

CIAU Method for Uncertainty Evaluation for System Thermal-Hydraulic code calculations

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Abstract – *Best-Estimate calculation results from complex thermal-hydraulic system codes (like Relap5, Cathare, Athlet, Trace, etc..) are affected by unavoidable approximations that are un-predictable without the use of computational tools that account for the various sources of uncertainty. Therefore the use of best-estimate codes within the reactor technology, either for design or safety purposes, implies understanding and accepting the limitations and the deficiencies of those codes. Uncertainties may have different origins ranging from the approximation of the models, to the approximation of the numerical solution, and to the lack of precision of the values adopted for boundary and initial conditions. The amount of uncertainty that affects a calculation may strongly depend upon the codes and the modeling techniques (i.e. the code's users). A consistent and robust uncertainty methodology must be developed taking into consideration all the above aspects. The CIAU (Code with the capability of Internal Assessment of Uncertainty) and the UMAE (Uncertainty Methodology based on Accuracy Evaluation) methods have been developed by University of Pisa (UNIPI) in the framework of a long lasting research activities started since 80's and involving several researchers. CIAU is extensively discussed in the available technical literature, Refs. [1, 2, 3, 4, 5, 6, 7], and tens of additional relevant papers, that provide comprehensive details about the method, can be found in the bibliography lists of the above references. Therefore, the present paper supplies only 'spot-information' about CIAU and focuses mostly on the applications to some cases of industrial interest. In particular the application of CIAU to the OECD BEMUSE (Best Estimate Methods Uncertainty and Sensitivity Evaluation, [8, 9]) project is discussed and a critical comparison respect with other uncertainty methods (in relation to items like: sources of uncertainties, selection of the input parameters and quantification of their uncertainty ranges, ranking process, etc.) is presented.*

I. INTRODUCTION

The best-estimate calculation results from complex thermal-hydraulic system codes are affected by approximations that are un-predictable without the use of computational tools that account for the various sources of uncertainty. Therefore the use of best-estimate codes within the reactor technology, either for design or safety purposes, implies understanding and accepting the limitations and the deficiencies of those codes.

In a general case when conservative input conditions are adopted together with a best estimate code, the conservatism in the results cannot be ensured because of the obscuring influence that an assigned input conservative parameter value may have upon the prediction of the wide variety of phenomena that combine for a typical reactor accident scenario. In addition, the amount of conservatism, when this can be ensured for an assigned output quantity, may suffer from two limitations: a) it does not correspond to a conservatism in the prediction of a

different system relevant variable (e.g. a conservative prediction for rod surface temperature does not correspond to a conservative prediction of emergency system flow-rate or of containment pressure) and b) the amount of conservatism is unknown.

Consequently a consistent and robust use of a best estimate code implies the adoption of realistic boundary and initial conditions and the evaluation of the uncertainties affecting the computed results. This type of analysis is referred to as a Best Estimate Plus Uncertainty (BEPU) approach. A best estimate approach provides more realistic information about the physical behaviour and can identify the most relevant safety issues evaluating the existing margins between the results of the calculations and the acceptance criteria.

Uncertainties may have different origins ranging from the approximation of the models, to the approximation of the numerical solution, and to the lack of precision of the values adopted for boundary and initial conditions. The amount of

uncertainty that affects a calculation may strongly depend upon the codes and the modeling techniques (i.e. the code-users). A consistent and robust uncertainty methodology must be developed taking into consideration all the above aspects.

A variety of uncertainty methods is available and they have been adopted by various institutions. Notwithstanding existing differences among the proposed methodologies, the major part of them are affected by two main limitations:

- The resources needed for their application may be very demanding, ranging up to several man-years;
- 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, and may threaten the usefulness or the practical applicability of the results achieved by an uncertainty method. Therefore, the Internal Assessment of Uncertainty (IAU) was requested as the follow-up of international conferences [10, 11]. The approach CIAU, Code with capability of IAU, has been developed with the objective of reducing the limitations mentioned above.

CIAU is extensively discussed in the available technical literature, Refs. [1, 2, 3, 4, 5, 6, 7], and tens of additional relevant papers, that provide comprehensive details about the method, can be found in the bibliography lists of the above references. Therefore, the present paper supplies only 'spot-information' about CIAU and focuses mostly on the advancements of the methodology, that constitute the original contributions of the present work. In particular, the extension of the uncertainty database and the development of a procedure for the 'internal' qualification of the method are discussed. Both aspects result in a more accurate CIAU uncertainty evaluation as they contribute respectively to improve the statistic (in fact more tests are inside the database) and to perform a systematic qualitative and quantitative analysis of the data constituting the CIAU database.

