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REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

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1. Introduction

The evaluations of radiological consequences for DBA conditions are done using conservative approaches that do not allow quantifying explicitly what would be the gains notably in terms of RC by additional safety measures or devices.

In addition to DBA safety assessment of Nuclear PowerPlants (NPP) is performed considering more severe situations (Design Extension Condition - DEC) than those typically contemplated for DBA. This is generally addressed taking into account additional events or combination of initial independent events. The development of specific countermeasures (procedures and hardware) is explicitly included in the design of the NPP.

DEC includes two different kinds of conditions: DEC-A, for which the prevention of significant core degradation is achieved by dedicated systems intervention and the DEC-B covering core melting occurrence, and severe accident management (SAM) is developed to mitigate the accident consequences.

The conservative approach was adopted because some relevant elements concurring to the results of safety analysis were poorly known: phenomenal taking place during the accident, the initial condition to be adopted for the analysis, the change of the conditions during operational working phase of the plan. In addition, the code capability to reproduce the behavior of the plant was not properly quantified.

The overcome of those aspects due to progress in the knowledge of the phenomena and the availability of more powerful and complex of computational tools, made possible the amendment of the conservative approach, and to move forward a Best Estimate (BE) approach.

However, the adoption of a BE approach requests to evaluate the uncertainties connected with the elements of the analysis to derive the total uncertainty related to the code results in reproducing the behavior of the plant during the accident.

The uncertainty evaluation is of course a relevant aspect in the assessment of assumptions, models and simulation codes to derive realistic safety margins in DBA and DEC-A conditions.

This task of the project aims at the identification of the uncertainty sources relevant when a BE approach is adopted to calculate a realistic evaluation of RC in DBA and DEC-A situations, focusing for simplicity's sake on two categories of accident: the Loss of Coolant Accidents (LOCA) and the Steam Generator Tube Rupture (SGTR) accidents.

In Figure 1 a general list of different calculation strategies is showed. The considered case of LOCA and SGTR, considering DBA and DEC-A conditions, are typically performed adopting a BE calculation plus Uncertainty.

This report qualitatively describes the potential uncertainty sources and a judgment of their relevance for the considered scenarios in Chapter 3 and Chapter 4. The overview of the approaches adopted to evaluate uncertainty is the content of the Chapter 5. Chapter 6 describe an approach to combine the uncertainty of the single calculations, when used coupled.

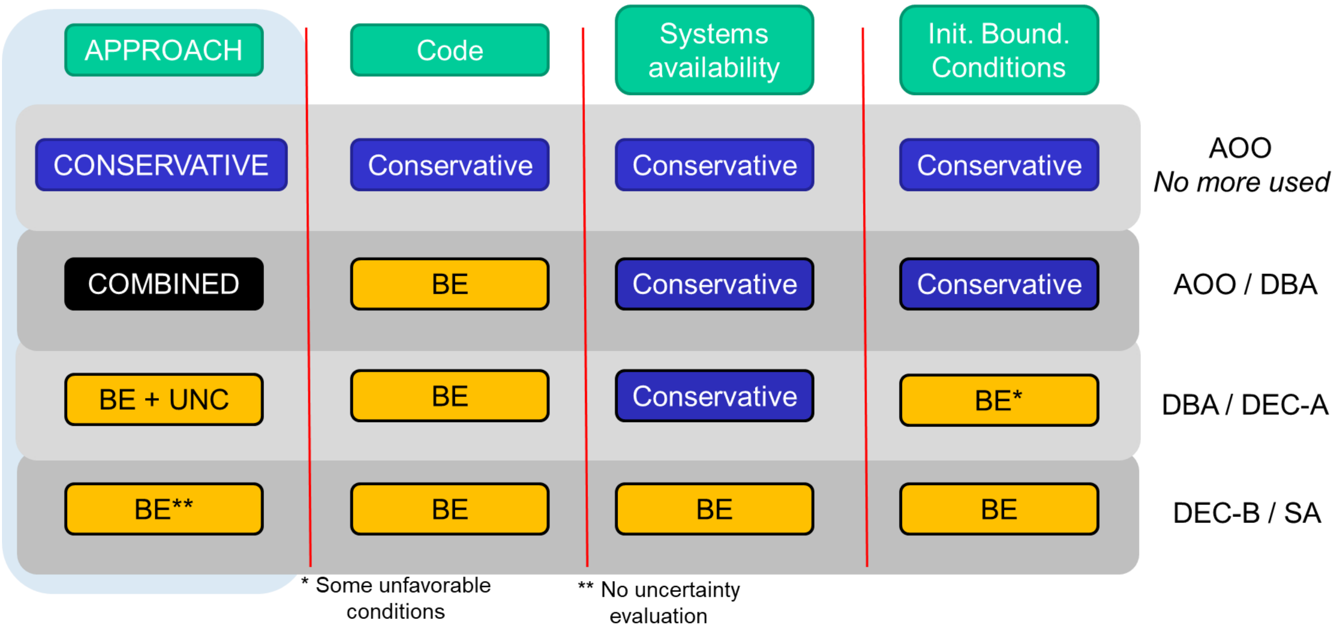

Figure 1 – List of possible calculation strategies

2. List of used acronyms

BE – Best Estimate
CCFL - Counter Current Flow Limitation
DBA - Design Base Accident
DC - Down Comer
DEC - Design extension conditions
DNB - Departure from Nucleate Boiling
ECCS - Emergency Core Cooling System
ITF - Integral Test Facility
LOCA - Loss of Coolant Accident
NDP - Not Dimensional Parameter
NPP - Nuclear Power plant
PAR - Passive Recombiners
PDF - Probability Density Functions
RC - Radiological Consequences
RCS - Reactor coolant system
RPV - Reactor Pressure vessel
SA - Severe Accident
SETF - Separate Effect Test Facility
SG - Steam Generator
SGTR - Steam Generator Tube Rupture
SRV - Safety Release Valve
UP - Upper Plenum

3. Uncertainty sources

The progression of an accident occurring in a NPP is complex and complicated. Complex because a lot of phenomena take place, and the phenomena affect each other. Complicated because each single phenomenon typically depends on many quantities and is represented by complicated equations.
The only possible approach to simulate complex transient is constituted by use of software code unless very simple scenarios are investigated. The code application implies the development of procedures and criteria regarding the use of the code itself, the setup of the model of the plant for the code and the data to be input. Particularly adopting the BE approach needs for evaluation of the uncertainties related to the obtained calculated results is generally requested.
Three major sources of uncertainty can be classified in these main groups:

- Models in the code. The phenomenological models implemented in the codes are typically obtained by the interpretation of the data issued from experimental tests. The implementation in the code can be adapted to optimize the mathematical solution and/or to better fit the conditions occurring in the plant during an accident.
- Representation and simulation of the plant. The representation of the plant is an important aspect, because a poor simulation of the plant can produce meaningless results. However, the simulation of the code, although some flexibility exists, giving different schematization options, is limited mainly to the necessity to discretize a continuous volume. In additions systems and related logic of actuation as well as conditions of the plant are reproduced with some approximations.
- Plant uncertainty. The data to be considered in the analysis are typically known in their nominal or most probable values. Different values, taken inside the range of possible variation of the data, can affect the calculated results in a relevant way.

Considering the above aspects more detailed uncertainty sources in the code can be derived. A list of code main uncertainty sources is reported in the Table 1.
Finally complex interactions among the basic uncertainty sources are to be expected.

Table 1 - Main uncertainty sources in the code

No.	Main uncertainty source in the code
1.	Code equations are approximate and/or the mathematical solution of the equation is approximated. • Not all the interactions between steam and liquid are included. • The equations are solved within cylindrical pipes; no consideration is given to geometric discontinuities, which is an uncommon situation for code applications to the analysis of nuclear power plant transient scenarios.
2.	The average of the fluid conditions (e.g., the lack of velocity profile in cross-section) and/or the approach simulating dynamic quantities in a prevalent direction (e.g., considering only one velocity vector along hydraulic mesh axis).
3.	Presence of different fluids/phases, having a single velocity (e.g., liquid droplets and film. Steam and not condensable gasses.
4.	Energy and momentum dissipation associated with vortices are not directly accounted for in the equations at the basis of the codes. Large vortexes may determine the overall system behavior (e.g., two phase natural circulation between hot and cold fuel bundles).

No.	Main uncertainty source in the code
5.	Irreversible processes occur as a consequence of accidents in nuclear reactor systems. This causes energy degradation (i.e., transformation of kinetic energy into heat). This process of energy transformation is not fully within the capabilities of current codes.
6.	Use of empirical correlations. Specific uncertainty aspects concerning this aspect are related to the ranges of validity, approximated implementation of the correlation in the code, correlation obtained in laboratories that have not necessarily the characteristics or of the plant. In addition, the data the correlation is based on can be affected by errors, scattering and uncertainty.
7.	Correlations are typically developed in steady state and fully flow conditions, but almost in no region of the nuclear power plant these conditions take place during the progression of an accident.
8.	The state and the material properties are approximate. This includes liquids, gases and solids. These data are of an empirical nature and their application are typically subjected to limitations.
9.	Code user effect. It is due to different development of the nodalization, different interpretation of the available information, that could be incomplete, different selection of code options, different interpretation of the code results. User effect is connected with user expertise and the quality and comprehensiveness of the code user manual.
10.	Computer and compiler effect. The same code with the same input deck applied within two different computational platforms produces different results. Differences are typically small in “smoothly running transients” but may become noticeable in the case of threshold or bifurcation driven transients.
11.	Imperfect knowledge of boundary and initial conditions. Some boundary and initial condition values are unknown or only approximately known.

Difficulties arising from this process are outlined below. The code assessment process emphasizes differences between predicted and experimental data that cannot be directly or easily assigned to any of the above listed categories in Table 1. In addition, improvement in the capability of the code to predict a particular experiment does not imply improvement of the capability to predict a different experiment. The process of code assessment improvement cannot be expected to fully eliminate the effect of all of the outlined sources of uncertainty.
However, the above evidenced points concerning the uncertainty are code feature and structure oriented. Those aspects affect the phenomena expected and to be simulated in the NPP analysis by the code application.
Concerning LOCA and DEC-A occurring in a NPP, a list of relevant phenomena/events can be set up for the scenarios of interest: LBLOCA and SGTR. Simulation of those phenomena/events is affected by uncertainty due to the uncertainty sources of the code. In the Table 2 the main phenomena or events of relevance for LBLOCA and SGTR are listed. The links betweenLBLOCA and SGTR phenomena or eventsand the uncertainty code sources (listed in the Table 1) are also indicated.
In the evaluation of the radiological consequence of DBA and DEC-A, the Containment analysis is also needed. A list of main phenomena or events relevant in the containment analysis as consequence of DBAand DEC-Ais reported in

Table 3.The links between containment phenomena or events and the uncertainty code sources (listed in the Table 1) are also indicated.
The general scheme of the connections between the code uncertainty sources and the uncertainty related to calculated phenomena and events for RCS and Containment in the case of DBA and DEC-B, is showed in the

Figure 2.

Table 2 - Main phenomena for the scenarios of interest (LBLOCA, SGTR) and link to the code sources of uncertainty

Main phenomenon/event	**Relatedto SGTR-LBLOCA**	**Code uncertainty sources affecting the simulation of the event/phenomenon.** *(The numbers refer to the list in Table 1)*
Natural circulation in 1-phase flow, primary side	SGTR	1, 2, 4, 5, 6, 7, 9, 11
Natural circulation in 2-phase flow, primary side	SGTR	1, 2, 3, 4, 5, 6, 7, 9, 11
Reflux condenser mode and CCFL	SGTR -LBLOCA (CCFL)	4, 5, 6, 7, 10, 11
Asymmetric loop behavior	SGTR	1, 2, 3, 9, 10, 11
Break flow	SGTR- LBLOCA	1, 3, 5, 6, 7, 9, 11
Phase separation	SGTR - LBLOCA	1, 2, 3, 6, 7
Mixture level and entertainment in SGsecondary side	SGTR	1, 2, 3, 6, 7, 9
Mixture level and entrainment and de-entrainment (Core, UP)	SGTR - LBLOCA	1, 2, 3, 6, 7, 9
Steam binding (liquid carry over, etc.)	LBLOCA	1, 2, 3, 4, 6, 7
Stratification in horizontal pipes	SGTR	1, 2, 3, 6, 7
Phase separation in T-junction and effecton break flow	SGTR	1, 2, 3,4, 5, 6, 7, 9
Mixing and condensation during injection	SGTR -LBLOCA	1, 3, 6, 7
ECCS bypass and penetration	LBLOCA	2, 3, 4, 5, 9, 10, 11
Loop seal clearing	SGTR	1, 2, 3, 9, 10 ,11
Pool formation in UP	SGTR - LBLOCA	1, 2, 6, 7, 10
Large void occurrence in the core and flow distribution	SGTR - LBLOCA	1, 2, 3, 6, 7, 9, 10, 11
Heat transfer in covered core	SGTR	1, 3, 6, 7, 8, 9
Heat transfer in partly/entirely uncovered core, incl. DNB, dry-out	SGTR - LBLOCA	1, 3, 6, 7, 8, 9
Heat transfer in SG primary side	SGTR	1, 3, 6, 7, 8, 9
Heat transfer in SG secondary side	SGTR	1, 3, 6, 7, 8, 9
Quench front propagation	LBLOCA	1, 3, 6, 7, 8, 9
Pressurizer thermal-hydraulics	SGTR	1, 2, 3,6, 7, 9, 11
Surgeline hydraulics	SGTR	1, 2, 3, 6, 7, 9
1- and 2-phase pump behavior	SGTR - LBLOCA	1, 2, 3, 4, 5, 6, 7, 11
Structural heat and heat losses	SGTR	1, 2, 3, 6, 7, 8, 9, 11
Non-condensable gas effects	SGTR - LBLOCA	1, 2, 3, 6, 7
Accumulator behavior	SGTR	1, 2, 9, 10 ,11
Boron mixing and transport	SGTR	1, 2, 3, 7. 11
Thermal-hydraulic-nuclear feed back	SGTR	1, 2, 3, 6, 7, 9
Separator behavior	SGTR	1, 2, 9, 10 ,11

Table 3 - Main phenomena occurring in the containment in case of DBA and DEC-A and link to the code sources of uncertainty

Main Phenomenon/Event	**Code uncertainty sources affecting the simulation of the event/phenomenon.** *(The numbers refer to the list in Table 1)*
TH Phenomena in the containment	
Stratification	2, 3
Flashing (flashing discharge)	1, 2, 3, 5, 6, 7, 9
Boiling heat and mass transfer	1, 2, 3, 5, 6, 7
Heat conduction in solids	1, 8
Convection heat transfer (natural and forced)	1, 2, 3, 4, 5, 6, 7, 8, 11
Condensation on surfaces	1, 2, 6, 7, 8
Pool surface evaporation and condensation	1, 2, 3, 6, 7, 8
Heat Removal by Dousing	1, 2, 3, 6, 7, 8
Direct contact condensation	1, 2, 3, 6, 7, 8
Buoyancy induced mixing in gases	1, 2, 3, 6, 7
Pressure wave propagation	1, 2, 3, 5, 6, 7, 8, 9
Mixing in water pools and mass diffusion in vapor	1, 2, 3, 6, 7, 8
Critical flow (choked flow)	1, 2, 3, 6, 7, 8, 9
Laminar/turbulent leakage flow	1, 2, 3, 6, 7
Vent clearing	1, 2, 3, 4, 6, 7
Pool swell / air injection	1, 2, 3, 6, 7
Liquid film flow	1, 2, 3, 6, 7
Gas dissolved in water	1, 2, 3, 6, 7
Gas entrainment by spray droplets	1, 2, 3, 6, 7
Heat and mass transfer of spray droplets	1, 2, 3, 6, 7
Mixing by sprays	1, 2, 3, 6, 7
Hydrogen	
Deflagration	1, 2, 3, 6, 7, 8, 11
Deflagration-to- detonation transition (DDT)	1, 2, 3, 6, 7, 8
Hydrogen mitigation - Passive autocatalytic recombiners	1, 2, 3, 6, 7, 8, 9
Aerosol	
Aerosol formation	1, 2, 3, 6, 7, 8,11
Aerosol impaction (Jet Impingement)	1, 2, 3, 6, 7, 8
Aerosol agglomeration	1, 2, 3, 6, 7, 8
Aerosol deposition	1, 2, 3, 6, 7, 8
Aerosol re-volatilization	1, 2, 3, 6, 7, 8
Pool scrubbing of aerosols	1, 2, 3, 6, 7, 8
Radionuclide transport	1, 2, 3, 6, 7, 8
Containment chemistry impact on source term	1, 2, 3, 6, 7, 8
Aerosol removal by sprays	1, 2, 3, 6, 7, 8
Iodine	
Aqueous phase oxidation and reduction of iodine species	1, 2, 3, 6, 7, 8,11
Inorganic iodine hydrolysis	1, 2, 3, 6, 7, 8,11
Organic reactions in water phase	1, 2, 3, 6, 7, 8,11
Iodine reactions with surfaces in the water phase	1, 2, 3, 6, 7, 8,11
Iodine reactions with surfaces in the gas phase	1, 2, 3, 6, 7, 8,11
Organic iodine reactions in gas phase	1, 2, 3, 6, 7, 8,11

Main Phenomenon/Event	Code uncertainty sources affecting the simulation of the event/phenomenon. *(The numbers refer to the list in Table 1)*
Interfacial mass transfer	1, 2, 3, 6, 7, 8,11
Iodine filtration	1, 2, 3, 6, 7, 8,11
Volatile iodine trapping by airborne droplets	1, 2, 3, 6, 7, 8,11
Iodine retention in leakage paths	1, 2, 3, 6, 7, 8,11
Iodine wash-down and scrubbing	1, 2, 3, 6, 7, 8,11
Iodine release from flashing pool or flashing jet	1, 2, 3, 6, 7, 8,11

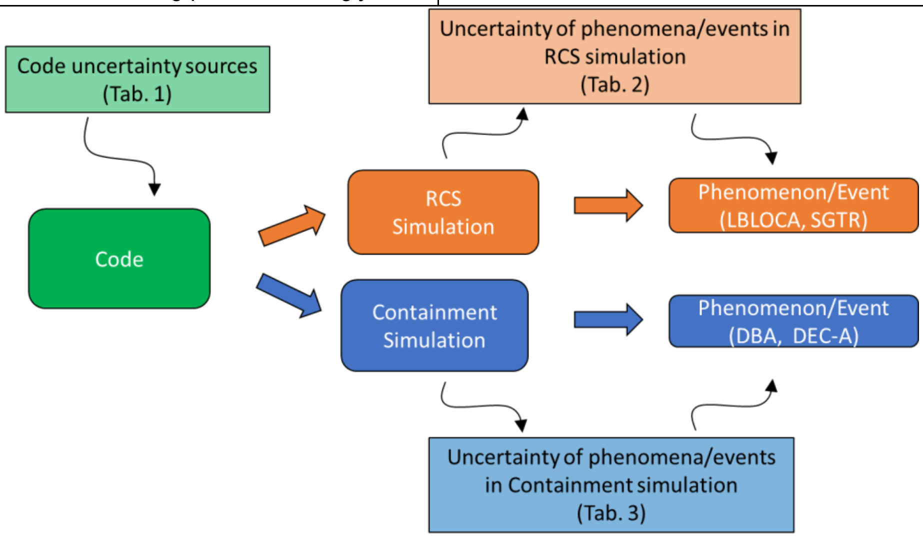

Figure 2–General scheme of the links between the code uncertainty sources and the uncertainty related to the results for the simulation of phenomena or events

4. Uncertainty relevance phenomena/action for the considered scenarios

Notwithstanding the effect of the code uncertainties on code prediction, not all the phenomena and events have the same relevance for the target of the analysis. Some phenomena or events can have a limited or negligible effect on the final results and specifically on the quantities used to be compared with target criteria. The uncertainty related to those phenomena or events can be tolerated to be larger than of other quantities. As an example, the thermal exchange between the primary and the secondary side can be affected by a large uncertainty, considering that they have a negligible relevance in the LBLOCA (but it is not true in SGTR). In addition, the absolute value of the uncertainties can be different for different the phenomenon or events (e.g., generally the uncertainty related to pressure evolution is smaller than uncertainty related to mass flow rate through a break).
In Table 4, Actions/Phenomena for the considered scenario, that can have a role as uncertainty sources are indicated and an evaluation of the relevance for uncertainty evaluation is also given related to code capabilities and knowledge gaps. The table also includes a list of challenging aspects. Under a single action listed in the table can be grouped different phenomena.
In the last two columns a judgment is also given related to:

- Code capability: it is about the contribution to uncertainty due to capability in reproducing the action/phenomenon (e.g., adoption of empirical instead of mechanistic approach).
- Knowledge gap: it is related to the knowledge of the phenomenological details of the action/phenomenon (e.g., lack in experimental tests and data).

To express a judgment based on an expert opinion, numbers from 1 to 5 are used.

- Code Capability : 1 means that for that Action/Phenomenon the code capability is less affecting and 5 largely affecting the uncertainty.
- Knowledge gaps: 1 meanscurrent Action/Phenomenon knowledge is less affecting and 5 largely affecting the uncertainty.

Table 4 – Evaluation of relevant actions/phenomena for uncertainty related to LBLOCA and SGTR (DBA/DEC-A conditions)

No.	Action/Phenomenon	Challenging aspects	Code capability affecting the uncertainty	Relevance of the knowledge gap for uncertainty
1.	Flow through the break	Break simulation Tube rupture simulation	4	4
2.	SG tube failure	Failure mechanism and weakness incl. ageing effects	3	3
3.	Injection of water by systems	Equipment capability simulation (e.g., pumps, local effect at injection points)	2	2
4.	Injection of water in-vessel	Core coolability and water distribution in the vessel, coolant bypass, injection strategy (e.g., DC and/or UP injection)	5	3
5.	RPV pressure evolution	Coolant flow in the plant Break position and orientation SG tube rupture configuration	2	2
6.	SG pressure evolution	SRV simulation SG tube rupture configuration SG tubes simulation	2	2

No.	Action/Phenomenon	Challenging aspects	Code capability affecting the uncertainty	Relevance of the knowledge gap for uncertainty
7.	Containment pressure evolution in LOCA accident	Emergency systems and structural elements heat exchange, condensation phenomena, containment flow circulation	2	2
8.	SG tube fluid circulation in the damaged SG	Effect of different SG tube simulation and break simulation on SG tube coolant circulation	4	3
9.	Core damage evolution	Core oxidation progression	4	4
10.	Hydrogen distribution in the vessel	Hydrogen accumulation in the vessel	4	4
11.	Containment hydrogen control	Hydrogen released in the containment, accumulation and stratification	3	3
12.	Fission products release	Rods damage Dispersion of radioactivity in RCS and containment	3	3
13.	Recriticality	Recriticality for various fuel types and accident configurations	4	4
14.	Environmental release (airborne and aqueous)	Containment leakage or containment bypass	3	3
15.	Iodine behavior in SG (in case of SGTR)	Chemistry, scrubbing, partitioning, transport in water/steam phase, transport at the break	5	5
16.	Aerosol and other FP behavior in SG (in case of SGTR)	Chemistry, scrubbing, partitioning, transport in water/steam phase, transport at the break	4	4

Some comments are here reported about the item indicated in the Table 4.

1. Flow through the break. The flow at the break is an important aspect of the accident, affecting the condition occurring in the RCS and containment. However, the break in the code is generally simulated with simplified components offering to the user the possibility to tune discharge coefficients. In addition, the actual details of the break geometries are never known apart if the break is single or double side.

2. SG tube failure. The occurrence of the break in the steam generator tubes is generally assumed/imposed or is calculated in a simplified way. Only in some cases a structural mechanical code is included to consider a more realistic simulation of the break occurrence during the accident progression.

3. Injection of water by systems. The systems injecting water is only fully simulated if details concerning those systems are of interest. Typically, they are simulated as boundary conditions including logic of actuation. This kind of approach is generally sufficient for the purpose of an adequate simulation.

4. Injection of water in-vessel. The distribution of the coolant injected in the vessel has a relevant role in the progression of the accident, and the phenomena to be considered are complex. The solution adopted for the simulation of the core/vessel and related code models are an important source of uncertainty.

5. RPV pressure evolution. The capability to evaluate the pressure in the RPV and RCS evaluation during the progression of an accident is generally adequate. Of course, it is largely affected by the events/phenomena occurring in during the accident.

6. SG pressure evolution. The same comment of the above point 5 is applicable. Less complex conditions occur in the SG compared with RPV.

7. Containment pressure evolution in LOCA accident. The same comment of the above point 5 is applicable. However, the relevance of the phenomena affecting the containment pressure evaluation is different compared with the phenomena in the RCS (e.g., condensation has a more relevant role than boiling). In addition, the same phenomena occurring in the RCS and containment, can occurs in different conditions (e.g., the coolant heat exchange on large surfaces, spherical in the case of external surface of LP, instead of rod surfaces).

8. SG tube fluid circulation in the damaged SG. The simulation of the flow in the tubes of the damaged SG is largely affected by the adopted schematization solution of the SG. It is relevant in evaluating the mass flow exchange occurring between the primary and secondary side in the SGTR.

9. Core damage evolution. The core damage (cladding failure and cladding oxidation) is a very relevant and complex situation affecting the final results of the analysis. The complexity of the situation is challenging for the code simulation capability.

10. Hydrogen distribution in the vessel. Hydrogen release and transport in the RCS has relevant safety relevance. The code simulates this condition assuming not detailed models for generation of hydrogen, and transport of hydrogen occurs only as a passive component of steam flow. No buoyancy of hydrogen is considered (e.g., no hydrogen accumulation in the upper part of the vessel is simulated)

11. Containment hydrogen control. The same comment of the above item 10 concerning hydrogen buoyancy and accumulation is applicable. The modeling of PAR is typically simplified.

12. Fission products release. The fission products release in DBA and DEC-A conditions are largely affected by other phenomena mainly relate to the cladding damage.

13. Recriticality: Relevant aspect, difficult to be properly stimulated. The limitation of the analysis in conditions of unchanged core geometry (BDA and DEC-A) makes the situation a little bit simpler then in SA situation. However, the adopted solutions for the core schematization, the distribution of the coolant and the composition of the fuel, play a relevant role in the recriticality evaluation.

14. Environmental release (airborne and aqueous). The release of the content of the containment in the environment is due to the physiological release of the containment (some volume percent per day) small leakages generated during the accident (e.g., some damage of sealing of containment penetrations). Larger releases can take place if containment bypass condition occurs (SGTR).

However, those are relevant aspects that are sufficiently inside the capability of simulation of the code.

15. Iodine behavior in SG (in case of SGTR). The iodine poses a big issue due to its complex chemical characteristics. In addition, the different phases (steam, mist, liquid) present in the SG during SGTR make the simulation very complex from the phenomenological point of view resulting very challenging for the code simulation capabilities.

16. Aerosol and other FP behavior in SG (in case of SGTR). The same comment in the above point 15 is applicable. However, the reduced chemical reaction of the other FP compared with iodine partially mitigate the complexity of the simulation.

The scaling issue

The setup and the validation of the phenomenological models in the codes are typically based on the experimental results performed in the test facilities. Data obtained in NPP are also used, but they cover only a small part of the range of the code phenomena models. Test facilities reproduce a part of the plant or specific phenomena (e.g., SETF) or the entire plant simulating the global behavior of the plant (ITF). In any case test facilities are scaled reproduction of the plant. The scaling process adopted in the design of the test facilities is characterized by a high level of complexity, because many aspects should be taken into account, but not all of them can be properly considered: the solution adopted for correct scaling of some aspects could be incompatible with the scaling of other aspects, some aspects cannot easily scaled (e.g. phenomena driven by gravity) or the hardware or the limits of the working conditions of the facility make not possible a proper scaled approach (e.g., heat losses).
As a consequence, model implemented in the code are for a certain extension affected by a scaling issue, it is an additional uncertainty contributor in the application of the code model at different scales moving from test facilities to the full-scale plant (NPP).
Figure 3 shows a simplified scheme of the connection between the scaling issue and uncertainty.

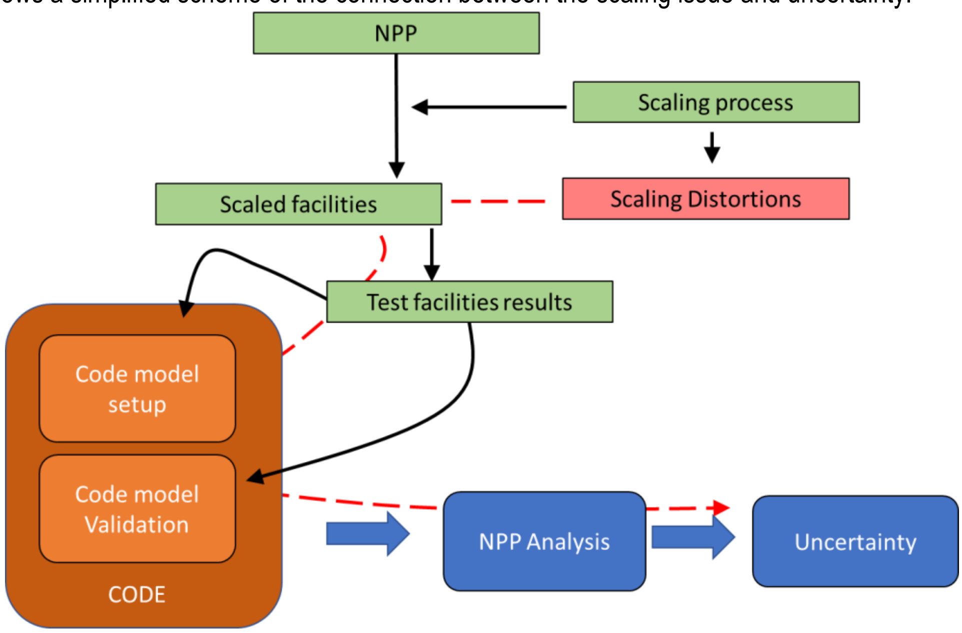

Figure 3 – Scaling effect on uncertainty (red dashed line)

The evaluation of the uncertainty contribution of the scaling issue is investigated comparing the uncertainty bands of the same accident/transient adopting different input scale. The procedure is constituted by the selection of a reference facility and to calculate the uncertainty for a selected scenario. The uncertainty is also calculated modifying the input moving from the facility scale to the scale of the NPP. The comparison of the uncertainty between the scaled calculations gives an idea of the code sensibility to the scaling issue.

An important role in the scaling effect evaluation is played by non-dimensional parameters (NDP). Those parameters can be used for a comparison between the scaled facilities and the full-scale plant to identify the main aspects affected by the scaling. It makes possible to consider the distortions introduced in the facility compared with the NPP, and to identify the relevant aspects mostly affected by scaling distortion for uncertainty evaluation.

Figure 4 shows a simplified scheme of the role of the NDP in the evaluation of the uncertainty contribution by the scaling issue.

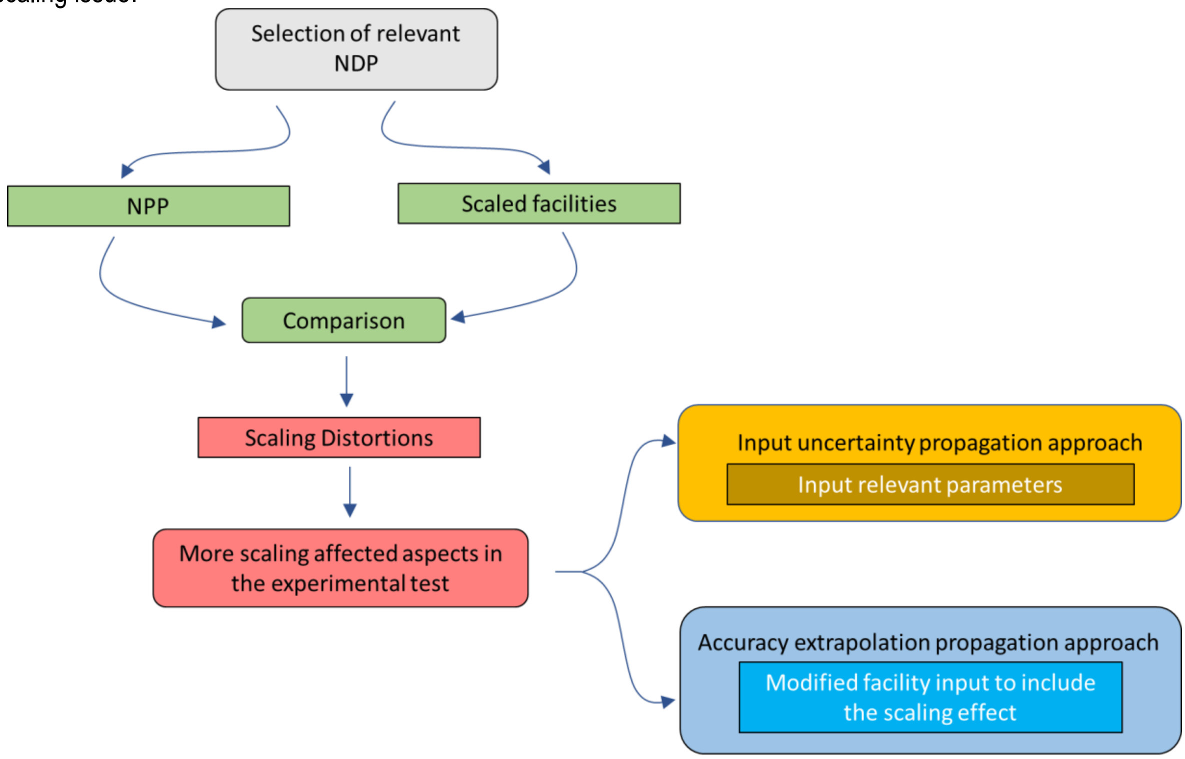

Figure 4 – Scaling effect on uncertainty (red dashed line)

