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Analyses in Regulatory Practice

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Trends in Computational Fluid Dynamics (CFD)

Multi-scale approach:

- Gain insights from smaller scales for better models in larger scales
- Depends essentially on reliable CFD analyses

Direct Numerical Simulation

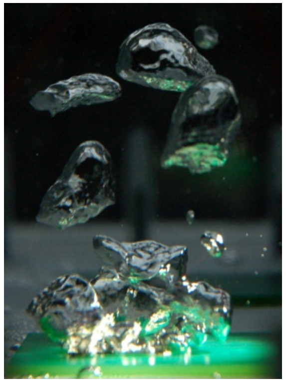
Large Eddy Simulations (LES)

(U)RANS Simulations

System codes (ATHLET, RELAP)

more simplifications

Micro scales



Macro scales

System scales

Nuclear supervising process

- Numerical software is applied for numerous issues:
  - Neutron kinetics (CASMO/SIMULATE)
  - System codes (ATHLET, RELAP)
  - Structural mechanics (ANSYS)
  - Pressure Surge analyses (DYVRO)

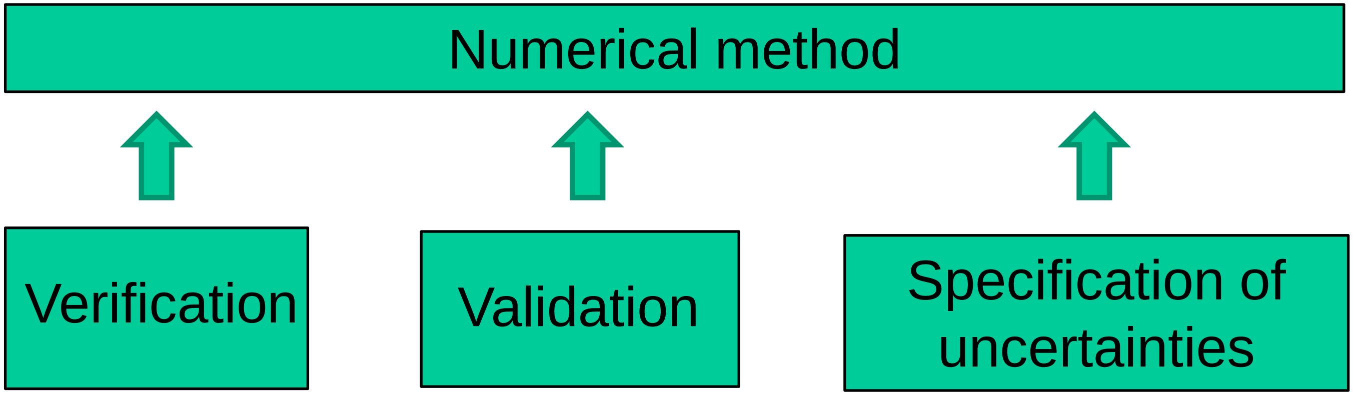
Qualified, validated and established in practice for many years

- Technical rules and standards specify requirements for numerical analyses

What is the status of CFD analyses?

Requirements for the application of numerical methods

Fundament of a reliable application of numerical methods:


Numerical method

Verification

Validation

Specification of uncertainties

Requirements can be found, e.g. in

- Guidelines of the Reactor Safety Commission (RSK),
- RSK recommendations,
- Guidelines of the Nuclear Safety Standards Commission (KTA),
- Safety Requirements for Nuclear Power Plants
- international: IAEA Safety Reports, NRC Guidelines

Requirements for the application of numerical methods

RSK guidelines for Pressurized Water Reactors, chapter 22.1.3 „Assumptions for Emergency Core Cooling Calculations“

- Experimentally verified analyses
- Boundary conditions are prescribed
  - Discharge flow rates, heat transfer, pump behaviour, power distribution in the core, …
- If no experimentally verified data is available

⇨ Guidelines dictate conservative boundary conditions/models

Requirements for the application of numerical methods

RSK recommendation from 20th/21th July 2005
„Anforderungen an die Nachweisführung bei Kühlmittelverluststörfall-Analysen“