II. THE BASES OF THE METHOD

The bases of the CIAU method can be summarized in four steps:

1. The use of the 'UMAE (Uncertainty Methodology based on Accuracy Evaluation [12]) method as tool for qualifying thermal-hydraulic code calculations' related both to Integral Tests Facilities (ITFs, used in the 'development process' of CIAU) and to Nuclear Power Plants (NPPs, for the CIAU 'application process', i.e. the step dealing with the uncertainty evaluation of the NPP code calculation);
2. The 'NPP status approach' to identify 'phase spaces' (i.e. combinations of finite intervals of selected – driving – quantities) to which associate single uncertainty values for each of the selected – output – quantities (i.e. responses);
3. The 'separation and recombination of time and quantity error' to split the physical- (i.e. phenomena based) statistical treatment of the uncertainty in two contributions associated with the values of the selected – output – quantities (i.e.

responses) and with the time when those values are reached during the transient;

4. The 'error filling process and the error extraction process' to first generate the accuracy database and second to use the derived uncertainty database for the uncertainty evaluation of the NPP code calculation.

II.A. The UMAE Qualification Process (the Engine of CIAU)

The UMAE methodology [12] can be used in combination with a thermal-hydraulic code to produce the CIAU. It involves the fulfillment of different 'conditions of acceptability' for demonstrating the achievement of qualified ITF and NPP nodalizations and related code calculations (in this term it can be considered like the 'engine' of the CIAU). Various steps in the method, including the use of statistics, are introduced to avoid the expert judgments at any level in the process. Data coming from generic experiments in integral facilities and in separate effect test facilities, other than counterpart and similar tests can be processed in the UMAE. One condition for the application of the method is the similarity between the concerned plant scenario, in relation to which uncertainty must be calculated, and the experimental database originating the accuracy of the code.

II.B. The NPP Status Approach

The usual characterization of any transient or event occurred or calculated in a typical LWR (Light Water Reactor) is through a number of time trends, e.g. pressures, levels, temperatures, 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 'time-domain', time is taken as 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 Thermalhydraulic Aspects (RTAs) [13, 14], that are common to classes of transients.

A different way to look at the same transients involves the use of the 'phase-space'. This approach consists in selecting a fixed, small group of quantities (called "driving quantities" Qd) and in describing any event taking place in a NPP not as a function of time, but by the group of values assumed by the selected quantities: each group of the selected variables represents a status of the plant. This approach is actually utilized to optimize the emergency procedures of NPPs. In the graphical representation, any relevant quantity can be used in the vertical or horizontal axis. Fig. 1 shows the comparison of relevant quantities among data of five experiments reproducing LBLOCA (Large Break Loss of Coolant Accident), SBLOCA (Small Break Loss of Coolant Accident) and LOFW (Loss Of

Feed-Water) scenarios in different PWR simulators (BETHSY, LSTF, LOFT, SPES and LOBI) and gives an idea of differences between the ‘time-domain’ and the ‘phase-space’ approaches, [15]. Differences in the two sets of graphics are obvious.

The basic idea of the CIAU method is that at any of the regions into which the ‘phase-space’ is subdivided can be assigned one uncertainty value for the selected output quantities (called “object quantities”, Y). In other words, the NPP status is a region of phase-space where the uncertainty in the code prediction is assumed to be ‘uniform’. The same idea, referring to specific thermalhydraulic phenomena, is discussed in Refs [15, 16]. Those papers show that phenomenological areas or regions in the ‘phase-space’ are suitable for the use in scaling and extrapolation studies. Additional support for planning the method come from the characterization of generic plant status for the actuation of accident management countermeasures, as discussed in Ref. [17]. Finally, the pursued approach is similar

to what proposed by D.C. Groeneveld and P. Kirillov [18]: in that case, pressure, quality and flow rate are entered into the ‘look-up’ table that produces a suitable value for the CHF (Critical Heat Flux). In the present case, proper ‘driving quantities’ are entered into matrices and vector and produce uncertainty values.

II.C. The Separation and Recombination of Time and Quantity Error

The definition of time and quantity error can be drawn from Fig. 2. The dotted line is the result of a system code calculation: Y is a generic thermalhydraulic code output plotted versus time. Each point value in the curve is affected by a time error (E_t in Fig. 2a) and by a quantity error (E_q in Fig. 2b). The availability of experimental data (measured in appropriate NPP simulators, i.e. ITFs) allows to quantify those errors and to

