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Uncertainty Evaluation of the Results of the MSLB Benchmark by CIAU Methodology

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The purpose of the presented research in this paper was to perform an uncertainty evaluation of a Main Steam Line Break (MSLB) transient scenario occurring in a PWR applying the CIAU-TN methodology (Code with - the capability - of Internal Assessment of Uncertainty for Thermal-hydraulics/Neutronics coupled codes).

The work has been carried out within a technical cooperation between Penn State University and University of Pisa where the CIAU-TN methodology has been developed. Two main objectives have been established. First, to supply the uncertainty evaluation to the results of the OECD/NRC PWR MSLB Benchmark. Upper and lower continuous limits have been predicted for the trends of the axial and the radial peaking factors of spatial power distribution and for the core power history. The second aim was to enlarge the CIAU-TN database that, currently, includes the uncertainty values derived by the analysis of the results of OECD/NRC BWR TT Benchmark.

KEYWORDS: Uncertainty, UMAE, CIAU, MSLB

1. Introduction

Evaluating nuclear power plant performance during transient conditions has been the main issue of safety researches in the thermal-hydraulic area carried out all over the world since the beginning of the exploitation of nuclear energy for producing electricity in the 50's (e.g. State of the Art Report by CSNI and Compendium of ECCS Researches by US NRC, both issued in 1989, [1]).

A huge amount of experimental data has been made available from very simple loops (Basic Test Facilities and Separate Effect Test Facilities) and from very complex Integral Test Facilities simulating all the relevant parts of a Light Water Reactor (LWR). On the other hand, sophisticated computer codes like Athlet, Cathare, Relap and Trac have been developed in Europe and United States and are widely in use at present. These are able to calculate time trends of any interesting quantity during any transient in LWRs with assigned boundary and initial conditions. The reliability of the predictions cannot be directly assessed owing to the lack of suitable measurements in the plants. So, the capabilities of the codes can be evaluated only from the comparison between calculation results and experimental data recorded in small scale facilities. In order to evaluate the applicability of a code in predicting a plant situation, one must be sure, at least, that the experimental data used for qualifying the codes are representative of phenomena expected in the plant and, subsequently that codes are able to reproduce qualitatively and quantitatively these data.

The (unknown) error made in predicting plant behaviour is called uncertainty, while the discrepancies

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between measured and calculated trends related to experimental facilities, are included in the <u>accuracy</u> of the prediction. The methodology here proposed aims at evaluating uncertainty from accuracy data.

The description of the general ideas, features and capabilities of the Code with (the capability of) Internal Assessment of Uncertainty (CIAU) [2], its extension to the prediction of uncertainty of 3D Neutron Kinetics Thermal-hydraulics coupled codes (CIAU-TN) [3, 4] and its application to the OECD/NRC PWR MSLB Benchmark constitutes the subject of this paper. CIAU has been developed from University of Pisa with the aim to realize the integration between a system code calculation and an uncertainty methodology. The code allows the assessment of the uncertainty calculation in a code subroutine even as the transient progresses (satisfying the need that the scientific community highlighted during the OECD/CSNI "Annapolis Meeting" organized by USNRC in November 1996), and makes it possible that uncertainty bands automatically supplement any NPP calculation result.

2. Classification of Uncertainty Methods

Two broad classes of uncertainty methods can be identified (Fig. 1) dealing with propagation of "input uncertainties" and of "output uncertainties" (note - propagation of "output uncertainties" is also characterized as "extrapolation of output errors"), respectively.

The main characteristics of the methods based upon the propagation of input uncertainties (Fig. 1a) derive from the need to reduce the number of input uncertain parameters, to assign subjective probability distributions and to propagate the uncertainty throughout codes that by their nature are approximations of the physical behaviour. The main characteristics of the methods based upon the propagation of output uncertainties (Fig. 1b), derive from the need of having available relevant experimental data and from the process of error extrapolation that is not supported by theoretical formulations.