- Distinction between best-estimate and simplified analyses
- „Best-estimate“ approach:
  - As physically correct models as possible
  - Validation needed to prove the suitability of the computational method
  - Consideration of scaling effects
  - Uncertainty analysis
- Simplified approach:
  - Requirement: conservative values for sensitive influence parameters
  - Uncertainties have to be covered
  - Uncertainty analysis may be omitted

Requirements for the application of numerical methods

KTA rule 3201.2 Annex B „Rechnerische Methoden“

- Discretisation errors:
    - Spatial and temporal discretisation
    - Rounding errors
    - Iteration errors
- Specification of number and locations of grid points
- Specification of load and time increments
- Documentation of the code
- Code reliability
    - Modular code structure,
    - Standardized programming language
    - Centralized support
    - Large user community and frequent application

Requirements for the application of numerical methods

KTA rule 3201.2 Anhang B „Rechnerische Methoden“

- Assessment of the results
  - Physical control (plausibility of the results)
  - Numerical control:
    - Analysis of the influence of iteration and discretization errors
    - Mesh refinements
    - Analysis of the solution vector
  - Comparison with results from other sources
    - Other computations
    - Other methods
    - Experiments

Requirements for the application of numerical methods

Safety Requirements for Nuclear Power Plant, Annex B, “Requirements for Safety Demonstration and Documentation”

- Technical rule passed by the authorities on 22nd November 2012
- No completely new requirements, but more details
- For instance (not complete):
  - Comparison with experiments is not sufficient for validation
    ➡ Check if the application range is covered by experimental data
  - Detailed requirements regarding the quality of data and documentation
  - Uncertainty analyses:
    - 95 % confidence level
    - Fulfillment of the acceptance criterion with a probability of 95 %
  - Definition of cases in which an uncertainty analysis is unnecessary
  - Detailed boundary and initial conditions for specific safety analyses and the respective safety level, e.g. LOCA

CFD analyses in regulatory practice

- Appropriate for topics which require an exact knowledge of local flow phenomena, e.g.:
  - Boron dilution transients after reflux condenser mode
  - Protection against brittle failure (thermal shocks)
- Still large need for validation and development of CFD models
  - Extension of the experimental data base for 3D analyses
  - Particularly for multi-phase flows
- „Blind“ calculations are difficult
  - In general CFD analyses are used to recalculate experiments
- Fulfillment of the requirements for reliable CFD simulations is labour-consuming and challenging

CFD analyses in regulatory practice

Status quo:

In general experiments or simplifying conservative approaches are used in the daily practice of the supervising process rather than CFD analyses.

CFD analyses are usually applied

- to support the proof of compliance,
- to clearify open questions or
- to lead to a better understanding of the underlying physics.

CFD analyses in regulatory practice

- Worldwide trend to use best-estimate analyses

  ⇨ Establishment of CFD analyses will go on

- Currently many research projects in order to satisfy the need for appropriate models and data
- Confidence in CFD analyses will increase due to continuous work on validation and best-practice guidelines
- Advantages of CFD analyses:
  - More realistic modelling
  - High spatial and temporal resolution
  - Deeper understanding of physics

Example 1:
Boron dilution transients after reflux condenser mode

Background

- SB-LOCA in a PWR: boron is necessary to keep the core subcritical
- Condensate from the pump seals may reach the core and reduce the boron concentration in the core after reflux condenser mode

Reduction of the boron concentration may not lead to recriticality!

Goal of the analyses:

Determination of the minimum boron concentration which may reach the core entry after reflux condenser mode

Example 1:
Boron dilution transients after reflux condenser mode

Experiments at different test facilities:

- Primärkreislauf-Versuchsanlage (PKL)
  - Scaled 1:145
  - Original heights
  - Exerimental objectives:
    - Size of the condensate slugs
    - Mass flows in the main coolant lines
    - Mixing phenomenons during emergency core cooling
- Rossendorf Coolant Mixing Test Facility (ROCOM)
  - Scaled 1:5
  - Mesh sensors in the coolant line, in the downcomer and at the core entry
  - Uses boundary and initial conditions based on PKL experiments

Example 1:
Boron dilution transients after reflux condenser mode

Experiment PKL III E2.3

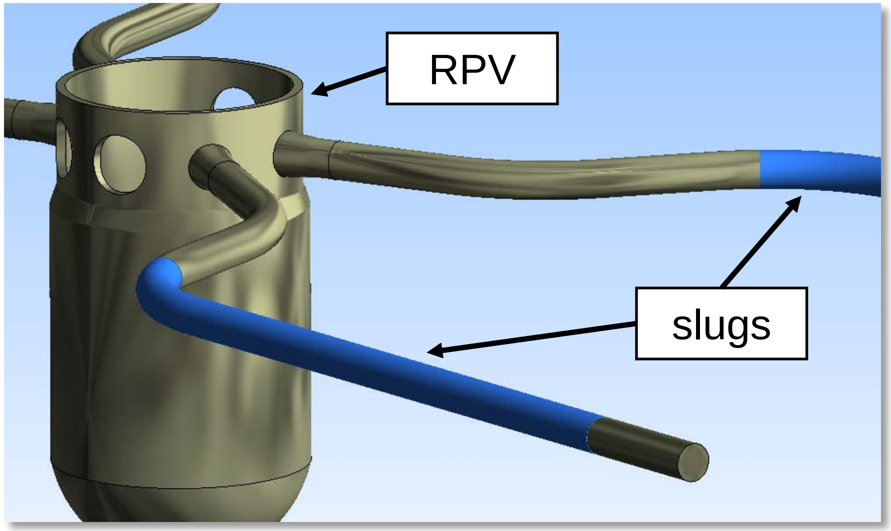
Scenario: small break in a hot leg and emergency coolant injection preferably in the hot legs

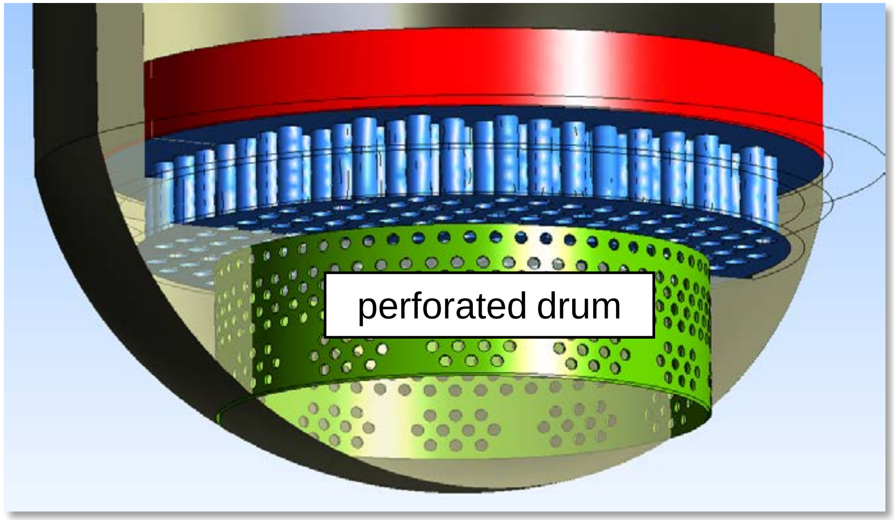
- So-called „LOBI“ scenario:
  - Emergency coolant injection in two loops
  - Redirection of the coolant towards the steam generators
    - ⇨ Natural convection breaks down only in the loops without coolant injection
  - incl. accumulator tanks
- Low pressure coolant injection has been ommited

Example 1:
Boron dilution transients after reflux condenser mode

ROCOM model:

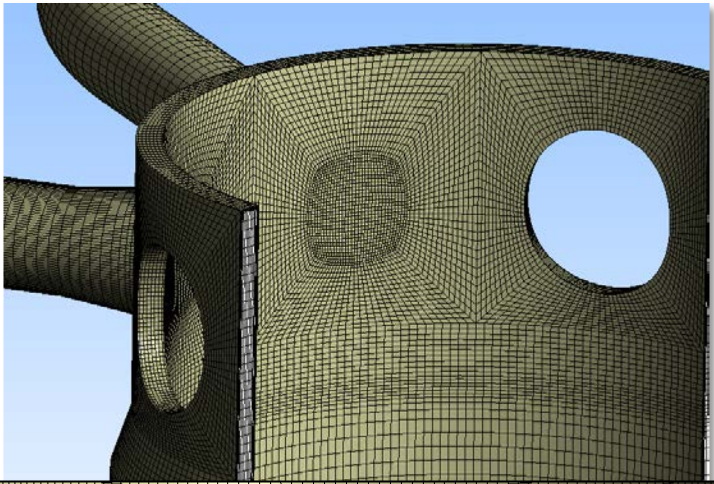
- RPV and four loops
- Detailed model of the perforated drum in the lower plenum
- For simplification the core entry consists of 193 tubes – one for each fuel assembly
- Condensate slugs (blue) in two loops (distance from RPV: 1.8 m)