5. Overview of uncertainty analysis approaches

Uncertainty analysis has been extensively studied in several international activities such as the OECD BEMUSE project. All the details on the different approaches to perform such an analysis can be found in [1] for example.
In general terms the approaches adopted for the analysis of uncertainty can be subdivided in two main groups. The relevant differences between the two approaches are related to the treatment of the calculation data to derive uncertainty. In “input uncertainty propagation” approach, the data of the calculations are generated by a proper statistical procedure to derive the uncertainty as the envelope of the possible results of selected calculations. In the “accuracy extrapolation” approach, the calculations results are used to derive the accuracy of the calculation, and with an extrapolation process the uncertainty is derived. In other word the first group is based on input uncertainty propagation and the second one on the extrapolation of the accuracy detected from the comparison between experimental and calculated data.
In
Figure 5, the scheme of the two strategies for the uncertainty evaluation are showed.

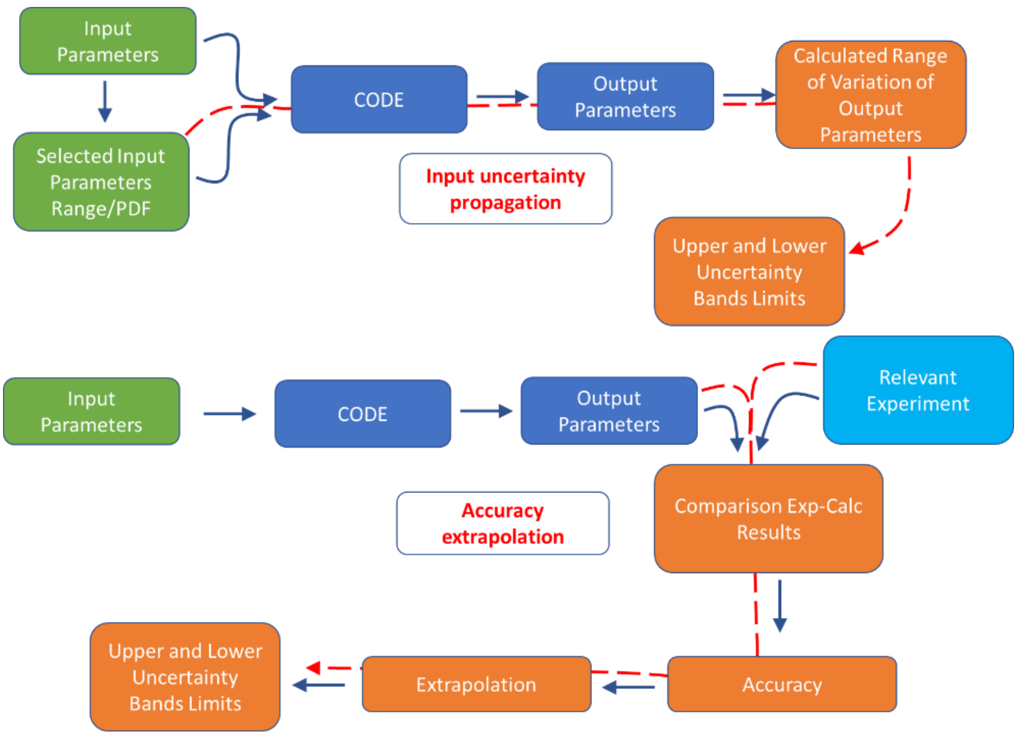

Figure 5 – Simplified scheme of the uncertainty evaluation strategies

Input uncertainty propagation. The code is assumed properly validated and this method is focused on the propagation of uncertainties generated by input parameters. The input parameters are related to initial and boundary conditions, solutions adopted in the schematization of the plant, options of the phenomenological models of the code. The input uncertainties are propagated to the simulation model output uncertainties via the code calculations, with sampled data from known or assumed (classically probabilistic) distributions for key input parameters. This type of method is performed in 4 steps:

1) Specification of the problem: All relevant code outputs and corresponding uncertain parameters for the codes, plant modelling schemes, and plant operating conditions are identified.
2) Uncertainty modelling: the uncertainty of each uncertain input parameter is quantified by a probability density function (PDF). If dependencies between uncertain parameters are known and judged to be potentially important, they can be quantified by correlation coefficients.

3) Uncertainty propagation through the computer code: the propagation is performed by Monte-Carlo simulations. In Monte-Carlo simulations, the computer code is run repeatedly, each time using different values for each of the uncertain parameters. These values are drawn from the probability distributions and dependencies chosen in the previous step. The results of a Monte-Carlo simulation lead to a sample of the same size for each output quantity.
4) Statistical analysis of the results: the output sample is used to get any typical statistics of the code response such as percentiles. A straightforward way to get information on percentiles is to use order statistics which is a well-established and shared methodology in the nuclear community. It also allows to derive the minimal number of computer runs to perform in order to obtain a lower or upper bound of a given percentile with a given confidence level.

This approach assumes that phenomenological models are properly qualified and that the identification of the relevant input parameters is performed. Moreover, when it is based on the probability theory, it requires the choice of a PDF for each selected input parameters. In addition, special tools have been developed to apply this approach in an automatic way by coupling computer codes to probabilistic tools, such as DAKOTA, RAVEN, SUNSET, SUSA, URANIE.

Accuracy extrapolation. The effects of all uncertainty sources can be obtained by comparing experimental results performed in the test facilities with the code results in simulating those tests. The results of the comparisons between experimental and calculation results constitute the accuracy of the code in reproducing that test. Combining (extrapolation) the accuracy obtained in several calculations related to tests relevant for the analysis to be performed, the uncertainties to be applied at a best estimate analysis of the plant is evaluated. This approach implies the set up for minimum level od validation of the code, input, data and user. In additions the availability of a statistically meaningfully number of experimental tests and related results is necessary. Example of those approaches is constituted by CIAU and NEMM.

In

Figure 5 the red line represents the path of the procedure to obtain uncertainties. In the case of the input uncertainty propagation the evaluation of the uncertainties starts from the selection of the relevant input parameters and their PDF, the use of the code and the management of the output parameters. In the case of accuracy extrapolation uncertainty evaluation needs the accuracy evaluation by exp-calc result comparison and the extrapolation process of accuracy.

- Specificity of the two approaches in evaluating the uncertainty.

