM-1999/235, Oak Ridge National Laboratory.

Dunn, M.E., Greene, N.M., 2002. AMPX-2000: A cross-section processing system for generating nuclear data for criticality safety applications. Trans. Am. Nucl. Soc., 86, 118–119.

Gai, E.V., Pronyaev, V., 2007. private communication by V. Pronyaev to M. Herman.

Gil, C.S. and Leal, L.C., 2008. A Sensitivity and Uncertainty Analysis of k_{eff} Values of Fast and Thermal Benchmarks with the Covariance Data, International Conference on the Physics of Reactors Nuclear Power: A sustainable Resource, PHYSOR-2008 Topical Meeting, Interlaken, Switzerland.

Herman, M.W., 2005. ENDF-6 Formats Manual: Data Formats and Procedures for the Evaluated Nuclear Data File ENDF/B-VI and ENDF/B-VII, National Nuclear Data Center, Brookhaven National Laboratory.

Herman, M., Capote, R., Carlson, B., Oblozinsky, P., Sin, M., Trkov, A., Wienke, H., Zerkin, V., 2007. EMPIRE: nuclear reaction model code system for data evaluation. Nuclear Data Sheets 108, 2655.

International Handbook of Evaluated Criticality Safety Benchmark Experiments., September 2006 (rev). NEA/NSC/DOC(95)03, OECD Nuclear Energy Agency.

Kawano, T., Shibata, K., 1997. Covariance evaluation system. JAERI Data/Code, Japan Atomic Energy Research Institute, Tokai, Japan.

Kawano, T., (Co-ordinator), 2006. Covariance Matrix Evaluation and Processing in the Resolved/Unresolved Resonance Regions. Final Report of the Working Party on International Evaluation Co-operation of the NEA Nuclear Science Committee, Vol. 20, NEA/WPEC-20, ISBN 92-64-02302-X.

Koning, A., Hilaire, S., Duijvestijn, M. , 2004. TALYS-0.64 a nuclear reaction program. Report 21297/04.62741/P FAI/AK/AK, NRG Petten.

Larson, N.M. 2003. Updated Users' Guide for SAMMY: Multilevel R-Matrix Fits to Neutron Data Using Bayes' Equations, ORNL/TM-9179/R6, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Leal, L., Mueller, D., Arbanas, G., Wiarda, D., Derrien, H., 2008. Impact of the ^{235}U covariance data in benchmark calculations, International Conference on the Physics of Reactors Nuclear Power: A sustainable Resource, PHYSOR-2008 Topical Meeting, Interlaken, Switzerland.

MacFarlane, R. E., Muir. D. W., 1999. NJOY99.0 Code System for Producing Pointwise and Multigroup Neutron and Photon Cross Sections from ENDF/B Data. RSICC Code Package: PSR-480.

Metropolis, N. et al., 1953. Equation of State Calculations by Fast Computing Machines. J. Chem. Phys. 21, 1087-1092.

Oblozinsky, P., 2007. Summary of the 57th Cross Section Evaluation Working Group Meeting November 6-8, 2007 and 10th U.S. Nuclear Data Program Meeting November 7-9, 2007," National Nuclear Data Center, Brookhaven National Laboratory.

Pigni, M.T., Leeb, H., 2006. Covariance model for Pb isotopes. Report ATI-NDC-2006-02.

Pigni, M.T., Herman, M., Oblozinsky, P., 2008. Low-fidelity cov ariances for neutron crosss ections on 57 structural and 31 heavy nuclei in the fast region. Report BNL-79985-2008-IR, see also BNL-79261-2007-IR.

SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation, November 2006. ORNL/TM-2005/39, Version 5.1, Vols. I–III, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-732.

Smith, D., 2008. A Unified Monte Carlo Approach to Fast Neutron Cross Section Data Evaluation. Report ANL/NDM-166.

SUS3D: A Multi-Dimensional, Discrete-Ordinates Based Cross Section Sensitivity and Uncertainty Analysis Code System, 2000. RSICC, Code Package: CCC-695.

Trkov, A. 2005. Summary Report of a Technical Meeting on Covariances of Nuclear Reaction Data: GANDR Project. Technical report INDC(NDS)-471, IAEA, Vienna.

Wiarda, D. And Dunn, M.E., 2006. PUFF-IV: A Code for Processing ENDF Uncertainty Data into Multigroup Covariance Matrices. Report ORNL/TM-2006/147, Oak Ridge National Laboratory.

Wiarda, D., Dunn, M.E., Greene, N.M., Larson, N. M., and Leal, L.C., 2006. New Capabilities for Processing Covariance Data in the Resonance Region, PHYSOR-2006 ANS Topical Meeting on Reactor Physics, Vancouver, BC, Canada.

Young, P.G., Arthur, E.D., Chadwick, M.B., 1996. Comprehensive nuclear model calculations: Theory and use of the GNASH code. Proc. of the IAEA Workshop on Nuclear Reaction Data and Nuclear Reactors — Physics, Design, and Safety Trieste, Italy, April 15-May 17. World Scientific Publishing, Singapore, pp. 227-404, Ltd., 1998.