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Uncertainty analysis of PKL SBLOCA G7.1 test simulation using TRACE with Wilks and GAM surrogate methods

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HIGHLIGHTS

- Uncertainty analysis using order statistics and metamodelling.
- Plackett-Burman design of experiments to select significant variables.
- Uncertainty analysis of an experiment conducted at PKL facility.

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ABSTRACT

The Nuclear Energy Agency auspices simulation of experiments in different facilities under several programs. One on them consisted of performing a counterpart test between ROSA/LSTF and PKL facilities, with the main objective of determining the effectiveness of late accident management actions in a small break loss of coolant accident. The results obtained by TRACE code for PKL experiment SBLOCA G7.1 (a scaled model of Konvoi reactor) were in good agreement with the experiments. However, in the simulation process, uncertainty was not accounted. Uncertainty analysis, following the principles of Best Estimate Plus Uncertainty (BEPU) approach, must be performed to measure the effect of uncertainties on the evolution of safety variables of interest, such as the maximum of the Peak Cladding Temperature (PCTmax) in the experiment. In this paper we present a comparison between two uncertainty analysis techniques. The first technique is based on order statistics that makes use of Wilks' formula. The second technique is based on a Generalized Additive Model (GAM) that substitutes the thermal-hydraulic code, without and with consideration of errors in adjusting the GAM model. The comparison of the uncertainty analysis results makes use of several performance metrics such as coverage, Coefficient of Variation and conservativeness. Based on the results of these metrics it can be concluded that the GAMPE (GAM Plus Error) provides the best performance, in particular, when using small sample size, i.e. n = 59, 93. For larger sample sizes, i.e. n = 124, 153, GAMPE and Wilks' results presents similar performance.

1. Introduction

Experimental facilities are of great importance in nuclear safety to improve the knowledge on commercial nuclear power plants (NPP) behavior under normal and accidental situations. Thus, it is possible to anticipate the evolution of the main safety variables under an accidental situation and identify generic issues that may affect the safety of nuclear power plants.

The results obtained in the experiments undertaken in such facilities are essential to develop and improve the models implemented in the thermal-hydraulic codes. The data collected in the experiments are necessary in the assessment of the capabilities of thermal-hydraulic codes to reproduce the different physical phenomena that may take place inside the reactor in accidental situations. Best estimate (BE) thermal-hydraulic (TH) codes, as RELAP-5 (Carlos et al., 2008), TRAC, CATHARE (Valette et al., 2011), ATHLET (Di Marcello et al., 2016) or TRACE (Belaid et al., 2010) are some examples. Nowadays, TRACE code (TRAC/RELAP Advanced Computational Engine) is being developed and validated to make use of the most favorable characteristics of RELAP-5 and

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Nomenclature

ACC	accumulators
AFW	auxiliary feedwater
AM	accident management
BE	best estimate
BEPU	Best Estimate Plus Uncertainty
BWR	Boiling Water Reactor
CC	core exit temperature
CET	conservativeness index
CD	Coverage standard Deviation
CM	Coverage Mean
CV	Coefficient of Variation
DOE	design of experiments
FOS	First Order Statistics
GAM	Generalized Additive Model
GAMPE	Generalized Additive Model Plus Error
HPIS	high pressure injection system
LOCA	loss-of-coolant accident
LPIS	Low Pressure Injection System
NEA	Nuclear Energy Agency
NPP	nuclear power plant
OECD	organisation for economic cooperation and development
OS	Order Statistics
PCT	Peak Cladding Temperature
PDF	probability distribution function
PKL	Primarkreislauf Versuchsanlage
PWR	Pressurized Water Reactor
ROSA/LSTF	Rig-of-Safety Assessment Large Scale Test Facility
SBLOCA	Small break Loss-of-Coolant Accident
SG	steam generator
STL	Standard Tolerance Level
TH	Thermal Hydraulic
TRACE	TRAC/RELAP Advanced Computational Engine
UQ	uncertainty quantification

TRAC codes to simulate both, Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR), technologies.