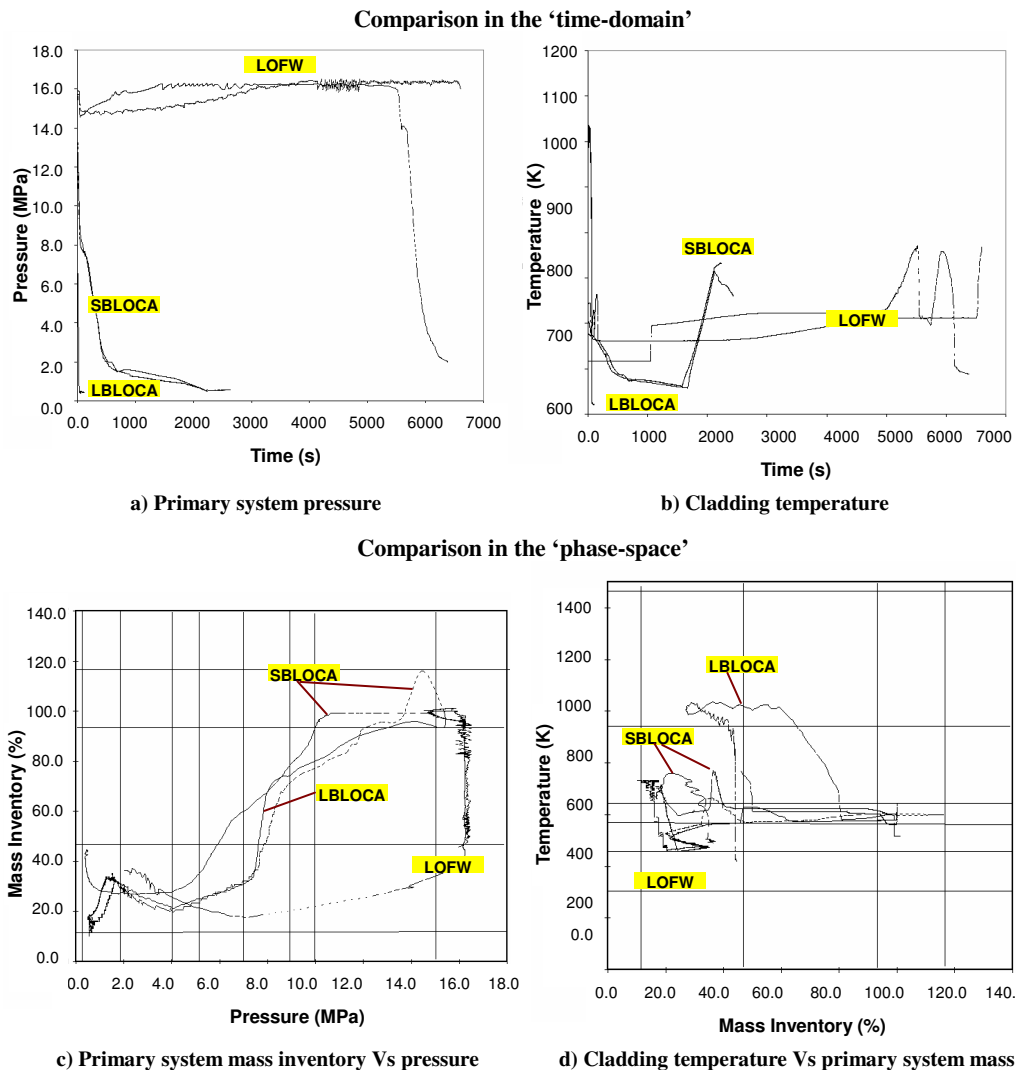


Fig. 1. Comparison between ‘time domain’ and ‘phase-space’ representation among selected quantity evolutions characterizing different transients.

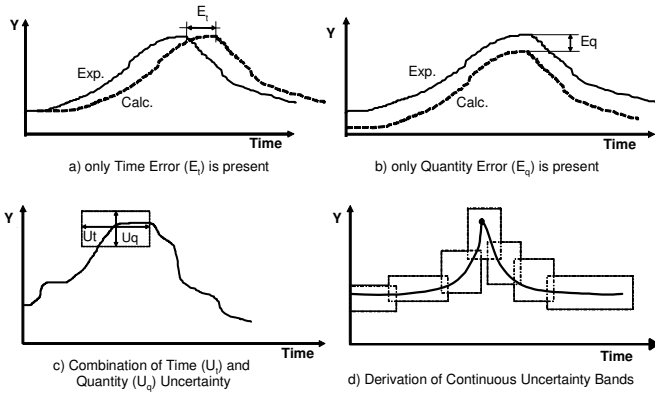


Fig. 2. Definition of quantity and time errors to be included into the quantity and time uncertainty database.

generate the so-called (in the CIAU nomenclature) Time and Quantity Accuracy database. Owing to the uncertainty affecting any thermal-hydraulic code calculation, each point value of the NPP code result may take any value within the rectangle (Fig. 2c) identified by the time (U_t) and quantity (U_q) error (uncertainty). The amount of the uncertainty value (i.e. each edge of the rectangle) can be defined in probabilistic terms, consistently with what recommended by current licensing approaches; e.g., a 95% probability level is considered acceptable to the US NRC staff for comparison of best-estimate predictions of postulated transients to the licensing limits in 10 CFR (Code of Federal Regulations) Part 50 [19]. The way used to combine the rectangles at the end of the CIAU process for generating the CIAU uncertainty bands can be seen in Fig. 2d. The adopted process is ensuring a higher (still non quantified) level of probability respect to the 95% probability usually associated with the edge of the rectangle.

