Nuclear Mathematical and Computational Sciences: A Century in Review, A Century Anew
Gatlinburg, Tennessee, April 6-11, 2003, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2003)

METHODOLOGY OF INTERNAL ASSESSMENT OF UNCERTAINTY FOR SAFETY ANALYSIS CODE

A. Petruzzi and K. Ivanov
Department of Mechanical and Nuclear Engineering
The Pennsylvania State University
230 Reber Building, University Park, PA 16802
axp46@psu.edu; kni1@psu.edu

F. D'Auria and W. Giannotti
Dipartimento di Ingegneria Meccanica, Nucleare e della Produzione
Università di Pisa
Via Diotisalvi 2, 56100 Pisa, Italy
dauria@ing.unipi.it; w.giannotti@ing.unipi.it

ABSTRACT

The paper stresses how the internal assessment of uncertainty is a desirable capability for thermal-hydraulic system codes. This consists of the possibility of obtaining proper uncertainty bands each time a nuclear plant transient scenario is calculated. A methodology suitable for introducing such a capability into a system code is discussed. At the basis of the derivation of the code with (the capability of) internal assessment of uncertainty (CIAU), there is the uncertainty methodology based on the accuracy extrapolation (UMAE), previously proposed by the University of Pisa, although other uncertainty methodologies can be used for the same purpose. The idea of the CIAU is the identification and the characterization of standard plant statuses and the association of uncertainty to each status. One hypercube and one time interval identify the plant status. Quantity and time uncertainties are combined for each plant status. The RELAP5/MOD3.2 system code has been used inside the CIAU to show the applicability of the proposed method. The derivation of the methodology is discussed, and reference results of pressurized water reactor plant transients are shown bounded by the CIAU calculated uncertainty bands. Recently, a new activity has been started with the aim to extend the CIAU to the 3D neutronics/thermal-hydraulics coupled codes.

Key Words: Uncertainty, Assessment, Safety, UMAE, CIAU.

1. INTRODUCTION

In the past, large uncertainties in the computer models used for nuclear power system design and licensing have been compensated using highly conservative assumptions. The loss-of-coolant-accident evaluation model is one of the main examples about this approach. However, the use of excessive conservatism results in significant economic penalty and not necessarily providing commensurate safety benefit. As a result, today two important trends can be identified:

- A move towards more probabilistic, rather than deterministic regulation;
- An use of "realistic" code predictions than "conservative" estimates.

Both of these approaches require to replace subjective judgments about the adequacy of a code or of the degree of conservatism in the assumptions used in order to obtain logical quantitative measures of "how good" a code is.

Notwithstanding the important achievements and progress made in recent years, the predictions of the system codes, including RELAP5, are not exact but remain uncertain because [1]:

I. The assessment process depends upon data almost always measured in small scale facilities and not in the full power reactors;
II. The models and the solution methods in the codes are approximate: in some cases, fundamental laws of the physics are not considered.

Consequently, the results of the code calculations may not be applicable to give exact information on the behavior of a nuclear power plant (NPP) during postulated accident scenarios. Therefore, best estimate predictions of NPP scenarios must be supplemented by proper uncertainty evaluations in order to be meaningful.

In addition, the comparison among different uncertainty methodologies [1] shows that:

- The methods lead to different predictions of the uncertainty;
- Different users of the same methodology can obtain different predictions of uncertainty;
- The effort required to apply each one of the methodologies may be large.

The availability of a code with the capability of internal assessment of uncertainty (CIAU) would eliminate the aforementioned drawbacks, and lead to the simplification of the application of any uncertainty methodology and, definitely, to the reduction of the costs. Therefore, a research activity has been started with the aim to realize the integration between the code and the uncertainty methodology. This process, called the internal assessment of uncertainty, makes it possible that uncertainty bands automatically supplement any NPP calculation result. In this case, the uncertainty is embedded into the code and comes out to bound the results obtained by any code user, without the need for extra resources or engineering judgments from the point of view of the code user. Any code and any uncertainty methodology can be coupled to form the CIAU, thus exploiting the idea discussed in this paper. The RELAP5/MOD3.2 system code, developed by the NRC is at the center of the activity; also considered the wide experience gained in its use at the University of Pisa [2]. Owing to a similar reason, the uncertainty methodology based on accuracy extrapolation (UMAE) [3], has been used as a tool for generating uncertainty data.

