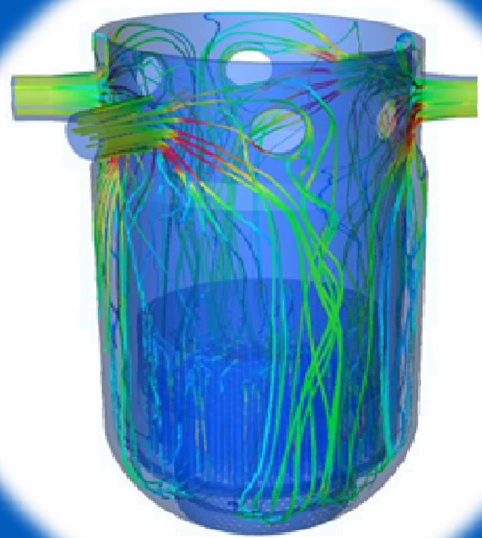
Uncertainty Quantification in CFD
EDF's challenges
EDF's first approach to UQ



ERCOFTAC SIG 45 meeting.

Manchester. November 12th 2012

Use of CFD at EDF - SEPTEN

- EDF R&D has been developing CFD codes for about 30 years.
  - *Code_Saturne* is EDF's most recent code for single-phase flows.

- The use of CFD in nuclear engineering studies (at EDF-SEPTEN) is more recent.
  - CFD calculations have been used for nuclear safety assessment issues for 5-6 years only.
  - RANS models used for engineering studies; LES is not used (yet) at EDF outside R&D.

- In a safety assessment study, CFD is usually just one part of a whole.
  - Usually, a global Thermal-Hydraulic study comes first.
  - A CFD study uses the results of the T/H study as inputs.
  - A third step (neutronics, mechanics…) may follow, based on the CFD calculation result.

- Examples :
  - Pressurized Thermal Shock (PTS) → CFD used to calculate conditions at the wall,
  - Boron Dilution Transient (BDT) → CFD used to calculate the mixing of a volume of boron-depleted water,
  - Other examples include spent fuel desactivation pool (racks) cooling, hydrogen distribution in the reactor building during a severe accident, etc.

Use of CFD at EDF – SEPTEN
Pressurized Thermal Shock

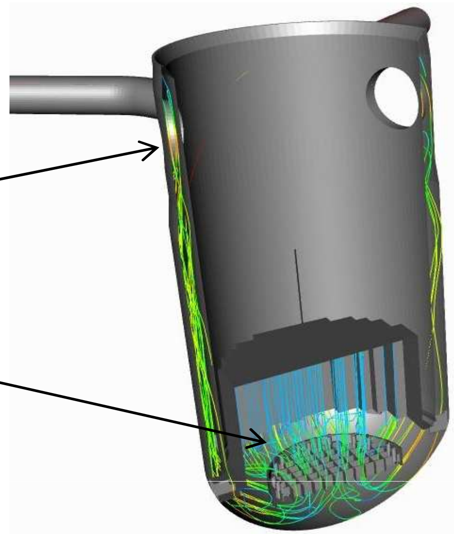
- Accident scenario → (cold) safety injection water is sent to the Reactor Pressure Vessel.
- Risk that must be avoided: PTS on the Vessel → rupture.

- CFD calculation → water T° and heat exchange coeff at the wall → mechanical code calculation.
- HYBISCUS mock-up to validate the CFD code (1/2 scale, 1/2 pressure vessel represented).

- Safety Authority request: to quantify the uncertainty in the thermal-hydraulics codes, or, if impossible, to prove that the results are conservative.

Use of CFD at EDF – SEPTEN
Boron Dilution Transient

- A volume of boron depleted water has accumulated in the primary loops.
- It is sent to the Reactor Pressure Vessel (pump startup, or restart of natural circulation).
- Risk of core re-criticality when the volume of boron-depleted water reaches the core.



- CFD is used to calculate how the volume of boron depleted water mixes with more borated water, before it reaches the core.
- Experiments to validate the CFD codes for this transient (1/5 scale).