In the simulation process there exist code parameters and models that may be unknown or uncertain. This uncertainty may result in differences when a certain transient is simulated with a TH code depending on the code inputs chosen by the analyst (NAP, 2012).

Therefore, it is necessary to identify the most influencing parameters and models and to characterize their impact on the code response uncertainty, in terms of Figures of Merit (FOMs) related with safety variables. Often, a probabilistic approach is used to formulate the uncertainty of input parameters and data, and to propagate them towards the output using the BE code, which is also referred as a BEPU (Best Estimate Plus Uncertainty) approach (Glaeser, 2007). The purpose of the application of uncertainty propagation methodologies is to obtain the probability distribution function (PDF) of the safety related FOMs, or at least, an estimator, as the 95/95 Standard Tolerance Level (STL) (IAEA, 2009).

One of the most employed technique to obtain estimators of PDF output variables, i.e. FOMs, is OS (Order Statistics) based on Wilks' formula (Wilks, 1941). This technique permits to obtain the STL with a determined coverage/confidence value with reduced number of simulations (Beal, 2012), but only provides the safety variable bound. Other techniques, such as, the construction of surrogate models, or metamodelling, in which the TH code is substituted by a model in order to obtain an estimate of the FOMs of interest, or a related variable, permits extracting more information from the PDF with a reasonable computational cost (Carlos et al., 2013; Di Maio et al., 2015; Di Maio et al., 2016). However, as the number of input parameters increase, the construction of a metamodel requires a larger number of TH code simulations. In addition, NPP transient analysis involve simulations of complex phenomena, which can increase the computational burden. In fact, computational effort is one of the main problems in NPP transients simulations including uncertainty analysis, i.e. BEPU, as each TH code transient simulation may have a high computational cost. Thus, it is necessary to reduce the initially proposed uncertainty parameters in order to make the study feasible.

In this work, uncertainty analysis of a Small Break Loss of Coolant Accident (SBLOCA) at the PKL Test Facility is performed by simulation using two techniques: a metamodel based in Generalized Additive Models (GAM) and an OS using Wilks' formula.

The paper is organized as follows. In Section 2, the proposed methodology is explained, which includes the Plackett-Burman design of experiment, the Wilks' method and the employed metamodel. In addition, performance metrics are also described, which are used in order to check the goodness of the methods. Section 3 presents the case of application, which includes: a brief description of PKL facility, the TRACE model developed to simulate the transient, a description of the experiment SBLOCA, the base case results and the uncertainty analysis using the different techniques. Finally, Section 4 presents the main conclusions obtained.

2. Methodology

The methodology applied in this work is shown in Fig. 1 and consists of the following steps. First, a calibration of the simulation model by means of a base case is performed using experimental data. In this case, the safety variable of interest is the Peak Cladding Temperature (PCT) and the maximum value along the transient, i.e. the PCTmax, is adopted as FOM. Then, a sensitivity analysis has been performed in order to select the most influencing code inputs for the selected FOM and transient. Once the inputs have been selected, the uncertainty analysis is performed by two different approaches: Wilks' method and metamodelling. The metamodel selected to substitute TRACE code in the uncertainty analysis is a GAM, which is applied both with and without a treatment of the error. Finally, performance metrics are used in order to assess the goodness of the different uncertainty analysis methods.

2.1. Design of experiments. Plackett-Burman design

Design of experiments (DOE) objective is to plan experiments for extracting the maximum amount of information with the minimum number of tests or runs. In this study the objective of the DOE is to obtain the most significant variables, which can help in reducing the number of uncertain parameters. This will result in less runs to build the metamodel.

Among the different methods of DOE, the Plackett-Burman design, which objective is to find experimental designs for investigating the dependence of some dependent variables (outputs) on a number of independent variables (inputs) using a limited number of experiments (Plackett and Burman, 1946). This method belongs to the screening experimental designs methods, in which each variable takes L levels. Thus, if k parameters are selected and, e.g. they have two levels, the minimum number of runs required by Plackett Burman design, is given by: