Annals of Nuclear Energy 83 (2015) 226–235

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Criticality Safety Evaluation of a Swiss wet storage pool using a global uncertainty analysis methodology

Marco Pecchia [a,*], Alexander Vasiliev [a], Hakim Ferroukhi [a], Andreas Pautz [a,b]

[a] Laboratory for Reactor Physics and Systems Behaviour, Paul Scherrer Institute (PSI), Switzerland
[b] École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

ARTICLE INFO

Article history:
Received 23 December 2014
Received in revised form 19 March 2015
Accepted 21 March 2015

Keywords:
Uncertainty quantification
Manufacturing parameters
Criticality safety evaluations
Monte Carlo codes
Repeated model structures

ABSTRACT

Uncertainty quantification is a key component in the Criticality Safety Evaluation (CSE) of spent nuclear fuel systems. An important source of uncertainties is caused by manufacturing and technological parameter tolerances. In this work, such class of uncertainties are evaluated for a Swiss wet storage pool. The selected configuration corresponds to a case where the target criticality eigenvalue is close to the upper criticality safety limits. Although current PSI CSE safety criteria are fulfilled, it is reasonable to apply uncertainty quantification methodologies in order to provide the regulatory authorities with additional information relevant for safety evaluations.

The MTUQ (Manufacturing and Technological Uncertainty Quantification) methodology, based on global stochastic sampling was the selected tool for the analysis. Such tool is specifically designed for the treatment of geometrical/material uncertainties for any target system. In particular the MTUQ advanced modelling capability allows the implementation of realistic boundary condition, with a resulting detailed evaluation of statistical quantities of interest in CSE. Therein, the computational code implemented is the MCNP Monte Carlo based neutron transport code.

The analysis showed the benefits in using realistic modelling compared to the traditional one-factor-at-time methodology applied to system modelled using repeated structures. A detailed comparison between the 2 approaches is also presented. Finally, it is discussed the role of asymmetrical probability distribution functions to feed the global statistical methods.

1. Introduction

Uncertainty quantification and sensitivity analysis (UQ/SA) are components in the Criticality Safety Evaluation (CSE) of spent nuclear fuel systems. The development of robust UQ/SA methodologies is a target of the on-going research at Paul Scherrer Institut (PSI). In the context of CSE, the main sources of uncertainties nowadays, when applying Monte Carlo continuous-energy codes, are nuclear data along with manufacturing tolerances and technological parameters. For the latter class of uncertainty was recently developed the MTUQ tool (Pecchia et al., accepted for publication).

The selected mathematical approach implemented in MTUQ is a probabilistic methods based on simultaneous stochastic sampling of system parameters. This method can, for an arbitrary (large) number of parameters, explore simultaneously various sources of uncertainties through statistical sampling of Probability Distribution Functions (PDFs) parameters. Therefore, the main advantage is to ensure the capability to capture possible higher-order non-linear interactions (Saltelli et al., 2008). This latter feature ensures that methods based on global stochastic sampling are superior to traditional analysis based on evaluating the effects of single parameters at once. This latter class of methods will be here referred as One-Factor-At-Time (OFAT) methodologies. To perform sensitivity analysis with UQ based on global statistical sampling, the MTUQ methodology is complemented by the so-called "Global Sensitivity Analysis" (GSA) methods Saltelli et al., 2008. In contrast, the sensitivity coefficients evaluated using OFAT methods, are here defined as local SA because evaluated using local partial derivative.

Within the MTUQ methodology, the Monte Carlo based particle transport codes MCNPX (Pelowitz, 2011) and MCNP6 (Goorley et al., 2012) were selected as main tool for the analysis. A relevant feature implemented in MTUQ is the capability to take into account functional relationships, including correlations or physical

* Corresponding author.
E-mail addresses: marco.pecchia@psi.ch (M. Pecchia), alexander.vasiliev@psi.ch (A. Vasiliev), hakim.ferroukhi@psi.ch (H. Ferroukhi), andreas.pautz@psi.ch (A. Pautz).

http://dx.doi.org/10.1016/j.anucene.2015.03.052
0306-4549/

constraints between the samples. In this work the MTUQ methodology is applied to analyse a Swiss wet storage pool. Previous CSE analyses investigated the criticality eigenvalue (*k*-eff) as function of the location of spent fuel assembly (FA) and initial enrichment (Kolbe et al., 2011). In that context, it was found that, in certain configuration, the calculated *k*-eff was close to the Upper Safety Limit (USL). In particular a preliminary PSI methodology based on MCNPX and SUSA3.6 tool (Kloos, 2008) (PSI-MCNPX/SUSA) was used to supply a UQ in such relevant case. Nevertheless, the PSI-MCNPX/SUSA methodology had several restriction in model variable constraints, hence, only a limited set of parameters was included in the analysis. The target of this work is to re-evaluate the uncertainty due to technological parameters benefiting from the advanced modelling capability provided by MTUQ. In particular, the effect of different modelling options is investigated, together with the effect of the selection of PDF to the statistical quantity of interest. Finally, a comparison with conventional UQ/SA based on OFAT based method is provided, highlighting the main advantages of global stochastic sampling based methods.

