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Assessment of the "Deterministic Realistic Method" Applied to Large break LOCA Analysis

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Abstract: *Electricité de France* (French Electrical Utility) presented a new method, called "Deterministic Realistic Method" (DRM) for the safety analysis of Large Break Loss Of Coolant Accident (LB LOCA). In principle, the method relies on the use of the CATHARE GB code, in association with the statistical evaluation of the peak clad temperature with a high probability level (95 %) for the verification of the safety criterion. However, in order to have a simpler methodology, Electricité de France defines the « DRM evaluation model »: this model consists in applying penalties on initial conditions and boundary conditions as well as on certain CATHARE GB code models, in such a manner as to obtain, by a single calculation, an evaluation of the peak clad temperature covering the peak clad temperature resulting from statisitcal method. Some insufficiencies concerning the statistical approach, both in its elaboration and its justification were identified by the assessment of the method. As far as the « DRM evaluation model » is concerned, the *Institut de Protection et de Sûreté Nucléaire* has concluded that this model provides a conservative evaluation of peak clad temperature, independently of the proposed stastistical method.

1 Introduction

Electricité de France (EDF, the French Electrical Utility) presented a new method, called "Deterministic Realistic Method" (DRM) for the safety analysis of Large Break Loss Of Coolant Accident (LB LOCA). This methodological development, which suggests, in particular, the use of the "best-estimate" CATHARE code, falls within the framework of the development of an American regulation, which authorises the use of methods called "best estimate" for the LB LOCA safety demonstration.

The aim of this document is to present:

- first, the main methodological developments proposed by the USNRC,
- the description of the method suggested by EDF,
- finally, the analysis of this method carried out by the *Institut de Protection et de Sûreté Nucléaire* (IPSN).

2 LB LOCA Evaluation Methods

In France, until now, LB LOCA safety demonstration has been carried out based on methodologies conforming to the regulations given in the 10 CFR 50 document produced by the USNRC in January 1974. Paragraph 50.46 of this document describes the criteria which must be met in order to estimate the safety injection efficiency. The required and acceptable features of models to evaluate the clad temperature and the oxidation rate are given in its appendix K:

- the peak clad temperatures are calculated for a reactor state corresponding to operating conditions of the reactor, envelope in terms of consequences for safety (100 % NP, FQ limit, residual power...). The initial plant state parameters are fixed at the penalised values (initial power fixed at 102 % NP, conservative residual power curve, maximised pressure, maximised temperature...);
- the initial and the boundary conditions being fixed, appendix K defines some recommendations (acceptable models) in order to evaluate peak clad temperature and oxidation rate, the aim of this being to obtain a conservative estimate of these parameters so as to compare them to the associated safety criteria. By the word conservative, we mean that the peak clad temperatures thus calculated are higher than the expected values in the case of a LB LOCA for these fixed reactor operating conditions.

Since the publication of 10 CFR 50 in 1974, several research and development programmes in accidental thermal hydraulics have been carried out in several countries and have led to an improvement in the understanding of the physical phenomena as well as in the LOCA transient simulation. Upon acquired knowledge from these research and development programmes, the specified recommendations given in appendix K appear very conservative.

From a regulation point of view, this evolution has led to an amendment of the regulations given in paragraph 50.46 of the 10 CFR 50 in 1988. The new regulation authorises the use of "best estimate" evaluation models, introducing major evolutions with regards to old methodologies for the following subjects:

- the treatment of the uncertainties on the initial conditions and boundary conditions: The study is still carried out for envelope operating conditions of the reactor in terms of consequences for safety (100 % NP, FQ limit...). However, plant state parameters are not fixed at the penalizing value of their variation range. The uncertainties affecting the initial and boundary conditions are statistically combined in such a manner as to estimate the scattering of possible peak clad temperature values resulting from these uncertainties,
- the peak clad temperature evaluation method: The regulation authorises the peak clad temperatures to be evaluated on the basis of a "best estimate" code. This implies that the code must provide results that are qualitatively correct and quantitatively representative of the average of the plotted points (and not necessarily the envelope values), where the code results are compared with representative test results. The evaluation method is therefore not intended to supply conservative results with respect to values which would be actually observed in the case of a LB LOCA. The uncertainties affecting the code models are statistically combined in such a manner as

to estimate the code response uncertainty,

- uncertainty of the calculation result, taking into account uncertainties referring to initial and boundary conditions and code models, must be considered and the maximum clad temperature must respect the criterion with a high probability level.