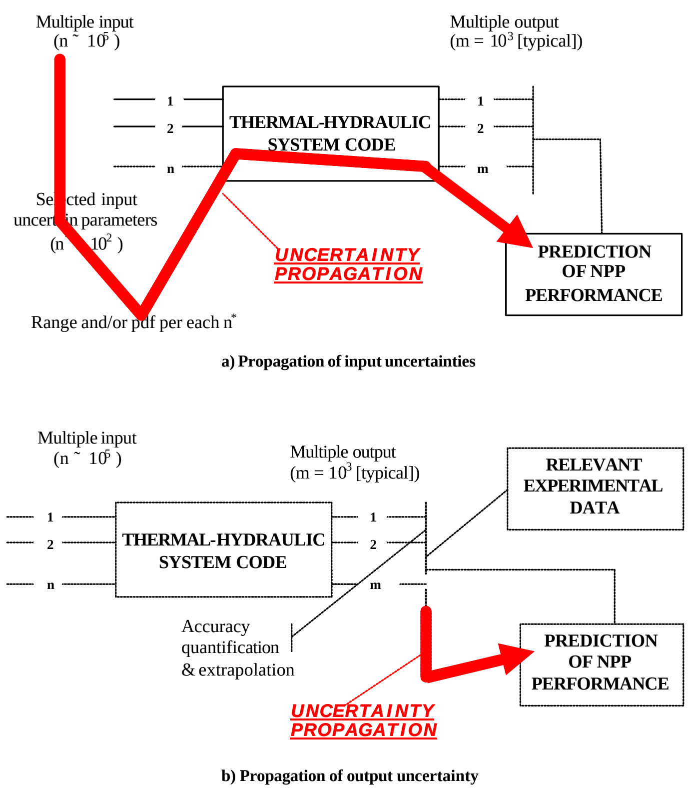


Fig. 1 Classification of uncertainty methodologies.

It shall be noted that almost all uncertainty methods are based upon the principle of 'propagation of code input uncertainties', while the CIAU method follows the principle of 'propagation of code output error'. Both the two principles have associated advantages and drawbacks. The main drawbacks for the first category are the need to select a reasonable number of variables and to associate range of variations and eventually distribution functions for each of these; in addition, the uncertainty propagation occurs throughout the code itself that, by definition, is an "imperfect" tool (this is the reason why uncertainty evaluation is needed). The main drawback for the second category are the lack of a formal analytical procedure to derive uncertainties and the need to have 'relevant experimental data' available; in addition, the sources of error cannot be distinguished as output from the application of the method. In the second category of methods, engineering judgement can be avoided in the phase of application of the method.

3. The CIAU-TN Methodology

CIAU-TN is derived as an extension of the CIAU methodology in order to perform the uncertainty evaluation of the results of 3D Neutron-Kinetics/Thermal-Hydraulics coupled codes. As CIAU-TN is based upon the same approach of CIAU, the sections from 3.1 to 3.3 deal with the derivation of the CIAU methodology. Section 3.4 is dedicated to the extension to CIAU-TN.

3.1 The Idea at the basis of CIAU

The usual characterization of any transient or event that occurred or was calculated in a typical 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 beginning of the event, 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 [1, 5] 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 [6, 7] consists in selecting a fixed, small group of quantities 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 represent a status of the plant (in the graphical representation, any relevant quantity can be used in the vertical or horizontal axis). This approach is actually utilized to optimize the emergency procedures of NPPs.

The basic idea of CIAU is that at any of the regions of the phase-space can be assigned one uncertainty value or, in other words, the NPP status is a region of phase-space where the uncertainty in the code prediction is assumed to be 'uniform'. Reference is made to any transient situation assumed to occur in BWR- or PWR-equipped NPPs. No distinction is made among 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 (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 1. If a BWR is considered, five driving quantities apply, i.e., all of the aforementioned except the one at item (3) in Table 1. 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 Table 1.

Six dimensions constitute the phase-space domain for a PWR, (1) to (6) mentioned earlier, and five in the case of a BWR (see Table 1). 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.

3.2 Uncertainty Values for the Status Approach

The overall uncertainty values in a transient thermalhydraulic system code calculation may be subdivided into two components:

- Quantity error: at a given time it is the error due to the differences between measured and predicted values of a certain quantity;
- Time error: at an assigned value of a quantity, it is the error due to the difference between measured and predicted time when that value occurs.

These two components are considered to be independent, so they can be evaluated separately. By this approach, one derives that if the same hypercube (i.e. a particular phase-space during a transient) happens in different times, the quantity error is the same, while time error is different. In this way it is possible to explain the differences in the uncertainty prediction between the different transient types (e.g. between a SBLOCA and a LBLOCA).