2. THE BASIC IDEA OF THE CIAU

The usual characterization of any transient or event that occurred or was calculated in a typical light water reactor (LWR) is through a number of time trends, i.e., pressures, levels, temperatures, and mass flow rates versus time. The event time, or the time elapsed since the event beginning, constitutes the main way to characterize the transient together with the initial and boundary conditions. In this case, which can be identified as the time domain, time is taken as the horizontal axis in the graphical representation of the transient evolution. Therefore, in the area of uncertainty evaluation, each transient becomes unique, thus requiring a specific evaluation of the error that characterizes any of the time trends. This is true notwithstanding the possibility to consider key phenomena or relevant thermal-hydraulic aspects (RTAs) [3, 4] that are common to classes of transients. A different way to look at the same transients involves the use of the phase-space. In the graphical representation, any relevant quantity can be used in the vertical or horizontal axis. The basic idea of the CIAU is that at any of the regions of the phase-space can be assigned one uncertainty value. The concept of plant status is introduced to implement the aforementioned idea in the uncertainty evaluation process. Reference is made to any transient situation assumed to occur in BWR- or PWR-equipped NPPs. No distinction is made among design-basis accidents (DBAs), beyond DBAs (BDBAs), operational transients, or transients involving multiple failures. The only boundaries are constituted by the values assumed by the considered transient driving quantities. However, the hypothesis is made that the transients do not evolve toward situations that imply core degradation and loss of geometric integrity. It can be premised that code validation must be proved within the fixed boundaries or ranges of variation of the assigned parameters. Referring to any plant transient scenario (i.e., SBLOCA, LBLOCA, transient, or operational transient), the status of a plant can be characterized by six driving quantities and by the transient time. The safety relevance and the consistency with the achievements in Ref. [1] have been considered in order to select the driving quantities. In the case of a PWR, the six quantities are listed as (1) through (6) in Table I. If a BWR is considered, five driving quantities apply, i.e., all of the aforementioned except the one at item (3) in Table I. In this case, the quantity at item (6) is the reactor pressure vessel downcomer level. About the transient time, a stable steady-state (or stationary) situation must occur, or be specified, when a code calculation is concerned, before $t = 0$. In relation to each of the driving quantities and the transient time, upper and lower boundaries must be fixed together with a minimum-optimal number of intervals. The assumed subdivision can be found in Tables I. Six dimensions constitute the phase-space domain, (1) to (6) mentioned earlier, and five in the case of a BWR. Each combination of intervals of the driving quantities identifies one hypercube in that domain. Therefore, a hypercube and a time interval characterize a unique plant status in the frame of uncertainty evaluation. All plant statuses are characterized by a matrix of hypercubes and by a vector of time intervals.

The definition of time and quantity uncertainty can be drawn from Fig. 1. The dotted line is the result of a system code calculation: Y is a generic thermal-hydraulic code output plotted versus time. Each point value in the curve is affected by a quantity error (U_q) and by a time error (U_t). Owing to the uncertainty, each point value may take any value within the rectangle identified by the quantity and the time errors (Fig. 1c). The amount of error, on each edge of the rectangle, can be defined in probabilistic terms, consistent with what is recommended in a licensing approach; e.g., a 95% probability level is considered acceptable to the NRC staff for comparison of best-estimate predictions of postulated transients to the licensing limits in 10 CFR Part 50. The way used to combine the rectangles at the end of the CIAU process can be seen in Fig. 1d. The idea at the basis of CIAU can be made more specific as follows: the uncertainty in code prediction is

Table I. Subdivision of driving quantities into intervals

Driving Quantities		(1) Upper Plenum Pressure (MPa)	(2) Primary Circuit Mass Inventory (%)[a]	(3) Steam Generator Pressure (MPa)	(4) Cladding Temperature at 2/3 Core Height (K)	(5) Core Power (%)[a]	(6) Steam Generator Level (%)[a]
Hypercube Limits	1	0.09 – 0.5	10 – 40	0.1 – 3.0	298 – 473	0.5 – 1.0	0 – 50
	2	0.5 – 2.0	40 – 80	3.0 – 7.0	473 – 573	1.0 – 6.0	50 – 100
	3	2.0 – 4.0	80 – 100	7.0 – 9.0	573 – 643	6.0 – 50	100 – 150
	4	4.0 – 5.0	100 – 120	-	643 – 973	50 – 100	-
	5	5.0 – 7.0	-	-	973 – 1473	100 – 130	-
	6	7.0 - 9.0	-	-	-	-	-
	7	9.0 – 10.0	-	-	-	-	-
	8	10.0 – 15.0	-	-			
	9	15.0 – 18.0	-	-	-	-	-