- <u>Safety Authority request:</u> to prove the CFD study results are penalizing, considering the initial and boundary conditions, and the CFD model uncertainties in relation with the validation.

The challenge for EDF
(CFD UQ challenge, industrial point of view)

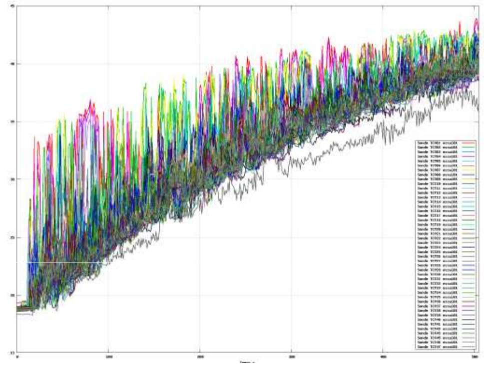
- We must be able to quantify the uncertainty associated with a CFD calculation result, in order to provide a “conservative” value (such as a temperature at the wall, a boron concentration at the entrance of the reactor core…) to be used in the safety assessment.

- A purely “propagation” approach of UQ might be useful, but it cannot be sufficient because it does not necessarily include a comparison with an “outside” (experimental) reality.
  - A “conservative” value must be more penalizing than the “real” value”, or more penalizing than xx% of possible “real” values with yy% confidence.

- Since the CFD analysis is only one step in the global safety assessment, EDF also has to find a way to quantify the uncertainty of the “global” study.
  - We put the emphasis on CFD uncertainty first.
  - Uncertainty propagation from one step to the next will have to be considered.

The challenge for EDF– A difficulty

- The transients we study are often complex, and involve the interaction of different physical phenomena.
- As a consequence, the variables of interest we calculate with a CFD code often have a chaotic behavior:
  - PTS: temperature and heat exchange coefficient at the wall.
  - BDT: Min boron concentration at core entrance.
- <u>This chaotic behavior can be observed in experiments too</u>.



- With such complex physics involved, we do not always have a clear notion of a “converged solution”, at least for local values.
  - The variable of interest in a safety study is usually a min or max value (for example, the min boron concentration at core entrance), so it is a local and instantaneous quantity → highly subject to chaos !
- How can we provide a “penalizing value” in such cases ?

EDF's first approach

- Approach based on:
  - An evaluation of the error of the code at mock-up scale; it is assumed the code error at reactor scale can be assimilated to the code error at mock-up scale.
  - A propagation of the uncertainty on the “true” reactor conditions.

- For a given (scalar) output S of a CFD calculation, the method allows us to determine a $S_{5/95}$ value, that is more penalizing than 95% of true possible values, with 95% confidence.

EDF's first approach

$$S(e)\big|_{CR} = \left[S(e) - S_{CFD}(e)\right]_{CR} + \left[S_{CFD}(e) - S_{CFD}(E)\right]_{CR} + S_{CFD}(E)_{CR}$$

True value

Code error for true conditions

Error propagated by the code (imperfect knowledge of true conditions)

Term B

(Reactor scale)

Hypothesis: code error is « scale independant ».

$$\left[S(e) - S_{CFD}(e)\right]_{CR} = \left[S(f_k) - S_{CFD}(f_k)\right]_{testk}$$

$$\left[S(f_k) - S_{CFD}(F_k)\right]_{testk} + \left[S_{CFD}(F_k) - S_{CFD}(f_k)\right]_{testk}$$

$$\left[m_k - M_k\right] + \left[M_k - C_k\right] + \left[S_{CFD}(F_k) - S_{CFD}(f_k)\right]$$

Term A_k

(Mock-up scale)

Terms	Significance
e	True (unknown) reactor conditions.
E	Our best estimate value of « e ».
f	True (unknown) conditions at mock up scale.
F	Our best estimate value of « f ».