Quantity and timing errors are finally combined to form the total uncertainty: a graphical example of the combination of the two components to form the total uncertainty is shown in Fig. 2. In this figure, Y_i is a generic quantity, U_q and U_t are respectively quantity and timing error, while the total uncertainty is represented by the rectangle area. In other words, owing to the uncertainty, each point value may take any value within the rectangle identified by the quantity and the time errors. The amount of error, on each edge of the rectangle, can be defined in probabilistic terms, and it is consistent with what is recommended in a licensing approach (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 Part 50).

A Quantity Uncertainty Matrix (QUM) and a Time Uncertainty Vector (TUV) can be set up each one including several values of U_q and U_t derived by the UMAE uncertainty methodology.

3.3 Implementation in the Code

The capability of Internal Assessment of Uncertainty (IAU) is achieved by implementing the above matrix and vector into a code. Thousands of variables are the output of a code calculation and are utilized

Table 1 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.

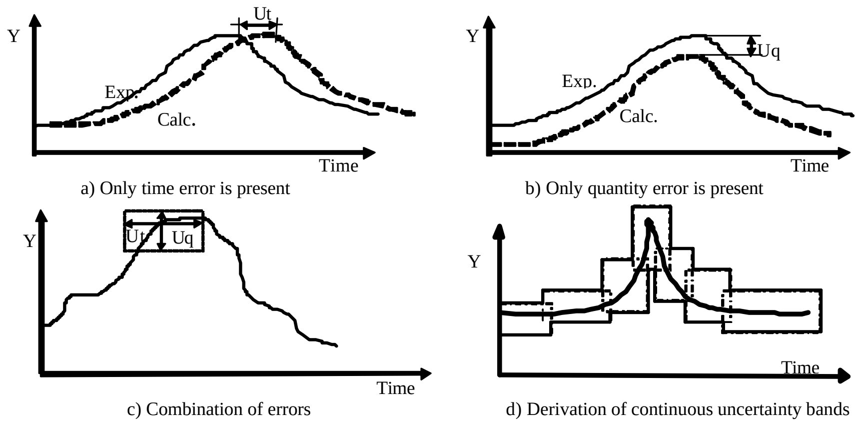


Fig. 2 Definition of quantity and of time errors to be included into the QUM and the TUV.

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 as 'object' quantities (i.e. the quantities in relation to which uncertainty is calculated for uncertainty evaluation): a) Primary system pressure, b) Rod surface temperature at 2/3 core height and, c) Primary mass inventory. Coincidence between the 'object' quantities and the driving quantities is due to the relevance of such variables and is not mandatory in the structure of the method (e.g. mass flow-rate at core inlet could be selected as 'object' quantity).

The uncertainty values can be put in the form of look-up tables where the independent axes are constituted by variables (1) to (6) from Tab. 1 and the dependent variables are the uncertainties associated with the time trends (a) to (c). Timing error is dealt with independently by a look-up vector. The approach pursued is similar to that proposed by Groeneveld et al. [8]: in that case, pressure, quality and flow rate are entered into the look-up table that produces a suitable value for the Critical Heat Flux. In the present case, the proper driving quantities (1) to (6) from Tab. 1 are entered into matrices and vector and produce the uncertainty values (a) to (c).

A simplified scheme of CIAU is reported in Fig. 3 where two main parts can be distinguished. The former deals with the development of the method and the latter with its application [2]. The relevant procedures foreseen in the development or application processes have been implemented in specific computer programs like the Accuracy Finalized to Extrapolation (AFE), the Data Analysis for Statistical Treatment (DAST) and the Uncertainty Bands Extrapolation Process (UBEP) [2].

3.4 Characteristics of CIAU-TN

The status approach at the basis of CIAU methodology, implies the selection of new 'driving' quantities to take into account the thermal-hydraulics/neutron-kinetics feedbacks between the two codes and to characterize the regions of the phase-space (hypercubes) to which assign the uncertainty values. In order to achieve this extension, the number of 'driving' quantities has been increased by two units, as can be seen in Table 2. The total reactivity and the core average exposure constitute the additional quantities able to characterize the series of subsequent statuses by which each transient scenario in NPP evolves.

The ranges of variation for these variables and their subdivisions into intervals together with the new adopted subdivision for the total core power are identified in Table 2. The total number of hypercubes, resulting from the combination of all intervals of the eight variables, is increased to 311040 instead of the 8100 hypercubes used in CIAU. However, this number can be reduced taking into account some physical conditions when the NPP status is identified; e.g. the possibility of getting status with very low pressure and core power greater than 100% is excluded.