[a] Percent of the initial nominal value

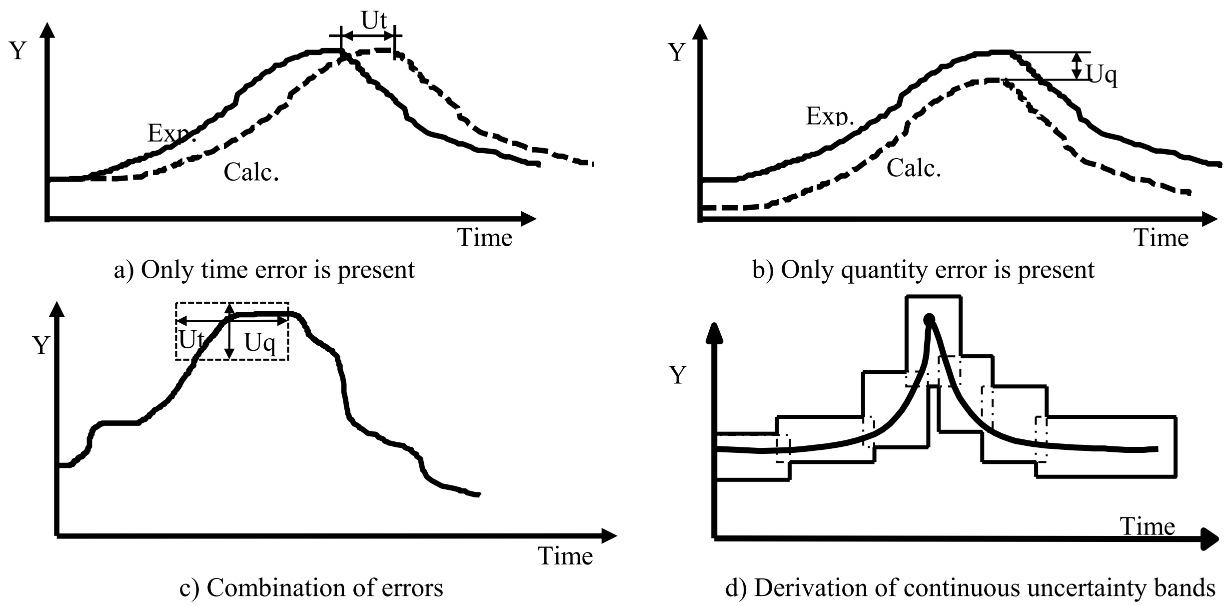


Figure 1. Definition of quantity and of time error to be included into the QUM and the TUV.

constant within each plant status. A quantity uncertainty matrix (QUM) and a time uncertainty vector (TUV) can be set up, utilizing the definitions in Fig. 1.

3. THE CIAU PROCESS

A simplified flow diagram of the CIAU is given in Fig. 2, where two main parts can be seen. The former deals with the development of the method and the latter with its application.

3.1. CIAU Development

The development of the method implies the availability of qualified experimental data (block a in Fig. 2), of qualified system code calculation results (block b), of postulated transients including the definition of plant status (block c), and the selection of variables in relation to which the uncertainty must be calculated (block e). The support of experimental data (block a) is considered mandatory, whatever is the qualification process. Qualified code results (block b) signify the run of qualified code in a qualified computer/compiler, by a qualified user using a qualified nodalization [2]. The qualification level of the code results should be evaluated from a qualitative and a quantitative point of view.

Any uncertainty methodology, supported by a system code, can be used at block b for producing data that are concerned with block c, thus producing an uncertainty database. Thousands of variables are the output of a code calculation and are utilized to characterize a postulated transient scenario. It may be impractical and unnecessary to evaluate the uncertainty connected with any quantity. The safety relevance and the consistency with the achievements in Ref. [1] have been considered in the present framework. Therefore, three variables have been selected for uncertainty evaluation: the system pressure taken in the upper plenum of the main vessel, the (maximum) rod cladding temperature at two-thirds core active length and the fluid mass