II.D. The Error Filling Process and the Error Extraction Process

Two processes are foreseen for the realization of the CIAU method: the ‘error filling’ process and the ‘error extraction’ process (Fig. 3). The former is dealing with: a) the selection of relevant experiments (ITF and SETF), i.e. of those experiments whose geometrical properties of the facility and boundary and initial conditions are similar to those of the concerned plant scenarios; b) the code calculation results qualified following the UMAE criteria; c) the derivation of the separate time and quantity accuracy (error) database; d) the identification of the NPP statuses; e) the storing of the time and quantity accuracy (error) values inside the selected (by the ITF and/or SETF experiment scenario) NPP statuses.

After that a qualified NPP code calculation has been made available by UMAE, the ‘error extraction’ process is used to draw out from the selected (by the transient) NPP statuses the uncertainty values to be associated with the nominal (best estimate) values of the object quantities for the uncertainty evaluation. It shall be noted that only one NPP best-estimate

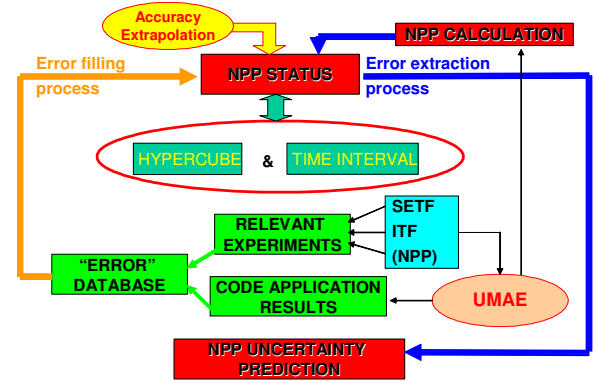


Fig. 3. The error filling process and the error extraction process.

calculation per transient is sufficient for performing the uncertainty analysis. Between the two processes, the step dealing with the accuracy extrapolation is performed for passing from the accuracy database (output of the ‘error filling’ process) to the uncertainty database (input of the ‘error extraction’ process).

III. BEPU APPLICATIONS BY CIAU

Best Estimate Plus Uncertainty applications of the CIAU methodology with relevance to the nuclear industry are presented hereafter. More details may be found in Refs [20, 21, 22, 23].

III.A. Uncertainty Analysis of the LBLOCA-DBA of the Angra-2 PWR NPP

Angra-2 is a 4 loop 3765 MWth PWR designed by Siemens KWU. The NPP is owned and operated by the ETN utility in Brazil. The NPP design was ready in the ‘80s, while the operation start occurred in the year 2000 following about ten-year stop of the construction. The innovation proposed to the licensing process by the applicant consists in the use of a Best Estimate tool and methodology to demonstrate the compliance of the NPP safety performance with applicable acceptance criteria set forth in the Brazilian nuclear rule.

In this study [20], the CIAU application aimed at performing an ‘independent’ best-estimate plus uncertainty analysis of the LBLOCA-DBA of the Angra-2 PWR NPP. The analysis is classified as ‘independent’ in the sense that it was carried out by computational tools (code and uncertainty method) different from those utilized by the applicant utility.

The main results are summarized in Fig. 4 and 5, where the PCT and the related uncertainty bands obtained through the CIAU and through the computational tools adopted by the applicant, are given. The following comments apply:

- Continuous uncertainty bands have been obtained by CIAU related to rod surface temperature (Fig. 4), pressure and mass inventory in primary system. Only point values for PCT are considered in Fig. 5;

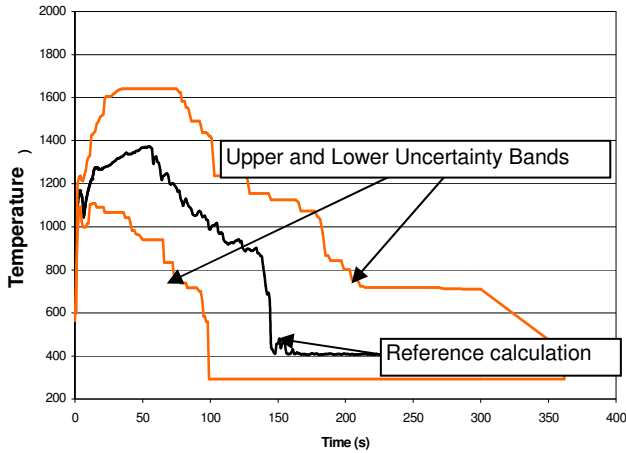


Fig. 4. Result of CIAU application to Angra-2LBLOCA analysis.