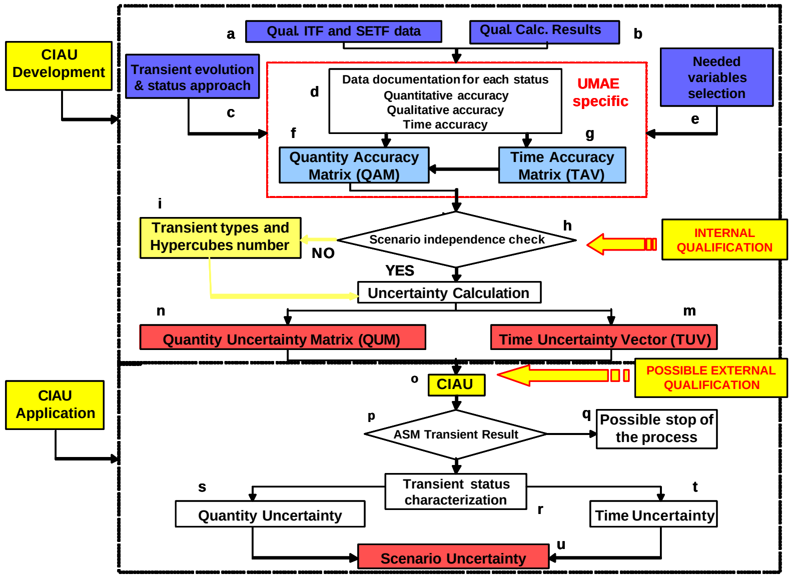


Fig. 3 Simplified flow diagram of the CIAU.

In order to achieve the capability to predict uncertainty affecting 3D neutron kinetics thermal-hydraulics calculations, the uncertainty matrices and vectors listen in Table 3 have to be filled following a similar approach to the one pursued for the filling of QUM and TUV.

Notwithstanding CIAU-TN is able to perform the uncertainty evaluation of the local factors at each time step of the calculation, hereafter the attention will be focused only on the peaking factors distributions corresponding to the time instant (t_p) when the core power peak occurs. The application of CIAU-TN is straightforward once these uncertainty matrices and vectors are available: each time the transient enters in one plant status, uncertainty values are picked up from the uncertainty database and transient enters in one plant status, uncertainty values are picked up from the uncertainty database and continuous uncertainty bands are automatically generated and superimposed to the following three new additional 'object' quantities (see also Section 3.3): a) Total core power history; b) Axial peaking factors distribution (F_z) at time t_p; c) Radial peaking factors distribution ($F_{x,y}$) at time t_p.

Table 2 Subdivision of the new driving quantities into intervals.

NEW DRIVING QUANTITIES	HYPERCUBE LIMITS					
	(1)	(2)	(3)	(4)	(5)	(6)
Total Reactivity (dk/k)	-0.400 ÷ -0.100	-0.100 ÷ -0.010	-0.010 ÷ 0.0	0.0 ÷ 0.0030	0.0030 ÷ 0.0050	0.0050 ÷ 0.0070
Core Average Exposure (GWd/t)	0 ÷ 10	10 ÷ 20	20 ÷ 30	30 ÷ 40	-	-

Table 3 Subdivision of driving quantities into intervals.

ID	Description	Objective
DTUV	Detailed Time Uncertainty Vector	Uncertainty on the Time when the Power Peak occurs
DPUV	Detailed Power Uncertainty Vector	Uncertainty on the Quantity of the Core Power
APFUV	Axial Peaking Factors (Fz) Uncertainty Vector	Uncertainty on the Quantity of Fz
ZUV	Axial (Z) Position Uncertainty Vector	Uncertainty on Axial Position of the Maximum
RPFUV	Radial Peaking Factors (F_R) Uncertainty Vector	Uncertainty on the Quantity of F_R
XUV	Radial (X) Position Uncertainty Vector	Uncertainty on Radial (X) Position
YUV	Radial (Y) Position Uncertainty Vector	Uncertainty on Radial (Y) Position

The dependence on the spatial position of the quantities b) and c) requires the development of specific tools in order to compare experimental (or reference) and calculated results to get accuracy values. The description of these tools is beyond the scope of this paper and can be found in detail in Ref. 3.