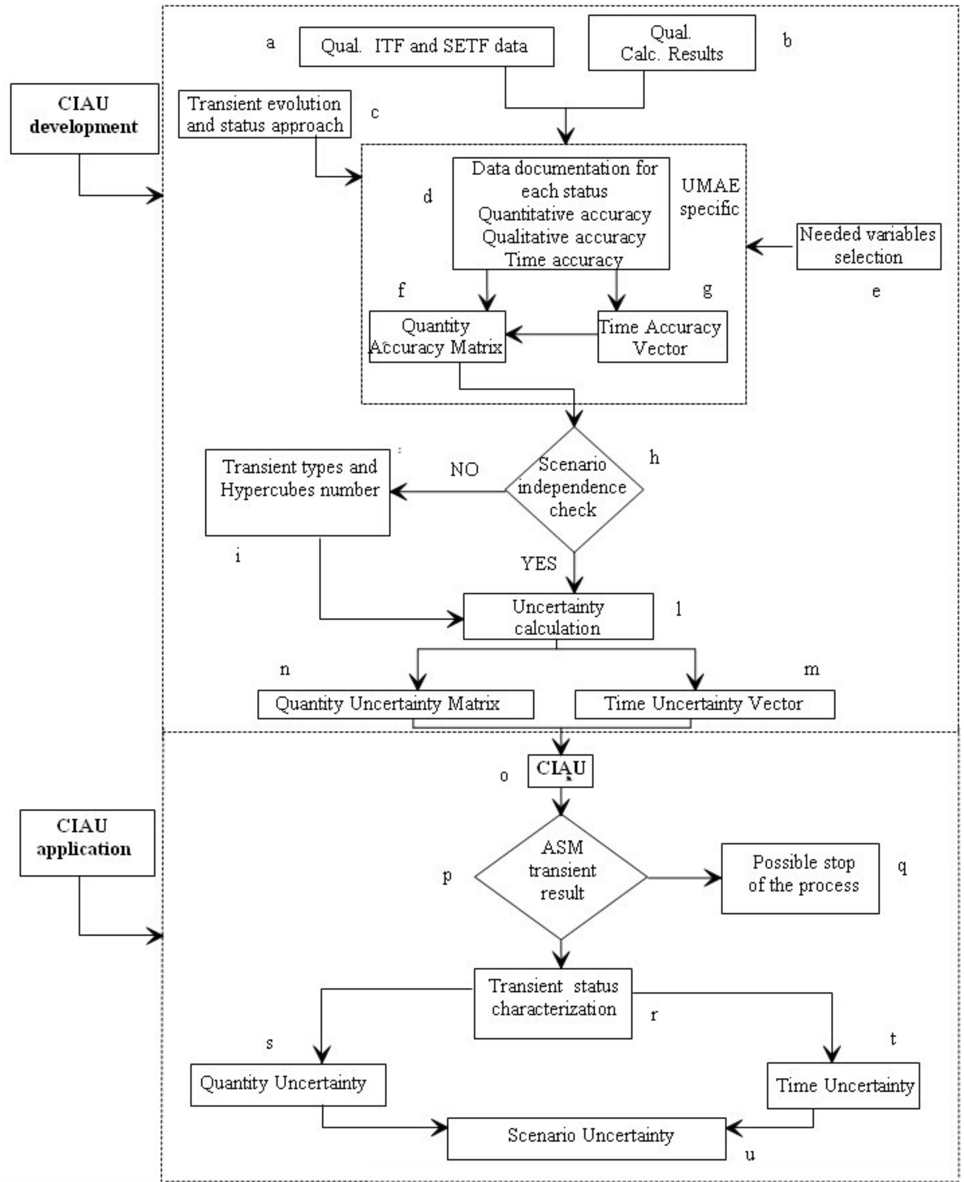


Figure 2. Simplified flow diagram of the CIAU.

inventory in the primary circuit. It may be noted that the foregoing quantities are the same as those utilized for characterizing plant status. If the UMAE uncertainty methodology is used (bounded area in Fig. 2), relevant experimental data and code calculation results (blocks a and b) are compared. Accuracy is evaluated qualitatively and quantitatively, block d. If accuracy is acceptable, block d, the quantity accuracy matrix (QAM) and the time accuracy vector (TAV) are generated, blocks f and g, respectively. Now, the various plant statuses identified under block c can be filled by data coming from block b or from blocks f and g in the case of UMAE. The scenario independence check (block h) needs to verify that the transient type does not affect calculated uncertainties in each hypercube. For instance, it might happen that data from the analysis of several SBLOCAs produce uncertainty values much higher than data from the analysis of a similar number of LBLOCAs, when the same hypercubes are concerned. In this case, the outlet "NO" from block h comes into block i. The number of hypercubes, i.e., the ranges of variation of the driving quantities, must be changed or the transient type must be identified inside each hypercube. If the scenario independence check is positively passed, uncertainty values can be meaningfully assigned to each plant status. The already mentioned QUM and TUV are generated.

3.2. CIAU Application and Current Status

The application of the CIAU is straightforward once QUM and TUV are available. The error matrices and the error vector are currently used as a postprocessor of a CIAU calculation. The analytical simulation model (ASM), i.e., a qualified NPP nodalization in the UMAE nomenclature is used to get the transient scenario. Once a generic event is predicted, block p, the six driving quantities (mentioned earlier) are used to identify the succession of hypercubes. The time intervals are also identified by the predicted event time, block r. This leads to the quantity uncertainty and the time uncertainty values, blocks s and t, respectively, which can be combined to get the searched uncertainty bands. It may be noted again that uncertainty bands only envelope the quantities selected under block e. The computer tool UBEP is used to combine time and quantity uncertainty at each time of the predicted event, block u. Continuous uncertainty bands are generated and envelope the ASM calculation results.

In the frame of the development of the CIAU, four QUM and four TUV have been developed. The first set, or couple QUM + TUV, constitutes the objective of the derivation of the CIAU. Any calculation used in the process and the corresponding experimental database is qualified in the sense required by UMAE. The second set has been considered in order to enlarge the database that can be derived through the UMAE, gathering the data from the literature. The third set of QUM + TUV has been created to test the numerical tools part of the CIAU, to prove the feasibility of the method and to show its capabilities. The uncertainty values have been arbitrarily assigned inside each hypercube and in relation to each time interval. The fourth set has been generated considering the wide experience gained and the resulting wide database from the application of RELAP5/MOD2 to SBLOCA analyses [5]. The objective is to apply uncertainty results derived by UMAE and related to the RELAP5/MOD2 code to calculations performed by the RELAP5/MOD3.2 code. The application field is restricted to SBLOCAs in PWRs.

4. THE SPECIAL NUMERICAL TOOLS OF CIAU

The relevant procedures foreseen in the development or application processes have been implemented in specific computer programs: the Accuracy Finalized to Extrapolation (AFE) and the Data Analysis for Statistical Treatment (DAST).

4.1. The AFE Tool

The accuracy is related to the comparison between measured and calculated time trends or quantities and the accuracy of a generic calculation can be quantified for use in the extrapolation process. The quantity $A_j = |1 - Y_E/Y_C|$ is considered in the AFE process, where Y_C and Y_E are the values of a generic thermal-hydraulic quantity. Therefore, quantity accuracy (QA) and accuracy in predicting timing into the transient, time accuracy (TA), are derived. QA and TA are evaluated in relation to any time interval, separately taken in the measured and the calculated data sets. A list of occurrences is given [6] to characterize the time spans in the experimental and calculated databases. The upper plenum pressure, the rod surface temperature at two-thirds of core height and the mass inventory in the primary loop have been chosen for filling the QUM. Transient time is necessary for filling the TUV. Assuming available experimental and calculated databases that fulfill the UMAE conditions, the AFE tools complete the following steps:

1. Derivation of time spans on the basis of the events listed in [6]. Time spans generally have different duration in the experimental and in the calculated scenarios.
2. Derivation of the time succession of hypercubes: each time span may belong to one or more hypercubes and to one or more time intervals.
3. Calculation of QA and TA from the A_j definition, inside each hypercube and time interval, respectively. In the case of QA, values at different times are considered; therefore, an average value and a standard deviation are obtained for A_j in each hypercube.