The new LB LOCA evaluation method developed by EDF and called the "Deterministic Realistic Method" (DRM) applied to LB LOCA, falls within the scope of this amendment of the American regulation.

3 Description of the DRM

EDF has defined, in collaboration with FRAMATOME, **a generic approach for the use of a "best estimate" code for design basis accident studies**, called “Deterministic Realistic Method” (DRM). This general procedure comprises the following stages:

1. physical analysis of the transient conditions and identification of dominant phenomena,

2. assessment of the code's ability to simulate these phenomena,

3. identification of key calculation parameters,

4. determination of uncertainty linked to key parameters,

5. combination of uncertainty linked to key parameters in such a manner as to estimate the uncertainty of the code's response: in the case of the LB LOCA, the aim is to estimate peak clad temperature covering 95 % of the peak clad temperature values (written as PCT95) taking into account the different sources of uncertainty, in such a manner as to compare the PCT95 to the associated safety criterion,

6. in practice, EDF does not directly compare the “code’s response with a high level of probability” to the safety criterion: assumptions are defined in such a manner as to penalise initial conditions and boundary conditions. Some models of the CATHARE code are also penalized in order to obtain by a single calculation an envelope estimate of the “code’s response at 95 %” calculated at the end of stage 5,

   The first five stages of the procedure lead to evaluate qualitatively the several sources of uncertainty with regard to the code’s response. Within the scope of a purely statistical procedure, the calculated “code’s response with a high probability level”, stemming from these stages, would be compared with the safety criterium.

   The aim of stage 6 is to provide a deterministic methodology producing results covering those obtained by the statistical method. The deterministic evaluation model is aimed at providing a practical and industrial tool available for the application's studies. The statistical method needed to estimate the “code’s response with a high probability level” is indeed the result of numerous and lengthy calculations whereas in a deterministic calculation with relevant penalties, only one CATHARE calculation may be carried out.

4 Application of the DRM to the LB LOCA

The procedure suggested by EDF for the LB LOCA analysis combines the statistical approach with a determinist approach:

- the PCT95 are estimated by the statistical approach,
- a penalising mode, called the « DRM evaluation model » enabling a CATHARE calculation enveloping the PCT95, is put forward.

The application of this procedure to the LB LOCA case presents the following main characteristics:

- EDF uses the CATHARE GB code, comprising version V1.3L_1 of the CATHARE 2 code, completed by some developments in the aim of improving the LB LOCA transient simulation,
- The key parameters taken into account in the statistical analysis are chosen according to their potential importance on the dominant physical phenomena of the transient, then their uncertainty ranges and their probability density functions are determined,
- The evaluation method for the peak clad temperature at 95 % (PCT95) relies upon the use of a response surface: this response surface makes up an approximation of the peak clad temperature as a function of the key parameters, and is used as a substitute for the CATHARE calculation to estimate of PCT95,
- The penalised parameters in the "DRM evaluation model " are chosen according to their relative importance with regards to global uncertainty, and without modification of main physical phenomena.

5 Analysis by the IPSN

The IPSN was requested by the French Safety Authority to assess the DRM method. The IPSN analysis has focused on the following points:

- verification of the "best estimate" nature of the CATHARE GB code for the LB LOCA transient (i.e. the code's ability to simulate this transient condition),
- the method for the peak clad temperature evaluation with a high probability level (PCT95) suggested by EDF, including identification of the transient key parameters, determination of their ranges of uncertainty and the method of spreading of this uncertainty in order to evaluate the global uncertainty of the peak clad temperature,
- the “DRM evaluation model”.

5.1 The CATHARE GB Code

The USNRC defines, in the “Regulatory Guide 1.157”, the nature of a "best estimate" code: a "best estimate" code must provide results that are qualitatively correct and quantitatively representative of the average of the experimental values (and not necessarily envelope values), where results are compared with representative test results. The first stage of any "best estimate" method is thus to check the code's ability to simulate the dominant phenomena of the transient under consideration. In particular, the implementation of the statistical method is not aimed at compensating for the code deficiencies, but at estimating the uncertainty of the code's response.

After a description of the CATHARE 2 code, the verification process of the "best estimate" nature of the CATHARE GB code is presented, in particular with regards to EDF’s motives for suggesting an amended version of the code.