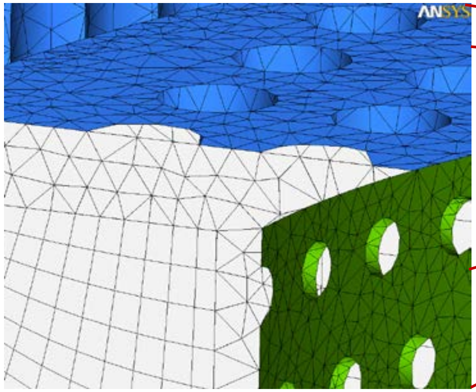


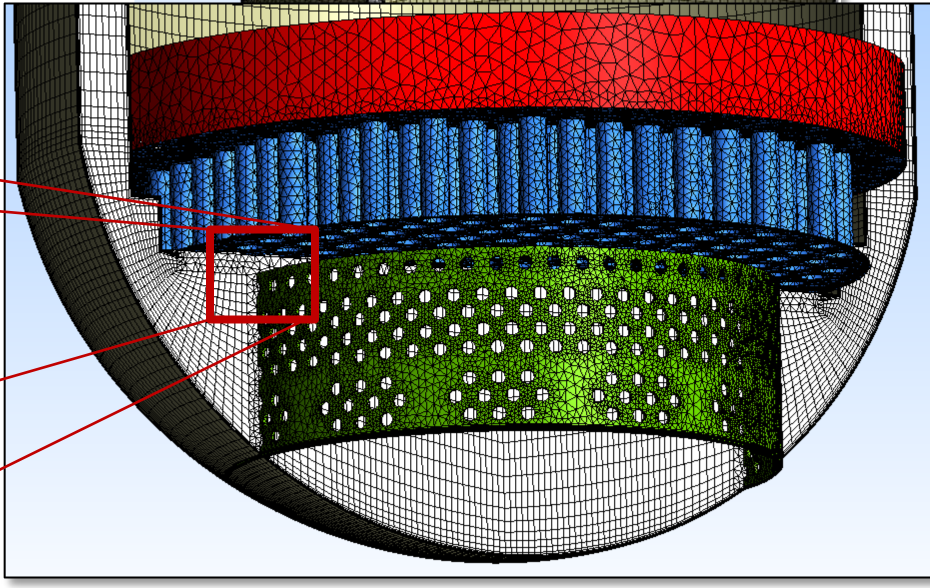


Example 1:
Boron dilution transients after reflux condenser mode

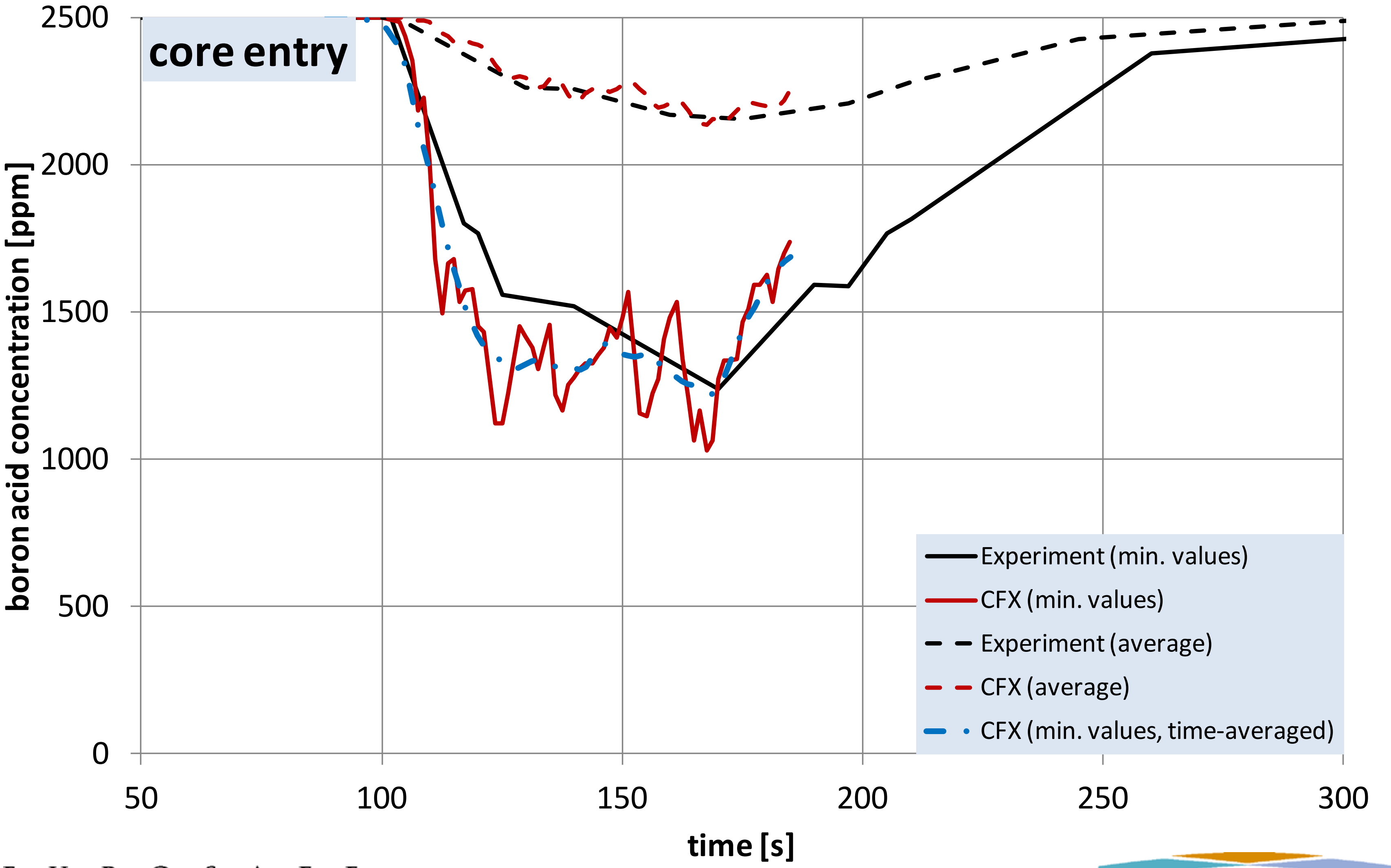
- Hybrid mesh:
  - Cold legs, downcomer and lower plenum: structured mesh with hexaeder elements
  - Perforated drum and core entry: unstructured mesh with tetrahedras
- 3.5 Million elements