4.2. The DAST Tool

The results from AFE are available in hypercubes and time intervals. These are related to different facilities and different test types, each of these being identified. Once a suitable number of data points are gathered in each hypercube or time interval, DAST performs the statistical evaluation [6]. Several accuracy values are transformed into one uncertainty value per each hypercube and per each time interval. The following formula is adopted:

$$U = (A + E_V + E_S + E_\sigma) \times |R| \quad (1)$$

where U is one side of the uncertainty band width, A is the extrapolated accuracy inside the hypercube, E are the extra errors coming from sources detailed later and R is the reference value calculated by the code. The term in parentheses constitutes the nondimensional uncertainty and is directly available into QUM and TUV. In Eq. (1), E_V, Es, and E_σ are extra contributions to the error originated by the dimensions of the facility, and by the dispersion of accuracy inside each hypercube or time interval coming from a single experiment and from the combination of experiments, respectively. The term Es is originated by the dispersion of accuracy data in each hypercube due to the same experiment. This term is zero in each time interval. In addition, in deriving A, weighting factors have been used to account (1) for scaling distortions of each facility, (2) for measurement errors and (3) for data dispersion originated by the accuracy averaging process in each hypercube or time interval (outputs of the AFE). The weights constitute engineering judgment that is part of the development process of the CIAU (and of the UMAE) that must not be exercised during the application of the methodology. The impact of the selected values of the weighting factors upon the predicted uncertainty results has been evaluated: different sets of reasonable weighting factors do not bring substantial changes (less than 1%) in the uncertainty bands. The results of the DAST constitute the QUM and TUV. In particular, QUM and TUV 1 and 2 are generated by running this computer tool. An idea of the database that is related to the sets of QUM + TUV 1, 3, and 4 could be obtained from observing Figs. 3 and 4. The abscissa in Fig. 3 is the sequential number of hypercubes that are reported from 1 to 8100 (i.e., hypercube 1 is the one identified as 111111, and hypercube 8100 is the one identified as 943553). The abscissa in Fig. 4 is the physical time into the transients. In this case, the data pertaining to TUV 1 and 3 coincide.

5. RESULTS FROM THE APPLICATION OF THE METHODOLOGY

Results from the use of the CIAU dealing with the derivation of uncertainty in the prediction of NPP scenarios have already been documented. These involved the use of the sets of QUM + TUV 1 [7] and 2 [8]. Hereafter, reference results about the application of the CIAU to different transients calculated in the two-loop Westinghouse of Krsko are given. In the paragraph 5.2 some recent achievements about the use of CIAU are outlined.

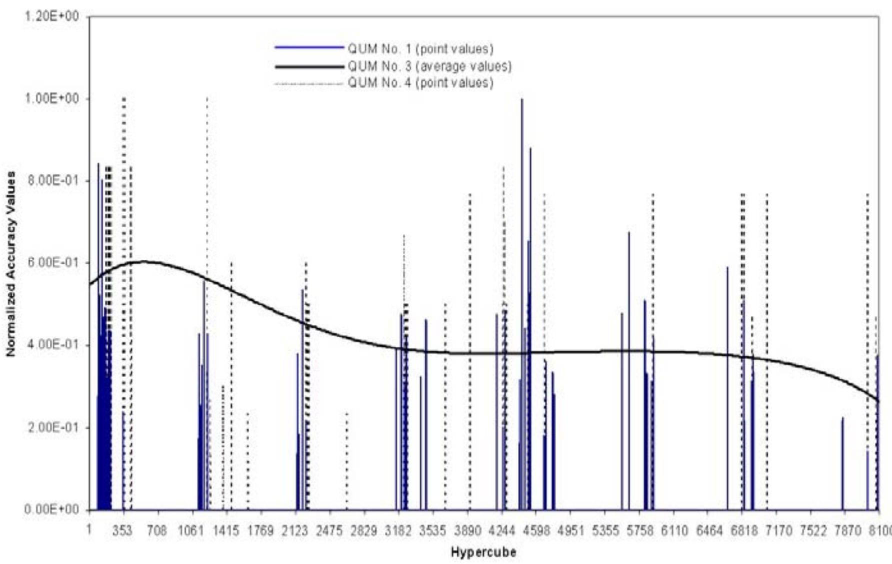


Figure 3. Distribution of accuracy inside the hypercubes: primary system pressure.

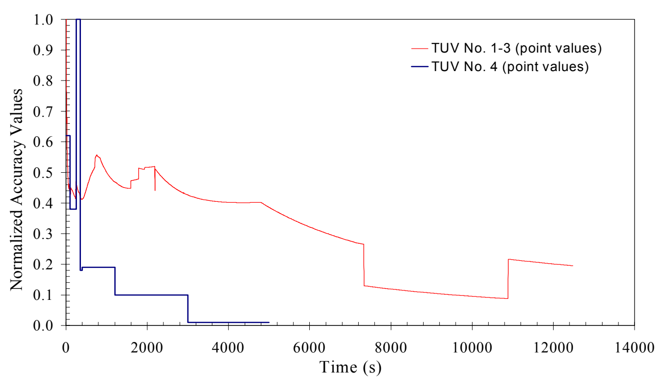
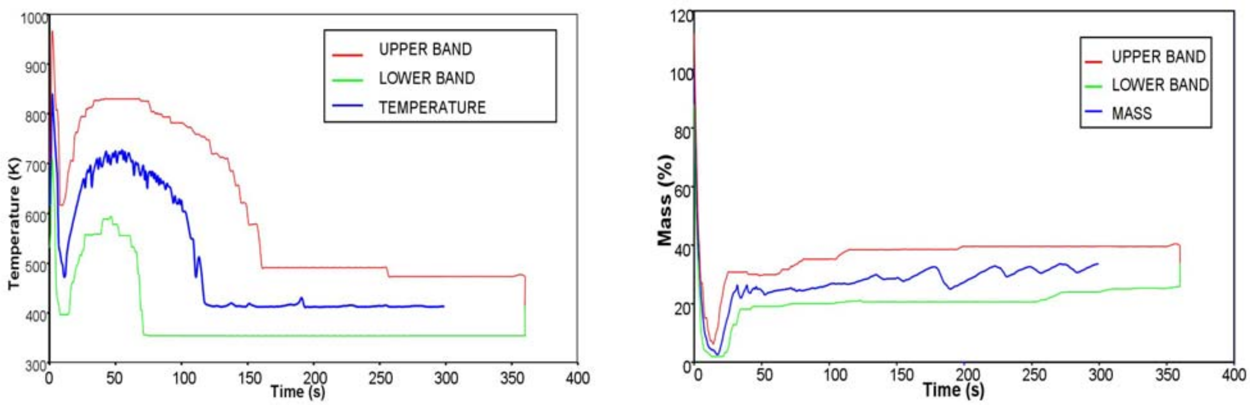


Figure 4. Distribution of accuracy inside the time intervals (see Table II).

5.1. Analysis of the transients in the two-loop Westinghouse of Krsko

The QUM + TUV 3 have been used to give an idea of the capabilities of the method. Owing to the derivation of the QUM + TUV 3, the uncertainty bands presented in the following discussion might not be considered as representative of the results expected by the use of QUM + TUV 1, from the quantitative point of view. The two-loop Westinghouse reactor of Krsko (~ 650 MWe) constitutes the reference NPP. The list of transients that have been calculated by the RELAP5/MOD3.2 can be found in [6]. The adopted nodalization consists of ~ 300 hydraulic nodes and 2500 mesh points for conduction heat transfer and it cannot be considered as an ASM because it did not undergo the qualification process shown in Fig. 2. Large and small break LOCA and transients not involving the loss of integrity of the primary circuit are part of the list. The results of the use of the UBEP, i.e., the final step of the CIAU process, related to the LBLOCA transient is given in Fig. 5. The methodology predicts an upper and a lower bound for the rod surface temperature. In this case, even the lower bound is concerned with a dry-out situation. This may not be the case when the difference between dry-out and rewet times from the ASM calculation is smaller than the time uncertainty derived from TUV data. In such a



(a) Rod surface temperature (b) Mass inventory.

Figure 5. Application of the CIAU to the analysis of an LBLOCA scenario in Krsko.

situation, the methodology predicts a phenomenological bifurcation. The errors affecting the prediction of the timing of dry-out and rewet occurrences can also be derived from Fig. 5a. The mass inventory transient and the calculated error can be seen in Fig. 5b for the same scenario.

5.2. Recent Achievements

Independent evaluation of uncertainty has been performed by CIAU to support the licensing authority in the licensing process of the ANGRA-2 NPP LBLOCA. Angra-2 is a four loop PWR (Siemens) of 3765 Mw_{th}. The applicant submitted to the regulatory authority a LBLOCA DBA licensing analysis based on best estimate plus uncertainty calculation. The CIAU application has been supported by extensive sensitivity study (more than 150 code runs) and the results related to peak cladding temperature (PCT) are shown in Fig. 6. The CIAU produced uncertainty results qualitatively and quantitative similar to what was obtained by the applicant.

Kozloduy-3 is a VVER-440/213, Gidropress – six-loop reactor. A LBLOCA of 200 mm break was requested to support license renewal activity. Evaluation of uncertainty has been performed by CIAU and it has been shown that Cathare predictions about PCT time trends were bounded by the uncertainty bands predicted by the Relap5 best estimate analysis (Fig. 7).

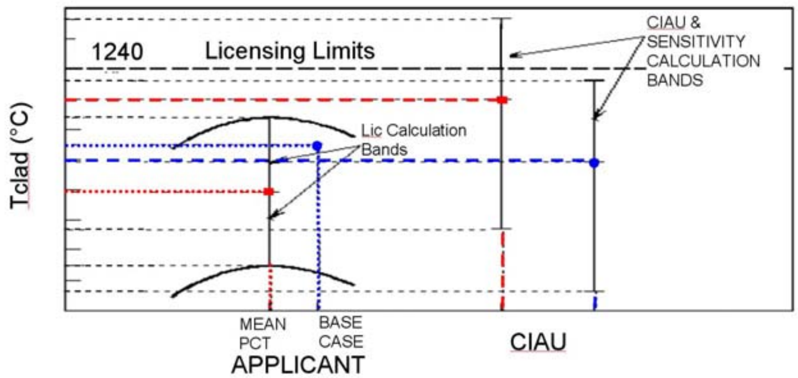


Figure 6. Application of the CIAU to the licensing process of the ANGRA-2.

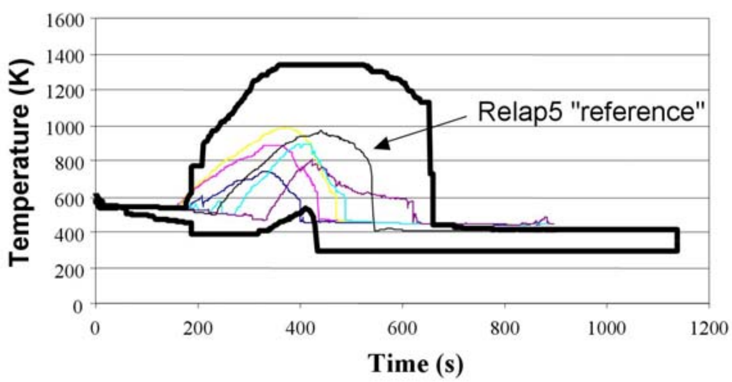


Figure 7. Application of the CIAU to support license renewal activity in Kozloduy-3.

6. EXTENSION OF THE CIAU METHODOLOGY TO 3D COUPLED CODES

The CIAU methodology has been recently extended to the uncertainty analysis in the 3D Neutronics-Thermal-hydraulics coupled codes. The point of view of status approach, at the basis of CIAU, implies the selection of new driving quantities to take into account the neutronic feedbacks and to characterize the regions of the phase-space (hypercube) to which assign the uncertainty values. The total reactivity and the core average exposure (in addition to the quantities already used) are the new quantities able to identify the series of subsequent statuses throughout which each transient scenario in NPP evolves. Other uncertainty vectors and matrixes have been produced in addition to TUV and QUM to quantify the uncertainty about the values, the amplitudes and the "time-spatial" positions of the power peaks. In this way, continuous uncertainty bands have been derived for a) core power history, b) axial peak factors distribution and c) average radial peak factors distribution. The development and the assessment of the CIAU for the uncertainty evaluation in the coupled codes has been performed using the Peach Bottom Turbine Trip Benchmark as a test demonstration problem [9]. The PBTT2 Benchmark constitutes a validation basis for the new generation best estimation codes and the availability of measured data and multiple code predictions provide the opportunity to perform uncertainty analysis and to test the results and the capability of the CIAU methodology for the uncertainty evaluation in coupled codes. Preliminary results that prove the feasibility of the idea and the capabilities of the CIAU applied to 3D coupled codes are shown in Figs. 8 and 9. They refer to the core power history and to the axial and radial peak factors distribution.

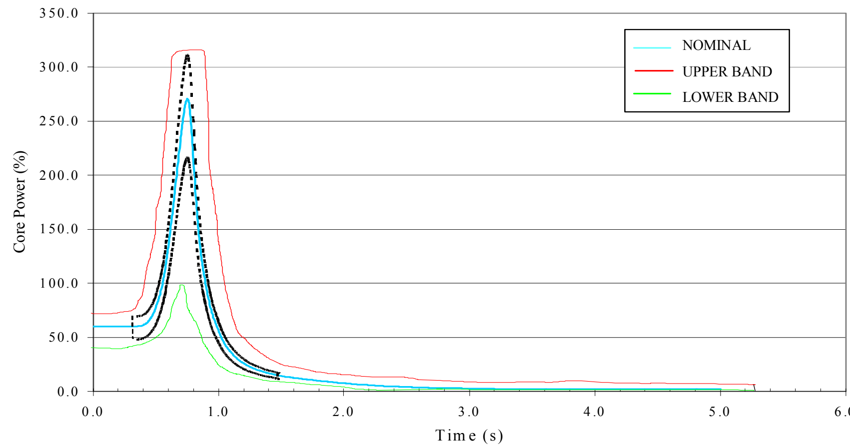


Figure 8. Core power history with lower and upper uncertainty bands.