EDF

EDF's first approach

Term A_k

Term B

$$S(e)\big|_{CR} = [m_k - M_k] + [M_k - C_k] + [S_{CFD}(F_k) - S_{CFD}(f_k)] + \left[S_{CFD}(e) - S_{CFD}(E)\right]_{CR} + S_{CFD}(E)_{CR}$$

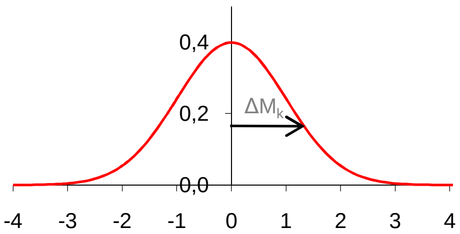
Measurement noise

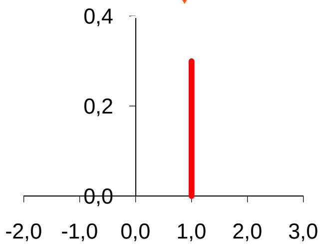
Difference btw measurement and calculation

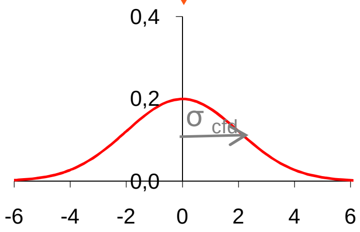
Propagated uncertainty, lack of knowledge of true mock up scale conditions

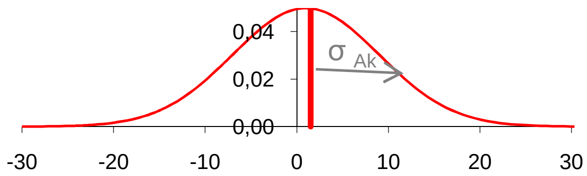
Propagated uncertainty, lack of knowledge of true reactor scale conditions

Distribution :

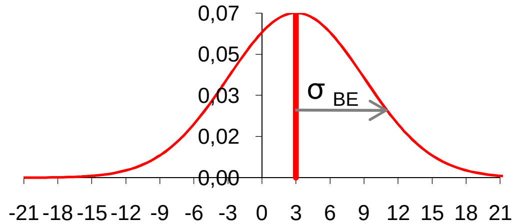




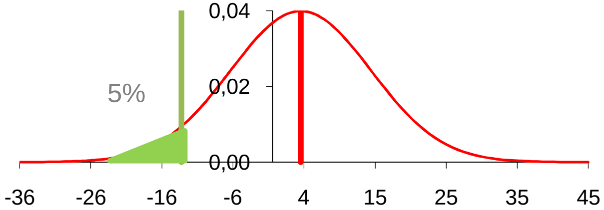




+



And finally, for test « k »



EDF's first approach

- A "95%" value of scalar Cb is thus obtained for each test "k" available.
- A 95/95 value is obtained using the Owen number for a total of K tests :

$$S_{5/95} = Avg(S_5(k)) \pm Owen(5,95,K).\sigma(S_5(k))$$

- This method is closely related to the code validation (use of mock-up scale results).
- Method based on experimental results: even if the exp. results are imprecise, they are used as a reference.

- Weaknesses :
  - The code error "scale hypothesis".
  - Gaussian distributions assumed.
  - Method applies to one scalar output only.

Workshop proposal

- In 2010, EDF sent a questionnaire to a number of experts on the subject of UQ in CFD.
  - Workshop was first mentioned, as a possible continuation.

- ERCOFTAC SIG45 started in 2012:
  - ERCOFTAC is a good framework for organizing this workshop.

- Proposed date : **June 17-18th, 2013.**
- Location : **Lyon, France.**

- A web site will soon be set up for inscription and abstract submission.
  - Need abstract reviewers !

Workshop proposal

- Objectives:
  - Discuss and clarify the terminology, the different sources of uncertainty (including “model” uncertainty).
  - Propose a benchmark of UQ methods based on a simple case in the context of VVUQ.
  - Identify and discuss the difficulties specific to CFD in UQ.
- Proposed planning:
  - 2 or 3 keynote lectures:
    - From V&V to UQ.
    - State of the art on UQ.
    - ?
  - Participant presentations; each presentation should include:
    - Terminology used.
    - Description of a UQ approach.
    - Applications (if available).
  - Round tables on:
    - Terminology.
    - UQ approaches.
    - Applications.