5.1.1 General Presentation of the CATHARE 2 Code

The CATHARE code (**C**ode for **A**nalysis of **Th**ermalhydraulics during **A**ccident and for **R**eactor safety **E**valuation) is aimed at simulating the thermal hydraulic behaviour of a pressurised water reactor under accident conditions. The physical phenomena simulated by the code are roughly of two types:

- hydraulic: the code enables simulation of several two phase (liquid and steam) flow conditions with the dynamic exchange between the two phases,
- thermal: the code takes into account the heat exchange between the two phases, between the fluid and the walls (especially in the reactor core) and the primary - secondary heat exchange in the steam generators.

In order to do this, the primary and secondary circuits are described in CATHARE by a succession of « modules » (axial elements, tees, volumes) and « sub-modules » (pumps, exchangers, accumulators...).

Two modules are connected by a junction. A module has internal variables and junction variables: the internal variables satisfy conservation equations (mass, momentum and energy quantity balance) which are solved according to the junction variables, ensuring continuity of physical phenomena produced in the different components which constitute the reactor.

The sub-modules enable the description of heat exchange (e.g. in the steam generators), fuel rod thermal mechanics, primary fluid transport by the pumps, boundary conditions as containment pressure.... The sub-modules are linked to modules, the internal equations of which they modify by means of source or sink terms on mass, energy or momentum quantity.

The simplified nature of the conservation equations constructed on the basis of physical assumptions has led to complete them by constitutive relationships. These constitutive relationships are developed in order to represent the mass, impulse and energy transfer, on one hand between each phase and the walls, and on the other hand at the interface between the two phases.

The validation of these constitutive relationships is carried out in two stages:

- analytical tests qualification calculations in order to validate each of the constitutive relationships,
- test verification calculation carried out on the system loops in order to check the general consistency of the constitutive relationships of the revision under consideration.

5.1.2 Verification of the "Best Estimate" Nature of the CATHARE GB

The "best estimate" nature verification process for the code is similar to the validation procedure for code physical grid revision:

- first of all, all the elementary models of the CATHARE code used in the simulation of a LB LOCA transient have been identified. This list of elementary models is in accordance with the list set up by the OECD committee CSNI (Committee on the Safety of Nuclear Installations). These elementary models have been compared with the CATHARE 2 code qualification matrix, in order to check that the qualification covers all the elementary physical phenomena which may be encountered in LB LOCA,
- the global behaviour of the code for the LB LOCA has then been checked on the basis of representative tests of dominant physical phenomena of the transient from system experimental programmes LOFT, UPTF, BETHSY and ROSCO: the calculation/measurement comparisons show that the code simulates satisfactorily the entire dominant physical phenomena of the transient.

However, some limits of the code were well known, which led EDF to suggest additional developments for the LB LOCA transient. The CATHARE 2 V3L_1 code, completed by these particular developments, makes up the CATHARE GB code. The question of validation of the CATHARE GB code now arises: validation of the constitutive relationships of the CATHARE 2 V1.3L_1 code having been carried out for a fixed version of the code, it is now necessary to ensure that the implementation of new models or functionalities will not question the initial validation conclusions carried out by the CATHARE code development team. The analysis done by the IPSN of the additional developments shows that these developments should not impair the initial validation of CATHARE 2, in so far as they are aimed at specific conditions which are not covered by the CATHARE 2 V1.3L_1 code validation basis. The CATHARE 2 V1.3L_1 validation document thus completed by validation documents concerning particular developments suggested by EDF enables the CATHARE GB code validation to be justified. In the light of these validation documents, the IPSN has considered that the justification of the "best estimate" nature of the CATHARE GB code for the transient of the LB LOCA was acceptable.

5.2 Assessment of the PCT95 in the DRM Applied to LB LOCA

In principle, the method relies on the use of the CATHARE GB code, in association with the statistical evaluation of the peak clad temperature with a high probability level (95 %) for the verification of the safety criterion. This requires the prior identification of the different sources of uncertainty (initial conditions and boundary conditions, code models).

5.2.1 Determination of Sources of Uncertainty

EDF is limiting its analysis to the transient dominant parameters, in particular where the code models are concerned.

Upon examination of the list put forward by EDF, the IPSN considered that:

- the code models of CATHARE that EDF has chosen as being key parameters indeed play a major part in the simulation of a LB LOCA,
- with respect to the code models not chosen by EDF, the variation of each model within its range of uncertainty, when considered independently of the others, has a limited impact on the peak clad temperature calculation by CATHARE (a few degrees).