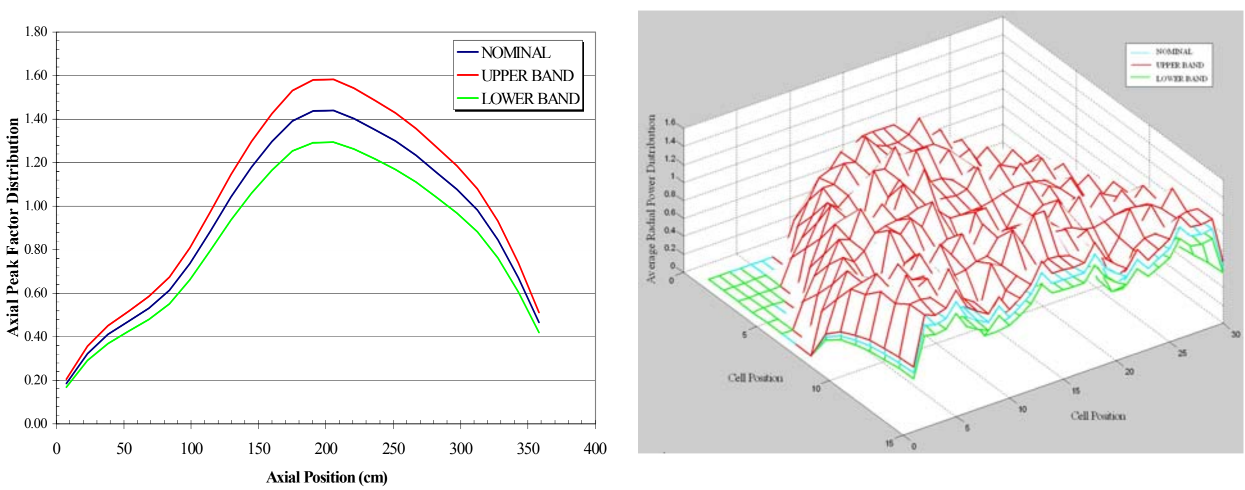


Figure 9. Axial and radial peak factors distribution when the core power peak occurs: lower and upper uncertainty bands.

7. CONCLUSIONS

The CIAU constitutes a powerful tool that is originated by the combination of a qualified best-estimate thermal-hydraulic system code and a suitable uncertainty methodology. Reference is made to the prediction of a transient scenario consequent to a postulated event in a generic LWR. The implementation of the CIAU capability allows the achievement of error (uncertainty) bands coupled with the time-dependent results of the concerned system code calculation. The idea at the basis of the CIAU is connected with the status approach. First, quantities have been selected to characterize in a multidimensional space the thermo-hydraulic status of an LWR during any transient. Hypercubes have been defined in this way and associated with time intervals accounting for the transient time duration. Then, accuracy has been calculated for each hypercube and time interval. The combination of accuracy values coming from hypercubes and time intervals allows the derivation of continuous uncertainty or error bands enveloping any time-dependent variables that are the output of a system code calculation.

The RELAP5/MOD3.2 system code and UMAE have been coupled to constitute the CIAU. Therefore, the uncertainty has been obtained from the extrapolation of the accuracy resulting from the comparison between code results and relevant experimental data: These may be obtained from integral test facilities, as well as from separate effects test facilities. However, any qualified system code and any uncertainty methodology could be applied in a way similar to that shown here for getting the same goal.

A consistent ensemble of uncertainty values is included in any set constituted by a QUM and a TUV. The QUM is formed by hypercubes whose edges are six selected variables representative of a transient scenario. The TUV is formed by time intervals. The results obtained prove the feasibility of the idea and the capabilities of the CIAU. The main advantage of the methodology comes from avoiding any need to interpret logical statements that are part of uncertainty methods, i.e., avoiding user effect when using uncertainty methodologies. In addition, negligible computer time or human resources are needed for the application of the CIAU.

REFERENCES

1. T. Wickett, et al., "Report of the Uncertainty Method Study for Advanced Best Estimate Therma1hydraulic Code Applications," *OECD/CSNI, NEA/CSNI R* (97) 35, **I, II** (1998).
2. F. D'Auria, and G. M. Galassi, "Code Validation and Uncertainties in System Thermalhydraulics," *Progress Nuclear Energy,* **33**, 1/2,175 (1998).
3. F. D'Auria, N. Debrecin, and G. M. Galassi, "Outline of the Uncertainty Methodology Based on Accuracy Extrapolation," *Nuclear. Technology,* **109**, 1, 21 (1995).
4. N. Aksan, et al., "A Separate Effects Test Matrix for Thermal-Hydraulic Code Validation: Phenomena Characterization and Selection of Facilities and Tests," *OECD/CSNI, OECD/GD* (94) 82, **I, II** (1993).
5. F. D'Auria, et al., "Application of the Fast Fourier Transform Method to Evaluate the Accuracy of SBLOCA Database," *Proc. 8th Int. Conf. Nuclear Reactor Thermal Hydraulics, NURETH-8,* Kyoto, Japan, Sept. 30-Oct. 4, 1997.
6. F. D'Auria and W. Giannotti, "Development of a Code with the Capability of Internal Assessment of Uncertainty*," Nuclear Technology*, **131,** pp 159-196 (2000).
7. F. D'Auria and W. Giannotti, "Development of Matrix and Vector for Internal Assessment of Uncertainty," *2nd Int. Symp. Validation of System Transient Analysis Codes: American Society of Mechanical Engineers/Japan Society of Mechanical Engineers, Joint Fluid Engineering Conf.*, San Francisco, California, July 18-22, 1999.
8. A. Madeira, W. Giannotti, and F. D'Auria, "Sample Application of CIAU to a Nuclear Power Plant Transient Simulation," *Proc. 9th Int. Conf. Nuclear Reactor Thermal Hydraulics, NURETH-9,* San Francisco, California, October 5-8, 1999.
9. J. Solis, K. Ivanov, B. Sarikaya, A. Olson and K. Hunt, "Boiling Water Reactor Turbine Trip Benchmark, Final Specifications",**1**, NEA/NSC/DOE, (2001) 1, June 2001.