4. CIAU-TN Application to MSLB

4.1 The MSLB Benchmark

The reference calculation for the uncertainty application concerns with the second scenario (case with return to power) of the Exercise 3 of the MSLB Benchmark [9]. This exercise consists in performing a best-estimate coupled core plant transient analysis.

TMI-1 NPP is the reference design for the PWR model. The MSLB may occur as a consequence of the rupture of one steam line upstream of the main steam isolation valves. The event is characterised by significant space-time effects in the core caused by asymmetric cooling and an assumed stuck-out control rod during reactor trip. Appropriate modelling of this scenario requires multi-dimensional core representation (coupled three-dimensional (3-D) neutronics/core thermal-hydraulics) supplemented by a one-dimensional (1-D) simulation of the remainder part of the reactor coolant system.

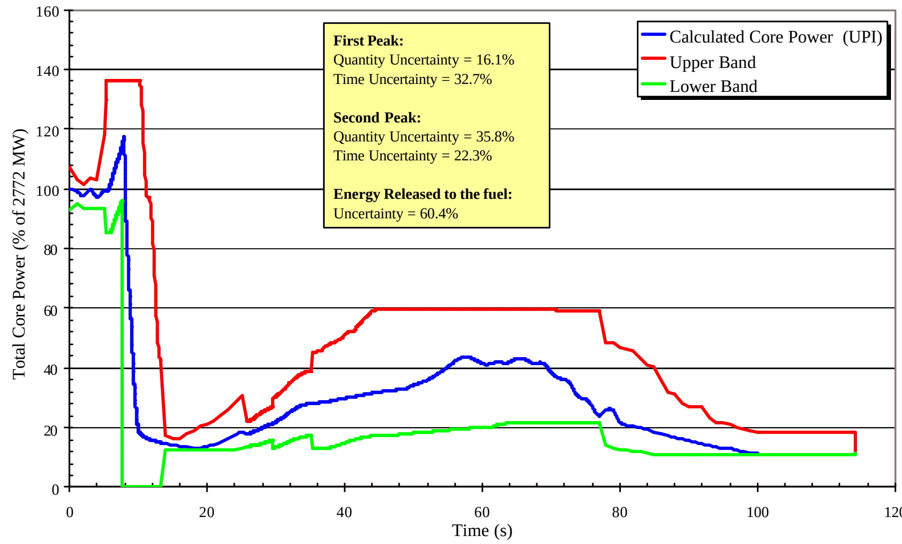
4.2 Results

Two set of uncertainty matrices and vectors have been derived using the results of the MSLB Benchmark. The first set constitutes the objective of the derivation of the CIAU-TN and any calculation used in the process is qualified in the sense required by the methodology. The second one has been developed in order to enlarge the database (all the results of the MSLB have been considered) and to prove the capability and flexibility of the method. However, it can not be used to supply the uncertainty evaluation because a process of validation has to be applied.

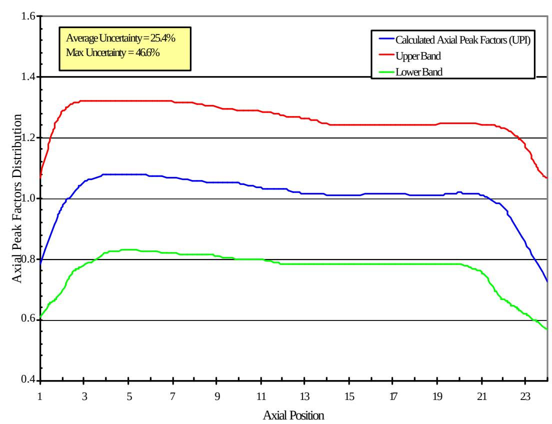
Related to set N° 1, the database have been calculated using only the results obtained by University of Pisa [10] through the use of RELAP5/PARCS coupled code. Continuous uncertainty bands bound the trends of F_z and F_{xy} distributions and the core power history (see Fig 4). Uncertainties values for the following parameters have been calculated:

- Core power:
  - first peak (117% of 2772 MW - t_P = 7.9 s): 16.1% of quantity uncertainty (QU), 32.7% of time uncertainty (TU);
  - second peak (44% of 2772 MW - t_P = 57.5 s): 35.8% of QU, 22.3% of TU;
- Energy released to the fuel: 60.4%;
- F_z distribution:
  - first peak (117% of 2772 MW - t_P = 7.9 s): average uncertainty value (U_{AVG}) of about 25.4% (maximum value 46.6%);
  - second peak (44% of 2772 MW - t_P = 57.5 s): U_{AVG} of about 33.6% (maximum value 35.4%);
- F_{xy} distribution:
  - first peak (117% of 2772 MW - t_P = 7.9 s): U_{AVG} of about 33.9% (maximum value 94.0%);
  - second peak (44% of 2772 MW - t_P = 57.5 s): U_{AVG} of about 45.8% (maximum value 135.3%).