2. Overview of the MTUQ methodology

The MTUQ methodology consists of a software platform developed with the PERL computer language and based on a modular design using an object-oriented programming paradigm. A detailed description of the methodology is reported in Pecchia et al. (accepted for publication); here, only the main features are highlighted. Like other uncertainty and sensitivity analysis tools, the MTUQ main modules are dedicated to

(a) Random sampling design;
(b) Interface with the computational code;
(c) Statistical analysis of results.

A flow chart of the MTUQ methodology is reported in Fig. 1. In this case, the MCNP codes have the role of the computation code. The selected tool for the random sampling design is the ROOT framework (Brun and Rademakers, 1997) developed by the Conseil Européen pour la Recherche Nucléaire (CERN) and upon which the URANIE platform (Gaudier, 2010) also used at PSI is based (Yun et al., 2014). Finally, an interface with the R language for statistical computing (R Development Team, 2008) is currently applied to conduct the statistical analysis of all the results obtained from the sampled MCNP model outputs (e.g. the *k*-eff of the system).

The sampled model inputs are the manufacturing and technological parameters. These parameters are grouped in 3 main families: geometry specifications, material isotopic compositions and material densities, which can be modelled separately and independently. Functional relationships (i.e. constraints) can also be defined to prevent geometrical overlapping among regions.

A unique feature of the MTUQ methodology is the capability to model independently elements belonging to the so-called 'repeated structures' facility (Pelowitz, 2011), which allows repeating basic structures in regular lattices. Such facility is commonly used to model many system of relevance in nuclear engineering (e.g. wet storage pools, transport cask, etc.). This level of modelling is achieved through the dedicated MC-TRIP (Monte Carlo codes auxiliary tool for recursive input deck parameterization) module developed at PSI to handle the pre-processing of the MCNP input. The role of MC-TRIP is to parameterize a generic MCNP input, and if necessary, expand the repeated structures such as to allow for an individual modelling of each system element. Hereinafter, the term "global modelling" will be used to refer to perturbations repeated in a uniform manner throughout a given system, whereas "individual modelling" will refer to perturbations of each individual component in repeated structures. An example of the global modelling is given in Fig. 2, in which the fuel pellet/cladding radiuses are perturbed and the effect is repeated equally throughout the lattice. As Fig. 2 shows, a global modelling overstates the perturbation effects and might also result in physically unrealistic perturbed models. The main consequence is a potentially over- or under prediction of statistical quantities evaluated from the output *k*-eff set.

This latter problem is an issue also when traditional OFAT methods are used, consisting in perturbing one parameter at time keeping all the other at nominal values. Application of OFAT methods plus repeated structure facility requires the use of several procedures in order to mitigate such effect (e.g. dividing the resulting perturbation of *k*-eff by the square root of the number of basic units (Dean, 2008); however, such procedures are still an approximation. A comparison between OFAT and stochastic sampling methods is discussed in more details in Chapter 4.3.

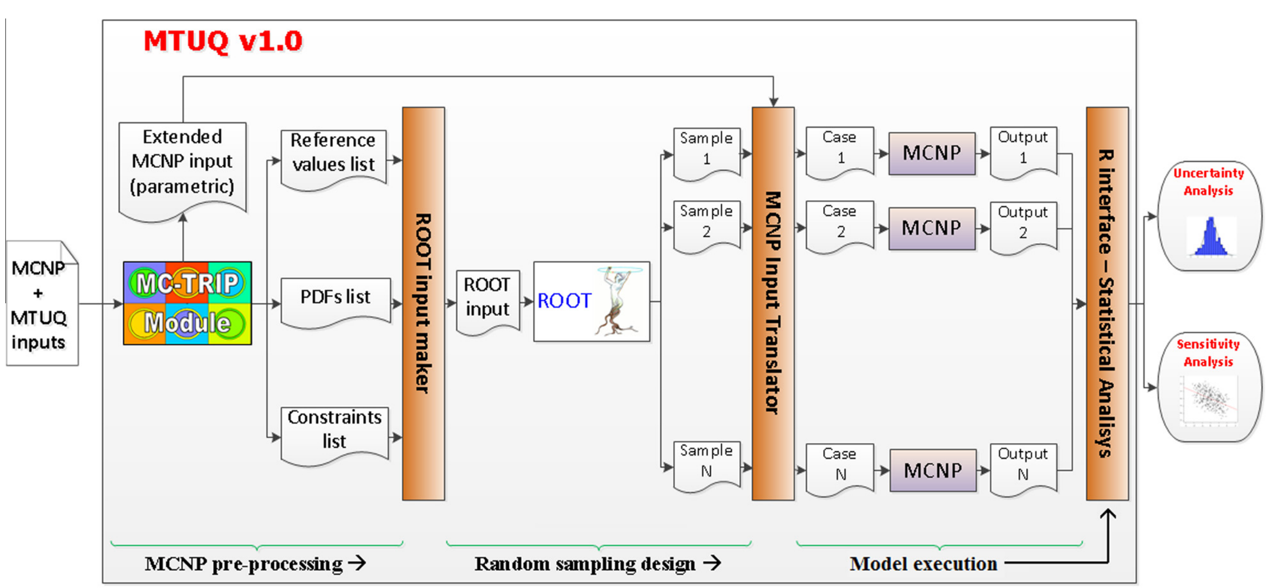

Fig. 1. MTUQ flow chart.