However, there was no demonstration concerning the impact of the parameters (code models) excluded for the PCT evaluation. Consequently, the IPSN has carried out a study in order to quantify the effect of the set of the parameters not considered by EDF upon the PCT95 evaluation.

This study was carried out to evaluate the uncertainty on the PCT calculation using a method developed by the IPSN. This method relies on Wilk's theorem and allows, given a limited number of calculations and for a given number of input parameters, to determine a PCT95 envelope value: 100 CATHARE calculations lead to a PCT95 envelope value with a level of confidence of 99 %. Furthermore, statistical treatment of the results enables the dominant input parameters with respect to the peak clad temperature evaluation to be determined.

The effect of the parameters not considered by EDF has been analysed on the basis of two statistical studies:

- an initial "PCT95 envelope" evaluation was carried out for a cold leg longitudinal split break of 1.2 times the cross sectional area of the cold legs of a CPY type reactor. This evaluation takes into account 30 input parameters, 27 of which are code models. At the end of this initial evaluation, a statistical treatment of the results has pointed out 8 dominant input parameters, 5 of which are code models,
- a second "PCT95 envelope" evaluation was carried out, for the same break, considering only the 8 identified dominant parameters from the previous stage as being input parameters.

The comparison of the obtained results for these two evaluations of the PCT95 envelope shows that the impact of parameters of "second importance" on the PCT95 evaluation may be considered as significant (25 % of the sum of the effect of the whole of the parameters).

The IPSN therefore considers that it is necessary for EDF to estimate the bias to apply to the determined PCT95 during the statistical analysis in order to take into account the effect of the parameters of "second importance".

On the condition that such a bias is determined, the IPSN has considered that the procedure proposed by Electricité de France, which consists in considering only the dominant code models in the statistical analysis to evaluate peak clad temperature, is acceptable.

Uncertainty affecting LB LOCA transient key parameters was then quantified.

For the code models, the uncertainties are estimated using the measurement/calculation comparison. In this respect, work carried out both at the IPSN and within the CATHARE code development team has highlighted the problems linked with the determination of ranges of uncertainty, in particular when several code models together participate in a significant manner in the test simulation, an infinite combination of ranges of uncertainty thus exist enabling the experimental results to be framed without the objective possibility of giving preference to one rather than another.

For the initial conditions and limiting conditions, uncertainty is evaluated using plant data and fuel data specified by the manufacturer.

5.2.2 PCT95 Assessment

The aim of this stage is to evaluate the impact of the uncertainties of key parameters on peak clad temperature results, this in order to determine the peak clad temperature values encompassing 95 % of the possible values (PCT95). This can be shown in the following manner:

key parameters and their uncertainty	—— CATHARE ——▶	PCT value at 95 %

The IPSN considers that, supposing that all the sources of uncertainty are known for the peak clad temperature calculation, the only method which enables the distribution function of the peak clad temperature to be closely estimated is the direct Monte-Carlo method. Given N random samples on the transient key parameters in their variation range, N peak clad temperature calculations are carried out with the "best estimate" code. By ordering the N values of the PCT obtained in ascending order, the envelope value of 95 % of the obtained results is determined. This value may then be compared with the criterion. Taking into account the time necessary to calculate a LB LOCA with an advanced thermal hydraulic calculation code such as CATHARE (around 6 hours on a PC) and the number of calculations required in order to obtain an acceptable estimation of the envelope value of 95 % (around 4,000 calculations), this method appears to be difficult to implement.

The PCT95 evaluation method suggested by EDF relies upon the use of a response surface, which approximates the function linking the peak clad temperature with the key parameters. The PCT95 is then determined using a Monte-Carlo method on the response surface: given N random samples on the key parameters in their variation ranges, N peak clad temperature values are calculated, no longer with the CATHARE code but using the response surface.