The Input uncertainty propagation is focused on the code application. Notwithstanding the validation of the code, if some not recognized inadequacies are in the code, they affect the entire process. However, those situations are generally early evidenced by calculations results analysis. A certain number of calculations are necessary to obtain a statistical meaning to the obtained uncertainty. Specific tools can be used to automate the process. A key point is constituted by the identification of the effective relevant input parameters for the performing analysis. Experimental tests and sensitivity calculations constitute a common way to solve the issue. This type of approach also requires selecting a PDF for each relevant uncertain input parameters. In practice, PDFs are typically well known only for few parameters. Engineering judgment, sensitivity calculations or advanced inverse methods [2; 3] can be used to address this topic.

The accuracy extrapolation has the central element in the comparison between experimental tests and calculations. The idea is to obtain a global evaluation of the calculation by comparing the code results with a real reference case (the experimental tests). To obtain a realistic evaluation of the performance of the calculations, some minimal acceptability criteria are set up for each element of the calculations (code, input data experimental quality) to avoid unreasonable large final uncertainty. This implies a complex preliminary process of validation. In addition, the availability of a proper number of experimental test results are necessary. This can be an issue for those field of investigation where few experiments exist, or experiments are not useful for the analysis to be performed (e.g., because not reproducing the conditions of the plant considered in the analysis). One possibility to bypass this issue is to adopt as realistic references the results obtained in previously performed validate calculations with other codes.

6. Proposal for global uncertainty approach

RC evaluation adopting a conservative approach was adopted in the past for two main reasons: the difficulties to derive good qualitative and quantitative results; to obtain a fast and easy-to-use tool that gives a (fast) estimation of the source term and RC without the necessity to investigate in deep all the phenomena occurring during the accident affecting the RC.
Nowadays a best estimate approach is largely adopted making possible a more realistic evaluation. A realistic evaluation of RC gives more adequate results for the response to the emergences that takes advantage from a realistic definition of the necessary resources to be allocated in a more efficient way: a more detailed evaluation using sophisticated methods results in a realistic and substantially lower dose estimations.
The valuation of the RC requires several phenomena to be modeled in the analysis. A list of phenomena/situations to be considered is as in the following.

- TH progression of the accident in the RCS
- Specific phenomena connected to the fuel
- Specific phenomena occurring in the SG (atomization, flashing, scrubbing..)
- Leakage/release from RCS
- Evolution of the conditions in the containment or bypass of containment
- Distribution of radioisotopes concentration in containment
- Radioactivity released to the environment

Just considering only the code those aspects important for uncertainty evaluation can be identified:

- phenomenological models
- modelling capabilities
- numerical implementations and solutions
- scaling effects

Results from the above discussion that the RC evaluation is a complex process involving different technological areas and related tools. In
Figure 6 the technological areas to be considered for RC evaluation for DBA and DEC-A are indicated.

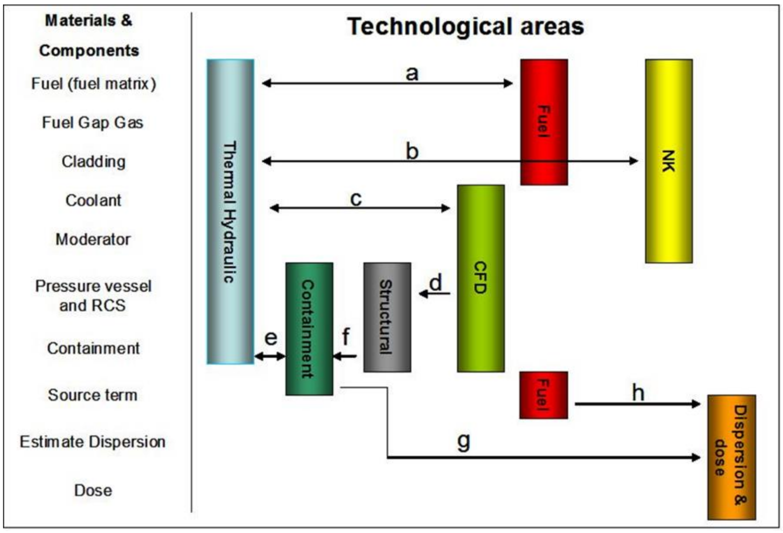

Figure 6 – Scheme of the areas of investigation for RC evaluation for DBA and DEC-A

In addition to the uncertainty sources considered in the Chapter 3, the possible use of coupled codes, in order to properly cover different aspects of the accident, poses the necessity to consider also the uncertainty related to the interface adopted to transfer data between the coupled codes. In

Figure 7 is reported the scheme of the coupled calculations and the transferring of data between them.

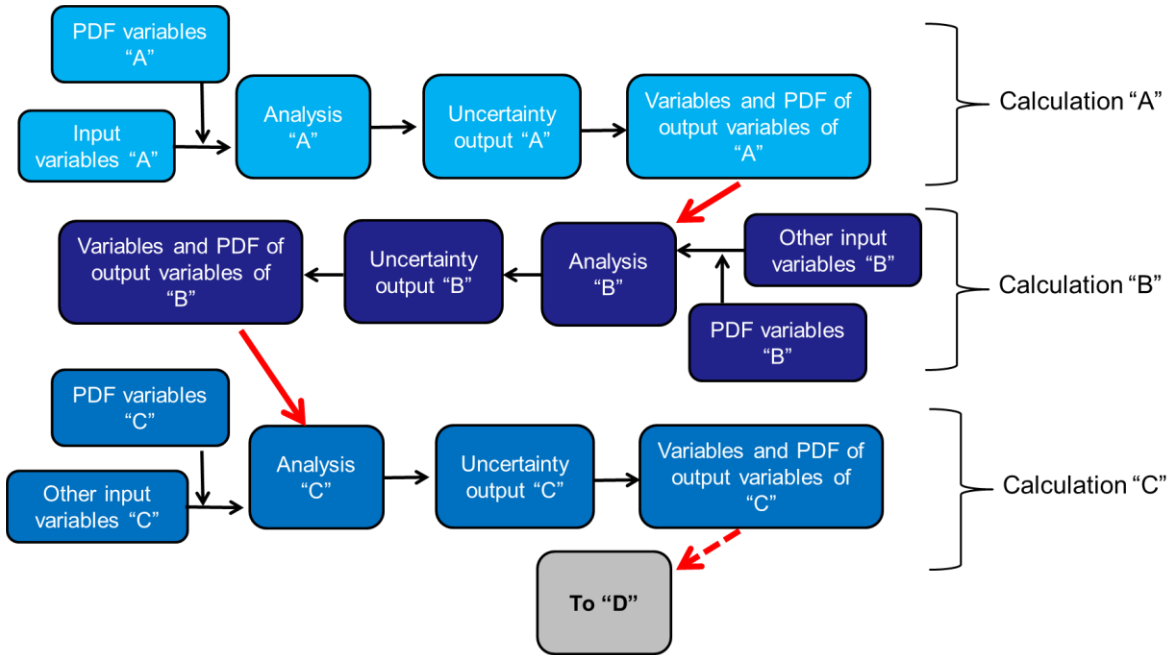

Figure 7 – Broad scheme for execution of coupled calculations

In Table 5, the sequence of actions for the process of coupling of the calculations "A", "B" and "C" is reported to clarify the meaning of
Figure 7. It is assumed that the selection of the codes to be used in the analysis has been done as well as the setup of the related plant schematizations (input).

