

1. Introduction

Deterministic safety analysis frequently referred to as accident analysis is an important tool for confirming the adequacy and efficiency of provisions within the defense in depth concept for the safety of Nuclear Power Plants.

Typical upgraded international licensing environments offer two acceptable options for demonstrating that the safety is ensured with sufficient margin: use of best estimate computer codes either combined with conservative input data or with realistic input data but associated with evaluation of uncertainty of results. The second option is particularly attractive because it allows for more precise specification of safety margins and their potential use for higher operational flexibility. This constitutes the framework for the present paper.

Thermal-hydraulic system codes are needed to perform deterministic safety analyses and are suitable to calculate complex accident scenarios expected in water cooled nuclear reactors. The outputs of those codes are affected by unavoidable errors that are referred as uncertainties, notwithstanding extensive qualification programs carried out in the last three or four decades. In the current situation it can be said that the experimental programs have not been capable to prevent those errors but to identify and to characterize them.

The present paper, based on an activity still in progress at the IAEA, [1], aims at discussing the major source of errors or uncertainties, at characterizing approaches for performing uncertainty studies and at presenting one successful uncertainty method proposed by the University of Pisa.

The first uncertainty framework was proposed by US NRC and denominated Code Scaling, Applicability, and Uncertainty (CSAU, [2]). The application of the CSAU methodology resulted in the calculation of the PCT during a LBLOCA Design Basis Accident (DBA) event for a Westinghouse 4-loop pressurized water reactor (PWR) with the uncertainty to a 95% confidence level. The PCT was calculated using the TRAC thermal-hydraulic analysis code and was given as a single-valued number with uncertainty bands. In the meantime, a number of uncertainty methodologies have been created in other countries, including the GRS, the UMAE and the AEA Technology methods, as summarized in [3] and [4]. These methods, although sharing a common goal with CSAU, use different techniques and procedures to obtain the uncertainties on key calculated quantities. More importantly, these methods have progressed far beyond the capabilities of the early CSAU analysis. Presently, uncertainty bands can be derived (both upper and lower) for any desired quantity throughout the transient of interest, not only point values like peak cladding temperature. For one case, the uncertainty method is coupled with the thermal-hydraulic code and is denominated CIAU (Code with capability of Internal Assessment of Uncertainty, [5]) and discussed below in more detail.

2. The Origin of Uncertainty

Application of best-estimate (realistic) computer codes to the safety analysis of nuclear power plants implies the evaluation of uncertainties. This is connected with the (imperfect) nature of the codes and of the process of codes application. In other words, ‘sources of uncertainty’ affect the predictions by best-estimate codes and must be taken into account. Three major sources of uncertainty are mentioned in the Annex II of the IAEA guidance Accident Analyses for Nuclear Power Plants, [6]: a) Code or model uncertainty; b) Representation or ‘simulation uncertainty’; c) Plant uncertainty. A more detailed list of uncertainty sources can be found in [4], where an attempt has been made to distinguish ‘independent’ sources of ‘basic’ uncertainty. The list includes the following items:
A) Balance (or conservation) equations are approximate. Namely, not all the interactions between steam and liquid are included, and the equations are solved within cylindrical pipes: no consideration of geometric discontinuities, situation not common for code applications to the analysis of Nuclear Power Plants transient scenarios.

B) Geometry averaging at a cross section scale: the need “to average” the fluid conditions at the geometry level makes necessary the ‘porous media approach’. Velocity profiles happen in the reality: These correspond to the ‘open media approach’. The lack of consideration of the velocity profile, i.e. cross-section averaging, constitutes an uncertainty source of ‘geometric origin’.

C) The 2nd principle of thermodynamics is not necessarily fulfilled by codes.

D) Models of current interest for thermal-hydraulic system codes are constituted by a set of partial derivatives equations. The numerical solution is approximate, therefore, approximate equations are solved by approximate numerical methods.

E) Extensive and unavoidable use is made of empirical correlations. These are needed ‘to close’ the balance equations and are also reported as ‘constitutive equations’ or ‘closure relationships’. A typical problem is connected with the ranges of validity that are not fully specified.