- The CIAU (and the applicant) analysis has been carried out as best-estimate analysis: however, current rules for such analysis might not be free of undue conservatism and the use of peak factors for linear power is the most visible example;
- The conservatism included in the reference input deck constitutes the main reason for getting the ‘PCT licensing’ from the CIAU application above the acceptability limit of 1200 °C;
- The amplitude of the uncertainty bands is quite similar between the CIAU and the applicant. Discrepancies in the evaluation of the ‘PCT licensing’ outcome from the way of considering the ‘center’ of the uncertainty bands. In the case of CIAU, the ‘center’ of the uncertainty bands is represented by the phenomenological result for PCT obtained by the reference calculation (1100 °C in Fig. 4). In the case of applicant the ‘center’ of the uncertainty bands is a statistical value obtained from a process where the reference calculation has no role (796 °C in Fig. 5);

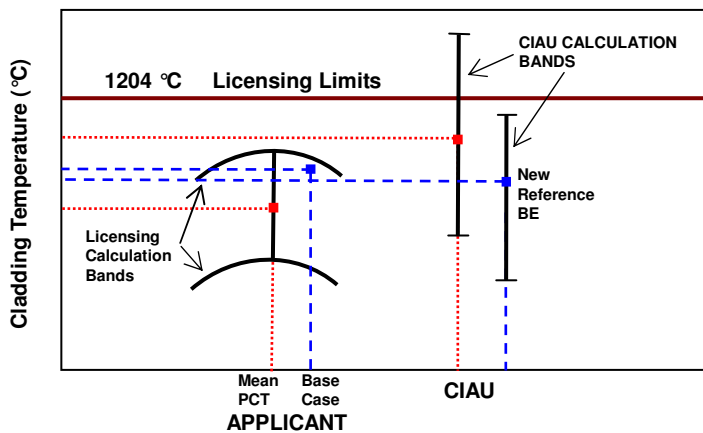


Fig. 5: Angra-2 LBLOCA uncertainty evaluation: final result from CIAU and comparison applicant results.

- The reference best estimate PCT calculated by the applicant (result on the left of Fig. 5) plus the calculated uncertainty is lower than the allowed licensing limit of 1473 K;
- The reference best estimate PCT calculated by CIAU (result on the right of Fig. 5) is higher than the PCT ‘proposed’ by the applicant and the upper limit for the rod surface temperature even overpasses the allowed licensing limit of 1473 K thus triggering licensing issues;
- Based on the results at the previous point, new evidences from experimental data have been made available by the applicant. This allowed to repeat the best estimate reference calculation (both for the CIAU and the applicant). The new reference best estimate PCT calculated by CIAU is lower than the previous (about 200 °C) and close to the new reference PCT calculated by the applicant (‘base case’ in Fig. 5);
- It is shown that the new CIAU upper limit for the rod surface temperature is lower than the allowed licensing limit of 1473 K.

III.B. Kozloduy-3 200 mm Break to show Similarity of Code Results

Results of independent safety evaluations [21] of the transient behaviour of the Kozloduy unit 3 VVER 440/230 NPP (675 MWth) following Large Break LOCA is discussed in the following. The considered LOCA is originated by a 200 mm single ended break in cold leg, and conservative boundary and initial conditions were assumed. A comprehensive analysis of the ‘LBLOCA 200 mm’ transient was carried out. The specific purposes of the analysis include:

- the demonstration that the use of the CATHARE code provides quantitatively and qualitatively similar predictions as the RELAP5;
- the execution of an independent safety analysis supported by CIAU uncertainty evaluation.

The following comments apply:

- The application of the uncertainty method to the results of the ‘LBLOCA 200 mm’ might be not justified owing to the use of some conservative input data. However, within the present context, the CIAU uncertainty evaluation to the RELAP5 analysis allows the quantitative evaluation of the results and of the CATHARE results predicted by UNIPI;
- Uncertainty results related to the rod surface temperature that are obtained from the application of CIAU having as reference the UNIPI-RELAP5 calculation are summarized in Fig. 6;
- The ‘PCT licensing’ predicted by CIAU (1062 °C) lies within the licensing acceptability threshold (1200 °C). The available safety margin is close to 150 K. The uncertainty results obtained by CIAU are supported by the outcome of the sensitivity study. The removal of the conservatism considered in the process (that could not be justified within the performed analysis) is expected to bring the predicted ‘PCT licensing’ below 1000 °C;

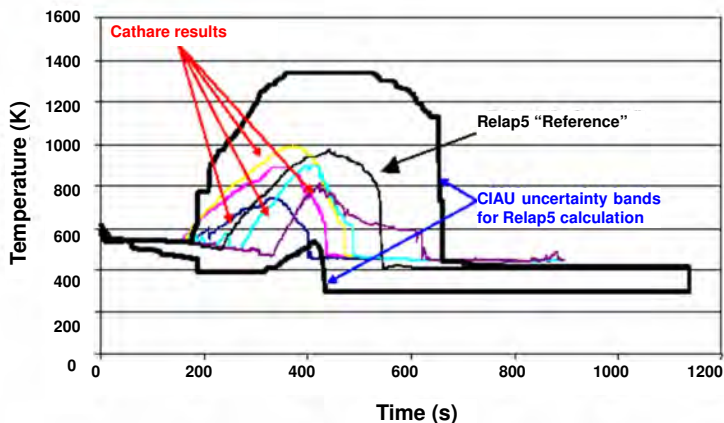


Fig. 6. Uncertainty analysis of the '200 mm' LOCA-DBA of VVER-440 NPP: main result from CIAU application.