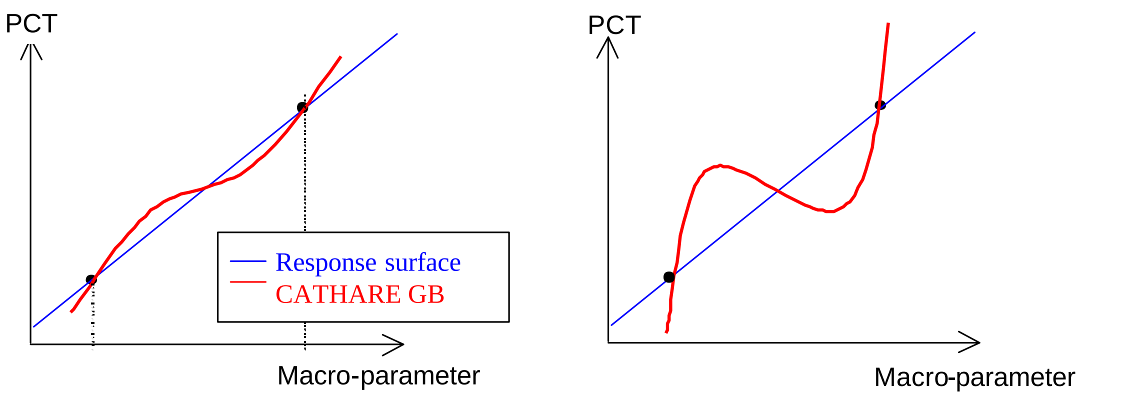
The function linking the peak clad temperature with the key parameters is using a 1st degree polynomial of each of its variables, using CATHARE calculations carried out for the extreme values of the variation range of each key parameters. The construction of this function thus requires 2^M CATHARE calculations, with M being the number of key parameters being studied.

In order to limit the number of CATHARE calculations required for the construction of this response surface, the method consists of the categorisation of certain key parameters into “macro-parameters”, each “macro-parameter” being characteristic of a dominant physical phenomenon. For example let {xi} be a sub-assembly of key parameters contributing to the same physical phenomenon. EDF then defines the « macro-parameter » X (thermal transfers in the core, for example). The aim of the categorisation into "macro-parameters" is to reduce the space of the {xi} down to one dimension only, in such a manner as to define the peak clad temperature as the function of one variable only.

As the response surface is used as a substitute for the CATHARE code, it is essential to check the capability of the surface response to be a “good” or a conservative approximation of the code:

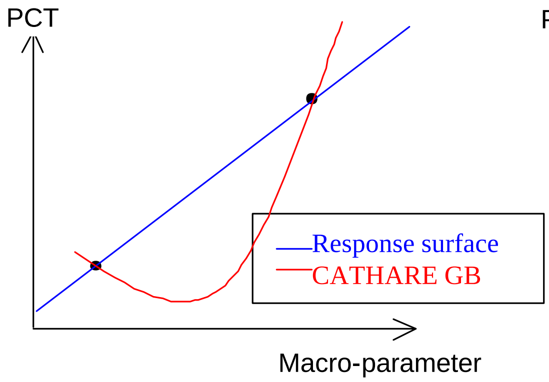
- the response surface is a “good” approximation if the differences between PCT calculated by the response surface and CATHARE GB remain small for any value of key parameters,
- the response surface is a conservative approximation if PCT calculated by the response surface are envelope of those calculated by CATHARE GB.

This can be illustrated by the following figure.