F) A paradox: shall be noted: ‘Steady State’ & ‘Fully Developed’ (SS & FD) flow condition is a necessary prerequisite or condition adopted when deriving correlations. In other terms, all qualified correlations must be derived under SS & FD flow conditions. However, almost in no region of the Nuclear Power Plant those conditions apply during the course of an accident.

G) The state and the material properties are approximate.

H) Code User Effect (UE) exists. Different groups of users having available the same code and the same information for modelling a Nuclear Power Plant do not achieve the same results. UE (see also below) is originated, for instance, by nodalisation development and by accepting the steady state performance of the nodalisation.

I) Computer/compiler effect exists.

J) Nodalisation (N) effect exists. The N is the result of a wide range brainstorming process where user expertise, computer power and code manual play a role. There is a number of required code input values that cannot be covered by logical recommendations: the user expertise needed to fix those input values may reveal inadequate and constitutes the origin of a specific source of uncertainty.

K) Imperfect knowledge of Boundary and Initial Conditions (BIC). Some BIC values are unknown or known with approximation: the code user must add information. This process unavoidably causes an impact on the results that is not easily traceable and constitutes a specific source of uncertainty.

L) Code/model deficiencies cannot be excluded.

3. The approaches to calculate the uncertainty

An uncertainty analysis consists of identification and characterization of relevant input parameters (input uncertainty) as well as of the methodology to quantify the global influence of the combination of these uncertainties on selected output parameters (output uncertainty). These two main items are treated in different ways by the various methods.

One approach is to evaluate the ‘propagation of input uncertainties’, Fig. 1: uncertainty is derived following the identification of ‘uncertain’ input parameters with specified ranges or probability distributions of these parameters, and performing calculations varying these parameters. The propagation of input uncertainties can be performed either by deterministic or by probabilistic methods. The other approach, Fig. 2, is the ‘extrapolation of output uncertainty’: uncertainty is derived from the (output) uncertainty based on the comparison between calculation results and significant experimental data.
Figure 1 – Uncertainty approach: propagation of code input uncertainty.

The propagation of code input uncertainty
The GRS is selected as the prototype method, [7], for the description of the “propagation of code input uncertainty” approach. In these methods, the state of knowledge of each uncertain input parameter within its range is expressed by a subjective probability distribution. The word “subjective” expresses the state of knowledge rather than stochastic variability. Dependencies between uncertain input parameters should be identified and quantified. Peculiarities of the GRS method are:

- The uncertainty space of input parameters (defined by their uncertainty ranges) is sampled at random according to the combined subjective probability distribution of the uncertain parameters and code calculations are performed by sampled sets of parameters.
- The number of code calculations is determined by the requirement to estimate a tolerance/confidence interval for the quantity of interest (such as peak clad temperature). The Wilks formula is used to determine the number of calculations needed for deriving the uncertainty bands.
- Statistical evaluations are performed to determine the sensitivities of input parameter uncertainties on the uncertainties of key results (parameter importance analysis).
- There are no limits for the number of uncertain parameters to be considered in the analysis and the calculated uncertainty has a well-established statistical basis.

Figure 2 – Uncertainty approach: propagation of code output errors.
Upper statistical tolerance limits are the upper $\beta$ confidence for the chosen $\alpha$ fractile. The fractile indicates the probability content of the probability distributions of the code results (e.g. $\alpha = 95\%$ means that PCT is below the tolerance limit with at least $\alpha = 95\%$ probability). One can be $\beta\%$ confident that at least $\alpha\%$ of the combined influence of all the characterized uncertainties are below the tolerance limit. The smallest number $n$ of code runs to be performed is given by the Wilks formula
\[
(1 - \alpha/100)^n \geq \beta/100
\]
and is representing the size of a random sample (a number of calculations) such that the maximum calculated value in the sample is an upper statistical tolerance limit. The required number $n$ of code runs for the upper 95% fractile is: 59 at 95% confidence level. The number of code runs is independent of the number of selected input uncertain parameters.

