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ScienceDirect
Nuclear Data Sheets 123 (2015) 21–26
Nuclear Data Sheets
www.elsevier.com/locate/nds

Nuclear Data Covariances in the Indian Context - Progress, Challenges, Excitement and Perspectives

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(Received 1 July 2014; revised received 30 August 2014; accepted 11 September 2014)

We present a brief overview of progress, challenges, excitement and perspectives in developing nuclear data covariances in the Indian context in relation to target accuracies and sensitivity studies that are of great importance to Bhabha's 3-stage nuclear programme for energy and non-energy applications.

I. INTRODUCTION

The paper presents the perspectives of the author on the role and importance of nuclear data covariances in the Indian context in advanced reactor design physics applications. Nuclear power is a viable option for meeting the energy needs of India. Indian approach involves a closed-fuel cycle involving multiple fuels. The Indian nuclear programme [1]–[4] envisages multiple fuel cycles including thorium utilization with closed-fuel cycle options such as in the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) [5] or equivalent. As multiple fuel cycles (e.g., U-Pu, Th-U), with the option of closing the fuel cycle are envisaged, the nuclear data requirements that are needed to develop the new systems with high burnup are demanding and include all the range of actinides and fission products for multiple fuels for a wide range of neutron energy spectra.

II. MOTIVATION IN INDIA TO GENERATE AND USE COVARIANCES IN NUCLEAR DATA

In the context of the Indian nuclear power programme [1]–[4], the importance and motivation in generating covariance error matrices in nuclear data has been recognized [6]–[9]. In reactor designs, the designer is interested in quantifying uncertainties associated with various integral quantities such as k_{eff}, control rod worth, coolant void coefficient, fuel temperature coefficient, shield thickness, burnup evolution, decay heat, foil dosimetry based spectrum determination etc. The calculated value of a given integral parameter has an associated uncertainty. This variance in the calculated value C of a given integral parameter arises from many components, arising from many causes, such as, uncertainties in nuclear data, approximations in modelling reactor calculations, uncertainty in modelling geometry, numerical approximations, treatment and collapsing of nuclear data (multigroup) etc. There also is the variance associated with the experimental value of the integral quantity. There is another uncertainty over and above all these above-mentioned uncertainties. That is the uncertainty in the reactor system characterization which is known, in the case of benchmarks, as the "benchmark uncertainty". In many cases, the nuclear data uncertainties dominate over other uncertainties in the final uncertainty in the ratio C/E of calculated value C to the experimental value E of the integral parameter. Rigorously, the uncertainty propagation using variance covariance matrices in nuclear data (of a very high rank matrix) results in a variance covariance matrix of the desired set of integral parameters of the power plant.

The safety and operational requirements of existing nuclear power plants have been engineered with a number of one-to-one mock-up experiments providing adequate and conservative safety margins. Even after 75 years since the discovery of the nuclear fission process, the basic nuclear physics experimental data remain more uncertain than the target accuracies needed by reactor designers who rigorously desire to assess propagation of uncertainties in simulations. Therefore, experimental critical facility programme to enable integral validation studies is also an essential part of any serious nuclear programme [9] to speed up implementation of nuclear energy with advanced generation systems. The critical facility programme requires generation and use of covariance data at both differential and integral level.

We recognize that cold critical experiments cannot be applied directly for all states and all design parameters (e.g. abnormal/accident conditions, void coefficient at operating conditions). Calculations with proper uncer-

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http://dx.doi.org/10.1016/j.nds.2014.12.005

tainty propagation tools are essential to assign margins. Basic physics understanding and better data physics of nuclear interactions and associated uncertainties in nuclear data are continuing to be rigorously sought by nuclear design communities in order to extrapolate, with uncertainty margins, to states of the nuclear power plant in conditions which are not covered or not possible to cover in "clean" and in one-to-one mock-up experiments [9].

In the early sixties and later, for instance, the 1971-81 WIMSD multigroup nuclear data libraries, the effective neutron-nuclear interaction cross sections of major fissile and fertile isotopes (^{235}U, ^{238}U and ^{239}Pu) were adjusted to fit the results of several hundreds of integral experiments. During those times, not only the nuclear data had large uncertainties but also the calculational models and approximations in condensing nuclear data were comparable or more as the computing resources were also limited. In many cases, in the sixties to eighties, the nuclear data seemed to have been available in greater detail than what the computing resources of reactor designers could accommodate with the approximations in number of multi-groups, resonance treatment, approximations in the treatment of anisotropy etc. Not all the adjustments made in earlier basic nuclear data were justified when improved differential measurements were conducted and results of new basic data became available several years later [10].

III. THE PHASE-I PROJECT ON COVARIANCES (2008-PRESENT)

The subject of nuclear data covariances is recognized as an important part of several ongoing nuclear data science activities in Nuclear Data Physics Centre of India (NDPCI), since 2007. A Phase-I project in collaboration with the Statistics department in Manipal University, Karnataka (Prof. K.M. Prasad and Prof. S. Nair) on nuclear data covariances was executed successfully during 2007-2011 period. In Phase-I, the emphasis was on a thorough basic understanding of the concept of covariances including assigning uncertainties to experimental data in terms of partial errors and micro-correlations, through a study and a detailed discussion of open literature, such as for instance, in Refs. [11]–[19].

During the Phase-I stage (2007-2011), the NDPCI has successfully conducted three national theme meetings sponsored by the Department of Atomic Energy-Board of Research in Nuclear Sciences (DAE-BRNS), in 2008 (Manipal University, Karnataka), 2010 (Vel-Tech University, Chennai, Tamilnadu) and 2013 (Bhabha Atomic Research Centre (BARC), Mumbai) on nuclear data covariance. These meetings helped sensitize the topic of covariances considerably. In order to give an idea to the interested reader on the content in these workshops, we mention below some of the topics, in a generic sense, as covered in these workshops.

- Basic probability, concept of error and error propagation.
- Linear systems, least-squares methods.
- Overview of uncertainties in measurements in nuclear data physics.
- Peelle's Pertinent Puzzle.
- Generalized least-squares using generalized inverse.
- Examples and exercises: Covariances and error propagation, sandwich error formula.
- Generation of covariance matrix using partial uncertainties and micro-correlations.
- Objective Bayesian theory.
- Modelling of nuclear reactions: Basic tools and methods.
- Nuclear data sensitivity coefficients in reactor physics: Adjoint flux and exact perturbation theory.
- ENDF formats on covariances.
- Bayesian evaluation technique, Kalman filter technique: Methods and application.
- Student seminars: Exercise on ZPR-6-7 fast reactor assembly; propagation of errors in k_{eff} using sandwich formula [7].
- Discussions on examples of numerical data of partial errors and micro-correlations and use of "cov" button in the IAEA EXFOR database [20].
- Total Monte Carlo approach for uncertainty propagation studies.
- Current status in India on progress in variance-covariance error matrix in nuclear data physics for advanced energy and non-energy applications.

These workshops on covariances were instrumental in improving basic understanding and in appreciating several difficult issues that were otherwise not straightforward to comprehend for beginners and researchers with the traditional background. For instance, the basic concept of nuclear data evaluation, new to the Indian system, such as the one which would provide output covariance data that are consistent with the cross section evaluation that weights input data with the inverse of its variance-covariance matrix was discussed in these workshops. Also it was stressed in these workshops that the documentation on Indian nuclear data experiments should attempt to have enough detail to allow full determination of the required input in terms of attributes, partial errors and micro-correlation matrices.