- The demonstration that the results of predictions by RELAP5 and CATHARE are not in contradiction has been obtained through the uncertainty bands calculated by CIAU having as reference the RELAP5 calculation. Fig. 6 shows that the CATHARE results are embedded within the uncertainty bands of the RELAP5, when the same transient is calculated with the same boundary and initial conditions, thus allowing a successful solution to the assigned problem.

III.C. Best Estimate and Uncertainty Evaluation of LBLOCA 500 mm for Kozloduy-3

The analysis of the 'LBLOCA 500 mm' (DEGB in CL) transient [22] was carried out by adopting the Relap5 code. The specific purposes of the analysis include the assessment of the results and the execution of an independent safety analysis supported by uncertainty evaluation. A BE transient prediction of the 'LBLOCA 500 mm' was performed. Evaluation of the uncertainty was performed by CIAU for the RPV upper plenum pressure, the mass inventory in primary system and the hot rod cladding temperature. Only the last parameter is shown in Fig. 7 together with the uncertainty bands. The most relevant result is the demonstration that the PCT in the concerned hot rod is below the licensing limit.

In the same Fig. 7, bounding results (PCT and time of quenching) from two conservative calculations (i.e. obtained by a BE code utilizing conservative input assumptions) are given: one is the conservative calculation ('driven' conservatism in Fig. 7) performed by the applicant, the other is the conservative calculation performed by UNIPI ('rigorous' conservatism in Fig. 7). The following can be noted:

- a) The 'driven' conservative calculation has been performed by the applicant using a set of values for the selected conservative input parameters different respect to the values adopted in a previous analysis and accepted by the regulatory body;

- b) The 'driven' conservative calculation is not "conservative" and does not bound entirely the BE + uncertainty upper bound. This implies that code uncertainties are not properly accounted for by the adopted conservative input parameter values; The 'rigorous' conservative calculation performed by UNIPI [22] is correctly conservative (i.e. it use the same set of values for the selected conservative input parameters previously licensed), but its conservatism is such to cause PCT above the licensing limit;
- c) The 'rigorous' conservative calculation performed by UNIPI [22] is correctly conservative (i.e. it use the same set of values for the selected conservative input parameters previously licensed), but its conservatism is such to cause PCT above the licensing limit;
- d) The comparison between the conservative PCT obtained by UNIPI and the CIAU upper band of the BE+uncertainty calculation shows the importance of using a full BE approach with a suitable evaluation of the uncertainty.

III.D. CIAU Evaluation of Zion NPP LBLOCA DEGB Transient (BEMUSE Project)

The present section deals with the Phase IV and V of the OECD BEMUSE (Best Estimate Methods, Uncertainty and Sensitivity Evaluation) project whose objectives were the prediction of the BE calculation of the ZION NPP LBLOCA scenario and the following uncertainty evaluation. Zion NPP, a dual-reactor nuclear power plant operated and owned by the Commonwealth Edison network, was a Westinghouse 4 loops PWR with a thermal power of 3250 MWth (1040 MWe). The 25-year old plant had not been in operation since February, 1997. In 1998 Commonwealth Edison, owner of the plant, concluded that Zion could not produce competitively priced power and the two-unit Zion Nuclear Power Station was retired in February, 1998. At this time, plans were started to keep the facility in long-term safe storage and to begin dismantlement after 2010.

RELAP5 code and CIAU method were used by UNIPI to predict the BE calculation of the ZION NPP LBLOCA scenario [24] and the following uncertainty evaluation [25]. A qualified application of CIAU to a selected NPP scenario requests to investigate whether the phenomena occurring during the NPP transient are covered by a sufficient number of ITF experiments implemented in the uncertainty database. This step constitutes a fundamental pre-requisite for the CIAU application and for generating uncertainty bands supported by experimental evidences. The fulfilment of this step can be derived from Ref. [23]. A more exhaustive process (not discussed here) is then apply to each identified experiment and consists in: a) characterization of the time span when the phenomenon is occurring, b) quantification of the accuracy between experiment and calculated values.