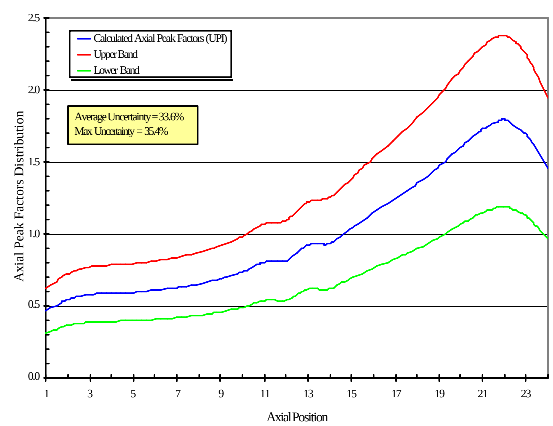
Notwithstanding the full implementation and use of the procedure requires a database of errors not available at the moment, the results obtained give an idea of the errors expected from the application of present computational tool to problems of practical interest.



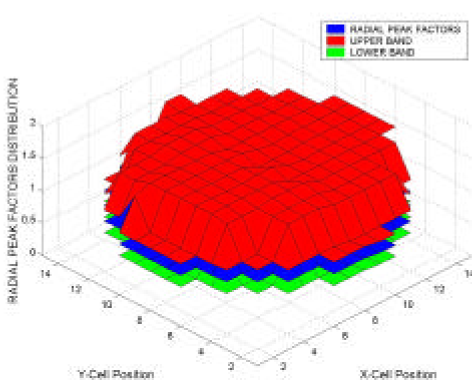
a) Core power history



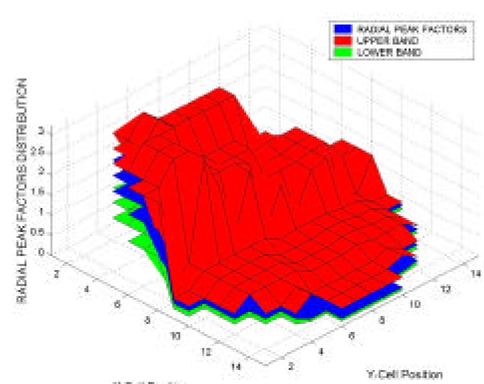
b) Axial Peaking Factors: First Peak



c) Axial Peaking Factors: Second Peak



d) Radial Peaking Factors: First Peak.



e) Radial Peaking Factors: Second Peak.

Fig. 4 Application of CIAU-TN to MSLB: Uncertainty Bands.

5 Conclusions

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. Therefore, uncertainty statements must supplement the application of best-estimate codes.

A method to calculate the uncertainty associated with NPP computer code calculations directly integrated in the code has been presented. The main advantage of an IAU approach consists in avoiding, from the methodology user point of view, to interpret logical statements that are part of the application process for all current uncertainty methods, i.e. avoiding user effect when using uncertainty methodologies. The above consideration does not exclude the use of engineering judgment: rather, engineering judgment is embedded into the development of the IAU method and not needed in its application.

CIAU constitutes a powerful tool that is originated by the combination of a qualified best-estimate 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 results of the concerned system code calculation.

CIAU-TN, extension of CIAU method to 3-D Thermal-Hydraulics/Neutron-Kinetics codes, constitutes a pioneering effort and a first possible answer to the requirements above. The capability to derive continuous uncertainty bands bounding the core power history and the axial and radial peaking factors distributions has been achieved and sample results related to the OECD/NRC PWR MSLB Benchmark have been shown. Notwithstanding the full implementation and use of the procedure requires a database of errors not available at the moment, the results obtained give an idea of the errors expected from the application of present computational tool to problems of practical interest.

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