The propagation of code output errors
The UMAE is the prototype method, [8], for the description of "the propagation of code output errors" approach. The method focuses on the propagation of errors from a suitable database calculating the final uncertainty by extrapolating the accuracy from relevant integral experiments to full scale NPP. The method utilizes a database from similar tests and counterpart tests performed in integral test facilities, that are representative of plant conditions. The quantification of code accuracy is carried out by using a procedure based on the Fast Fourier Transform characterizing the discrepancies between code calculations and experimental data in the frequency domain, and defining figures of merit for the accuracy of each calculation. Different requirements have to be fulfilled in order to extrapolate the accuracy.

Calculations of both Integral Test Facility experiments and NPP transients are used to attain uncertainty from accuracy. Nodalisations are set up and qualified against experimental data by an iterative procedure, requiring that a reasonable level of accuracy is satisfied. Similar criteria are adopted in developing plant nodalisation and in performing plant transient calculations. The demonstration of the similarity of the phenomena exhibited in test facilities and in plant calculations, accounting for scaling laws considerations, leads to the Analytical Simulation Model (ASM), i.e. a qualified nodalisation of the NPP. The flow diagram of UMAE is given in Fig. 3. The bases of the methods and the conditions to be fulfilled for its application, including the use of the FFTBM can be found in [9] to [13].

Figure 3 – UMAE flow diagram (also adopted within the process of application of CIAU).

4. The CIAU method
All of the uncertainty evaluation methods are affected by two main limitations: a) resources needed for their application may be very demanding, ranging to up to several man-years; b) The achieved results may be strongly method/user dependent. The last item should be considered together with the code-user effect, widely studied in the past, [9], and may threaten the usefulness or the practical applicability of the results achieved by an uncertainty method. The CIAU method, [5], has been developed with the objective of reducing the above limitations. The basic idea of the CIAU can be summarized in two parts, Fig. 4: i) consideration of plant status: each status is characterized by the value of six relevant quantities (i.e. a hypercube) and by the value of the time since the transient start; ii) association of an uncertainty to each plant status.

In the case of a PWR the six quantities are: 1) the upper plenum pressure, 2) the primary loop mass inventory, 3) the steam generator pressure, 4) the cladding surface temperature at 2/3 of core active length, 5) the core power, 6) the steam generator down-comer collapsed liquid level.

Figure 4 – Outline of the idea at the basis of the CIAU method.

A hypercube and a time interval characterize a unique plant status to the aim of uncertainty evaluation. All plant statuses are characterized by a matrix of hypercubes and by a vector of time intervals. Let us define $Y$ as a generic thermal-hydraulic code output plotted versus time. Each point of the curve is affected by a quantity uncertainty ($U_q$) and by a time uncertainty ($U_t$). Owing to the uncertainty, each point may take any value within the rectangle identified by the quantity and the time uncertainty. The value of uncertainty, corresponding to each edge of the rectangle, can be defined in probabilistic terms. This satisfies the requirement of a 95% probability level to be acceptable to the NRC staff for comparison of best estimate predictions of postulated transients to the licensing limits in 10 CFR (Code of Federal Regulation) Part 50.

The uncertainty in code prediction is the same for each plant status. A Quantity Uncertainty Matrix (QUM) and a Time Uncertainty Vector (TUV) can be set up including values of $U_q$ and $U_t$ derived by an uncertainty methodology. The UMAE constitutes the ‘engine’ for the rotation of the CIAU shaft. The QAM and TAV, respectively Quantity Accuracy Matrix and Time Accuracy Vector, are derived from an UMAE like process and are the precursor of QUM and TUV. However, within the CIAU framework, any uncertainty method can be used to derive directly QUM and TUV.

5. Conclusions

Mature methods exist nowadays that are capable ‘of fixing the boundaries’ for the error of thermal-hydraulic system codes. Two main approaches, characterized as “propagation of code input uncertainty” and “propagation of code output errors”, have been discussed in the paper. These approaches are pursued by two reference methods ready for applications, i.e. the GRS method and the CIAU. The last method has been described with more detail.
All the working methods to estimate the uncertainty derive from complex pictures of a complex reality that is constituted by the transient scenarios of water cooled NPP. Even though extensive documentation exist and (in most cases) is available, the level of common understanding about the capabilities and the drawbacks of the methods is not sufficient for achieving a full acceptability of the method. Therefore, rather than additional qualification of the methods, training and communication are needed for spreading the application of coupled best-estimate calculation and uncertainty evaluation.

6. References