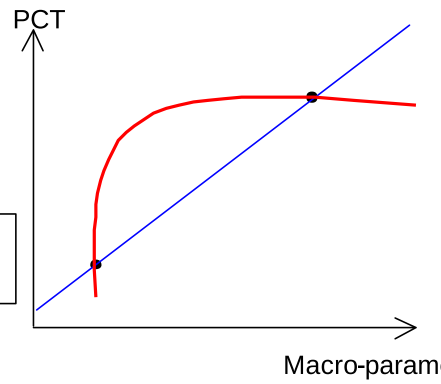


The response surface is a good approximation of CATHARE GB

The response surface is not a good approximation of CATHARE GB

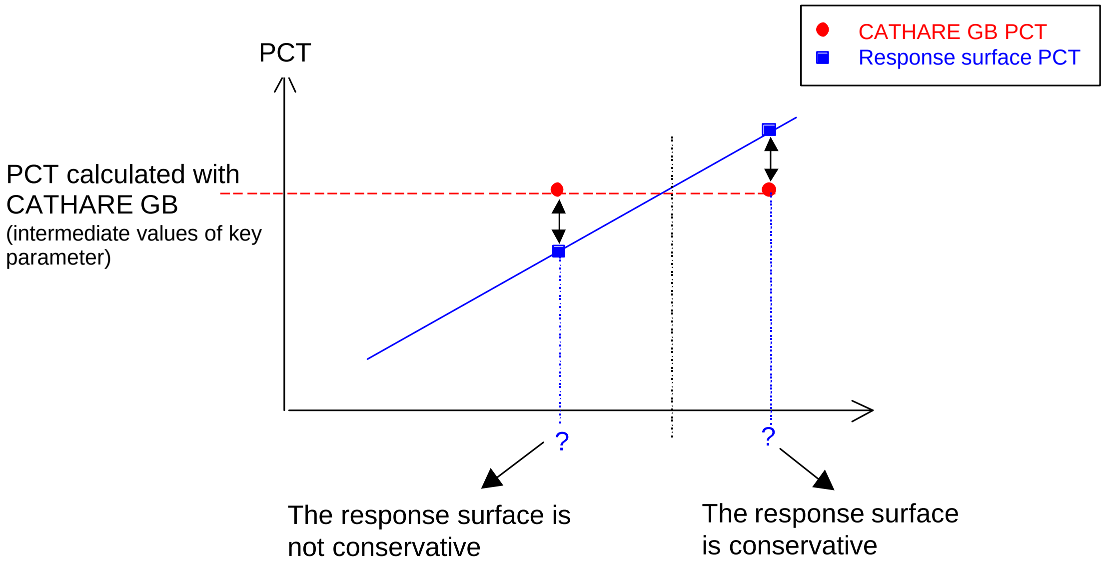


The response surface is conservative approximation of CATHARE GB



The response surface is not a conservative approximation of CATHARE GB

But as the function linking "macro-parameters" to key parameters is not explicitly known, it is not possible to associate to intermediate values of key parameters an intermediate value of the corresponding "macro-parameter". Therefore, it is not possible to associate to a PCT calculated with CATHARE GB for intermediate values of key parameters the corresponding PCT calculated by the response surface. This can be illustrated by the following figure.



As it is not possible to check the quality of the response surface, the IPSN concluded that the response surface quality used for the PCT95 evaluation was not reliable and that the conservatism of the statistical evaluation method was not demonstrated. As a consequence, the IPSN considers that peak clad temperature statistical evaluation as proposed is not applicable as it is for safety demonstration.

5.3 The « DRM evaluation model »

The statistical method based on the CATHARE GB code constitutes, for Electricité de France, the LB LOCA study reference tool for the calculation of the peak clad temperature. However, in order to have of a simpler methodology, EDF defines the "DRM evaluation model". This model consists on applying penalties on initial conditions and boundary conditions as well as on certain CATHARE GB code models, in such a manner as to obtain an envelope calculation of the peak clad temperature with respect to PCT95.

Therefore, the "DRM evaluation model" suggested by EDF is only valid on the basis of its PCT95 envelope nature. The lack of justification of the PCT95 evaluation has led EDF to justify, on the basis of representative tests (BETHSY, ROSCO, LOFT, PERICLES, FLECHT SEASET), that the CATHARE GB code with penalised models, called « penalised CATHARE GB " and which is used for the LB LOCA safety demonstration, provides conservative results in terms of maximum peak clad temperature.

Furthermore, the initial conditions and boundary conditions chosen for the LB LOCA safety demonstration are fixed at their penalised values. The applied values mostly conform to the previous practice, the changes observed being consistent with the enhancement of physical knowledge.

Therefore, the IPSN considers the safety demonstration relying upon use of the "penalised CATHARE GB" code and the initial conditions and boundary conditions of the « DRM evaluation model" to be acceptable for the LB LOCA transient on a three-loop reactor.

6 Conclusion

The IPSN has analysed the procedure put forward by Electricité de France, which combines a statistic approach with a deterministic approach.

- The PCT95 are estimated using the statistic approach based on the CATHARE GB code. The IPSN has considered the "best estimate" nature justification of the CATHARE GB code for the LB LOCA transient to be acceptable. Where the PCT95 statistical evaluation method is concerned, the IPSN has concluded that the method suggested by the Electricité de France for PCT95 evaluation should be completed in validation and justification,
- A penalising mode, called "DRM evaluation model" enabling a CATHARE calculation enveloping the PCT95 is suggested. The analysis of this penalising mode has shown that this relies upon a study that associates the penalising assumptions on the initial conditions and the boundary conditions with the use of the penalised version of the CATHARE GB code. EDF has completed its justification document by giving a test simulation representative of a LB LOCA through the "penalised CATHARE GB" code and demonstrated the "penalised CATHARE GB" code conservatism. Therefore, the IPSN considers that the "DRM evaluation model" provides a conservative evaluation of peak clad temperature, independently of the PCT95.