Figure 8 show the uncertainty bands calculated by CIAU for the maximum cladding temperature (defined as the maximum value - envelope value - of all the rod surface temperatures

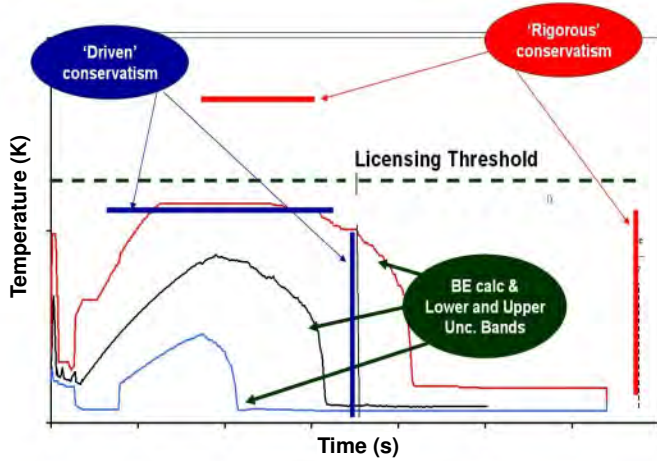


Fig. 7. BE reference 500 mm LBLOCA analysis for Kozloduy Unit 3 NPP: Surface temperature at the PCT location in hot rod and uncertainty bands derived by CIAU.

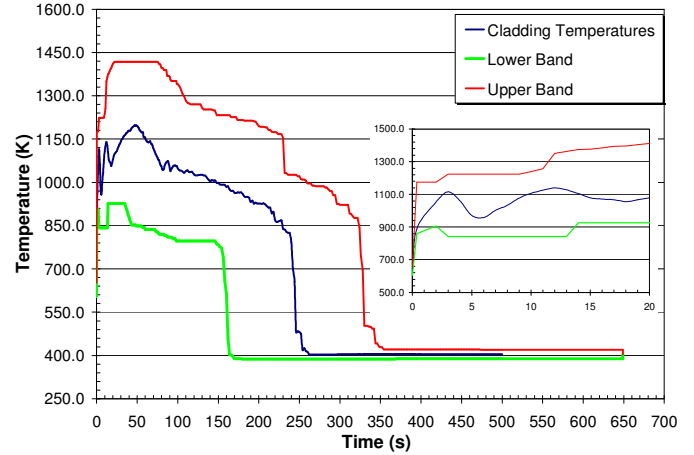


Fig. 8. Maximum cladding temperature: reference calculation and uncertainty bands.

irrespective of the location - assembly or elevation - and the power level). The uncertainty evaluation for some single value output parameters (i.e. first and second PCT, time of accumulator injection, time of complete quenching) are in Table 1. The analysis of CIAU uncertainty bands shall be done considering the following:

- CIAU is a method that gives emphasis (i.e. takes into account and propagates consistently) the time error: this implies a 'larger error' (and a larger band width) when gradients are steep. This fact shall be connected with the prediction of suitable error for the accumulator intervention time (see Table I);
- The CIAU uncertainty bands provide more than the 95% percentile: if the 95% percentile value for maximum and minimum values of the uncertainty bands are considered (typical value adopted in a licensing process), smaller band widths would be produced by CIAU.

TABLE I

Single value output parameters.

		OUTPUT UNCERTAIN PARAMETERS		
		LOWER UNCERTAINTY BAND	REFERENCE CALCULATION	UPPER UNCERTAINTY BAND
1st PCT	(K)	905.7	1053.5	1175.9
2nd PCT	(K)	848.2	1198.4	1418
Time of Accumulator Injection	(s)	5.8	16.2	27.2
Time of Accumulator Empty	(s)	42.7	80.1	118.5
Time of Complete Quenching	(s)	172	264	356

IV. COMPARISON BETWEEN CIAU AND OTHER UNCERTAINTY METHODS

Topic #1: List of uncertainty sources

The process of application of best-estimate (or realistic) computer codes to the safety analysis of NPPs implies the evaluation of uncertainties. This is connected with the (imperfect) nature of the code and of the process of code application. In other words, 'sources of uncertainty' affect the prediction results of best-estimate codes and must be taken into account. The list of uncertainty sources considered by CIAU method are independent on the uncertainty scenario and are listed in Ref [4].

Topic #2: Establishment of the input uncertain parameters

The UMAE/CIAU uses a data base of "relevant" transients in "relevant" facilities. It is therefore a necessary condition for the application of the methodology that such experimental data are available. "Relevant" facilities have been identified as those facilities designed having in mind the 'time preserving' and the 'power-to-volume' scaling ratios. LOFT, Semiscale, LOBI, SPES, BETHSY, LSTF, PKL, PMK, Pactel and Mist are examples of integral test facilities satisfying the above requirements in the PWR area. It is assumed that at least one experiment has been performed in at least one of these facilities having similar boundary and initial conditions to those of the selected reference transient.