Table 5 – Sequence of actions for coupled calculations (with reference to
Figure 7)

No.	Steps	Actions	Notes
1	Identification of the input parameters, identification of the relevant input parameters and setup of the related PDF, for the calculation "A"	Execution of the analysis	Execution of the analysis included the evaluation of the output results and the related uncertainty bands The uncertainty bands are calculated adopting one of the uncertainty methodologies currently available
2	Output results of the calculation "A"	Selection of the output parameters of calculation "A" to be used as input in calculation "B"	For the output parameters of calculation "A" to be used as input in calculation "B", the uncertainty band is also supplied

No.	Steps	Actions	Notes
3	Identification of the input parameters, identification of the relevant input parameters and setup of the related PDF, for the calculation "B"	Execution of the analysis	Execution of the analysis included the evaluation of the output results and the related uncertainty bands. The uncertainty bands are calculated adopting one of the uncertainty methodologies currently available. The PDF of the input parameters for calculation "B" obtained by calculation "A" are obtained by the uncertainty band identified in the step 1
4	Output results of the calculation "B"	Selection of the output parameters of calculation "B" to be used as input in calculation "C"	For the output parameters of calculation "B" to be used as input in calculation "C", the uncertainty band is also supplied
5	Identification of the input parameters, identification of the relevant input parameters and setup of the related PDF, for the calculation "C"	Execution of the analysis	Execution of the analysis included the evaluation of the output results and the related uncertainty bands. The uncertainty bands are calculated adopting one of the uncertainty methodologies currently available. The PDF of the input parameters for calculation "C" obtained by calculation "B" are obtained by the uncertainty band identified in the step 3
6	Output results of the calculation "B"	Selection of the output parameters of calculation "B" to be used as input in calculation "C"	For the output parameters of calculation "B" to be used as input in calculation "C", the uncertainty band is also supplied

The calculated uncertainty for each single calculation is transferred from one calculation ("A") to another calculation ("B) deriving PDF of output parameters of "A" used as input in "B" by the uncertainty bands calculated in "A". In Figure 7, the red arrows represent the transferring paths of uncertainty from one calculation to another calculation. The elements of the uncertainty transferred between codes are showed in
Figure 8. In addition to the uncertainty of the calculation output the uncertainty due to the interface between codes are also included:

- Uncertainty due to spatial discrepancy. It is due to the different spatial representation of the same zone in different input of different codes
- Uncertainty related to time discrepancy. It is due to different time resolution in different calculations
- Uncertainty related to data format discrepancy. It is due to the not adequate numerical accuracy of input parameters obtained from output parameters of another calculation. Or the uncertainty can be originated by the necessity to perform some treatments or operations on the data transferred from one code to another code

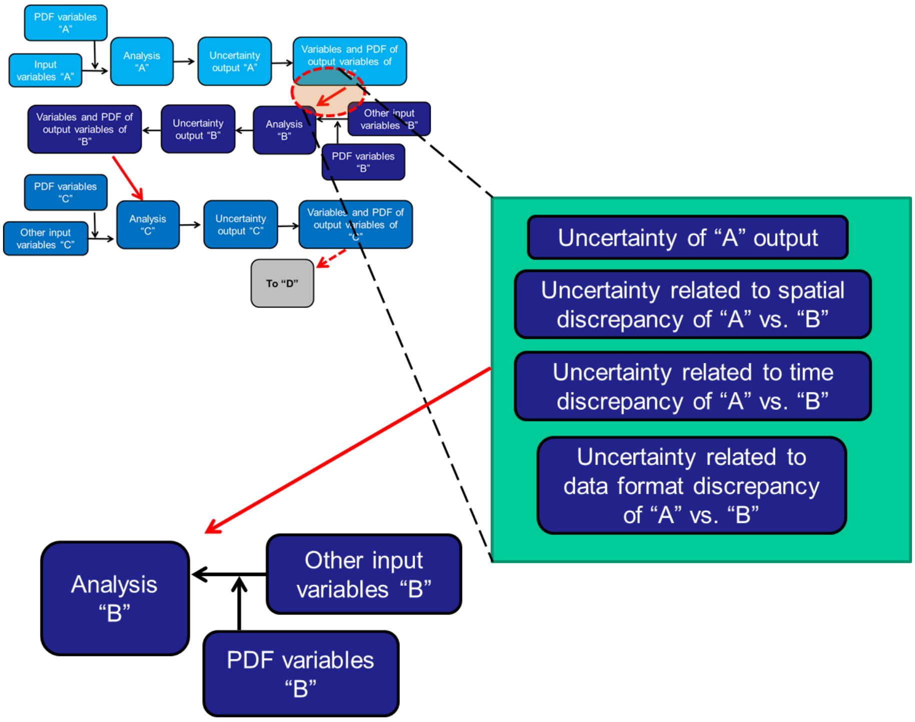

Figure 8 – Elements of the uncertainty transferred from one calculation (“A”) to the other calculation (“B”)

It is important to evidence that the application of BE approach and the valuation of the uncertainty requires the execution of preliminary steps related to the validation of the main aspect of the calculation (see Chapter 3). Any application of BE and uncertainty evaluation without those preventive steps leads to (in the best case) very large uncertainty having no practical meaning.

7. Final conclusions

Uncertainty is a complex and complicated process affecting the code predictions capabilities. However, the evaluation of uncertainty is integral part of the BE approach, and it is implicitly connected with the validation of the BE code.
Uncertainty is generated by the unavoidable approximations in the data used to setup the code phenomenological model and in the implementation of these models in the code itself.
Part of the uncertainty is also generated by the scaling issue related to the application of code models developed and validated using data obtained by scaled facility, to full scale NPP. This specific aspect can be addressed considering the non-dimensional analysis of the facility and NPP to derive the non-dimensional parameters useful in the identification of the distortions in the facility more affecting the NPP analysis.
Different approaches have been developed and currently used for evaluation of the uncertainty based on input uncertainty propagation and accuracy extrapolation. Both the approaches have advantages and weak aspects that should be taken into account (e.g., considering the level of knowledge of the considered phenomena, the availability of relevant experiments and data) that could suggest the preference of one approach instead of the other one.
The complexity of the analysis of an accident in a NPP require a multiphysic approach. Different specific codes are used in a coupled way to obtain a global best estimate evaluation of the NPP. This poses the issue of the evaluation of the uncertainty for such kind of calculations and the development of suitable methodologies.
In the framework of the project the potential uncertainties affecting the prediction of the plant behavior during selected accidents are investigated. The selected accidents are constituted by LOCA and SGTR. Both the accidents events are considered in the evolution as DBA and as DEC-A.

8. References

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