The information about the sources and the types of uncertainties is implicit in the data base constituted by experimental and calculated trends. The following process applies for the identification of uncertainties:

- a) Selection of the experiment representative of the reference NPP test scenario;
- b) Identification of Relevant Thermalhydraulic Aspects (RTA);

- c) Characterisation of RTA: each RTA must be characterised by numerical values constituting the SVP, NDP, IPA and TSE (Single Valued Parameters, Non Dimensional Parameters, Integral Parameters, parameters belonging to the Time Sequence of Events, respectively): at least forty parameters must be selected to characterise a test scenario (the consideration of a relatively high minimum number of parameters removes the importance of subjective choices in this phase of the method);
- d) Identification of a minimum number of similar experiments. The following considerations apply:
- Several tens of tests similar among each other exist for a generic NPP transient;
 - The adopted number of similar tests is a function of the resources available (increasing the number of selected similar tests increases the 'confidence' in the results);
 - Tentatively, the minimum number of similar tests to be specifically considered for each application can be fixed as three (provided no unexpected situations are measured); this means that if in any set of three tests, performed in differently scaled facilities, an unexpected situation occurs (in the sense that a RTA occurs only in one test) the three experiments cannot be used for the UMAE/CIAU unless the origin of the problem is very well understood (for example connected to the boundary conditions) and the new RTA is very well predicted by the code;
 - Limiting situations may be envisaged: let us assume that ten experiments are used for the extrapolation. It may happen that all the ten experiments are characterised by one RTA but only in five (or less) of the experiments another RTA occurs. In such a situation the extrapolation process implies that in the same transient 10 data are used to extrapolate the first RTA and only 5 (or less) data are used to extrapolate the second RTA. The realism in the data extrapolation is not substantially affected considering that, even in the worst situation, 10 overall similar scenarios remain the basis for the extrapolation process. In addition, this situation does not occur if one extrapolates the accuracy for pressure and residual mass; it may occur when extrapolating the accuracy of rod surface temperature in case of CHF;
- e) Execution of code runs simulating the selected experimental scenarios: several conditions, identified in the UMAE/CIAU description, must be fulfilled in relation to the development of the nodalizations, the achievement of steady state, the acceptability of the code results.

Topic #3: Quantification of the input parameters

The 'propagation of output errors' is at the basis of UMAE/CIAU method. In no case a characterization of the input uncertainty parameters is adopted (as explained above all possible input uncertain parameters are considered by the

method through the direct comparison between experiment and calculation results). The following applies to the characterization of the output uncertainties:

- a) The 'Accuracy A' (*experimental value / calculated value*) is a measure of the discrepancy between the experimental and calculated value of any of the parameters (RTA) discussed above;
- b) The quantity A is a stochastic variable.
- Uncertainties associated with nodalization inadequacies (including the need to nodalize 3D systems with 1D components), model inadequacies including numerics, imperfect knowledge of boundary and initial conditions and user effects), are combined all together in the UMAE/CIAU process (see also Ref. 28). In this case it is assumed that the same uncertainty ranges characterise the facilities and the reference NPP. There are no assumptions connected with the linearity between parameters (RTA) and phenomena and with the mutual independence of the input uncertainties.

Topic #4: Phenomena identification and ranking process

A prioritization process constituted by phenomena identification and phenomena characterisation tables are included in different steps of the UMAE/CIAU. However in no case 'ranking' is adopted.

In connection with the prioritization process it seems worthwhile to report here two observations, giving a reason why the ranking of phenomena is not considered in the UMAE/CIAU:

- The phenomena identified (RTA in the case of the UMAE/CIAU) are not independent among each other (i.e. misprediction of break flow may be caused by misprediction in CCFL and vice versa): so, ranking of one phenomenon implies the ranking of many others that are not usually identified;
- A highly ranked phenomenon (phenomenon (a), e.g. forced convection heat transfer) might be known with high level of accuracy; a low ranked phenomenon (phenomenon (b), e.g. behaviour of non condensable gases) might be known with a very low level of accuracy. In the frame of uncertainty evaluation the phenomenon (b) might cause a greater error than phenomenon (a), but owing to its low rate it is not considered.

V. CONCLUSIONS

Best-estimate applications of complex thermal-hydraulic system codes are recommended to be supported by uncertainty evaluation for the relevant output quantities. The Internal Assessment of Uncertainty is a desirable capability in the area that was already identified by the technical community in 1996: it allows the 'automatic' association of uncertainty bands to code calculations results, considering the uncertainty as a 'peculiarity' of the assigned code. Consequently, the influence of code-user upon the predicted uncertainty values should be negligible when a robust uncertainty method is available. The

recommendation to explore this area considering the economic benefit of IAU applications has been followed at University of Pisa through the consideration and development of the CIAU method.

The key applications discussed in the present paper reveal the achieved maturity level of the CIAU methodology that is characterized by the capability a) to deal with all source of uncertainty, b) to takes into account and propagates consistently the time error and c) to minimize the engineering judgements (in the phase of the application of the method) needed for performing the uncertainty evaluation.

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