Example 1:
Boron dilution transients after reflux condenser mode

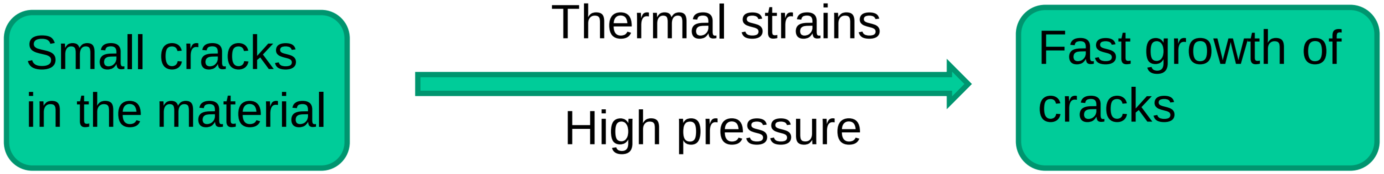


Example 2:
Protection of the RPV against brittle failure

Background

The RPV has to withstand thermal loads and brittle failure has to be avoided!

Brittle failure:



Small cracks in the material

Thermal strains

High pressure

Fast growth of cracks

Causes:

- Fast temperature changes
- Large, local temperature differences
- Brittleness due to neutron fluence

Example 2:
Protection of the RPV against brittle failure

Example: Loss of Coolant Accident

Thermal shock:

- Guillotine break of a main coolant line
  - Fastest cooling-down in the RPV
  - High injection rates → very good mixing in the RPV
  - ATHLET

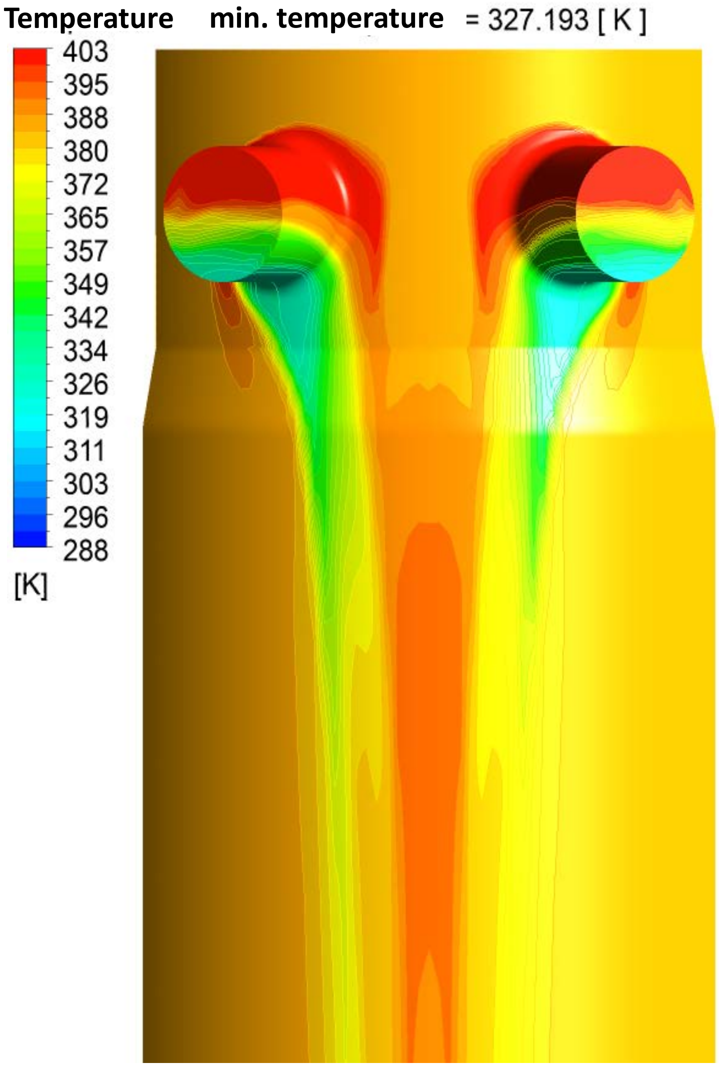
Local temperature differences:

- Small and middle size breaks in the primary ciruit
  - Cold water streaks in the downcomer
  - Low temperatures below the inlet nozzles
  - High temperatures outside the cold water streaks
  - 1D analyses not appropriate → CFD analyses

Example 2:
Protection of the RPV against brittle failure

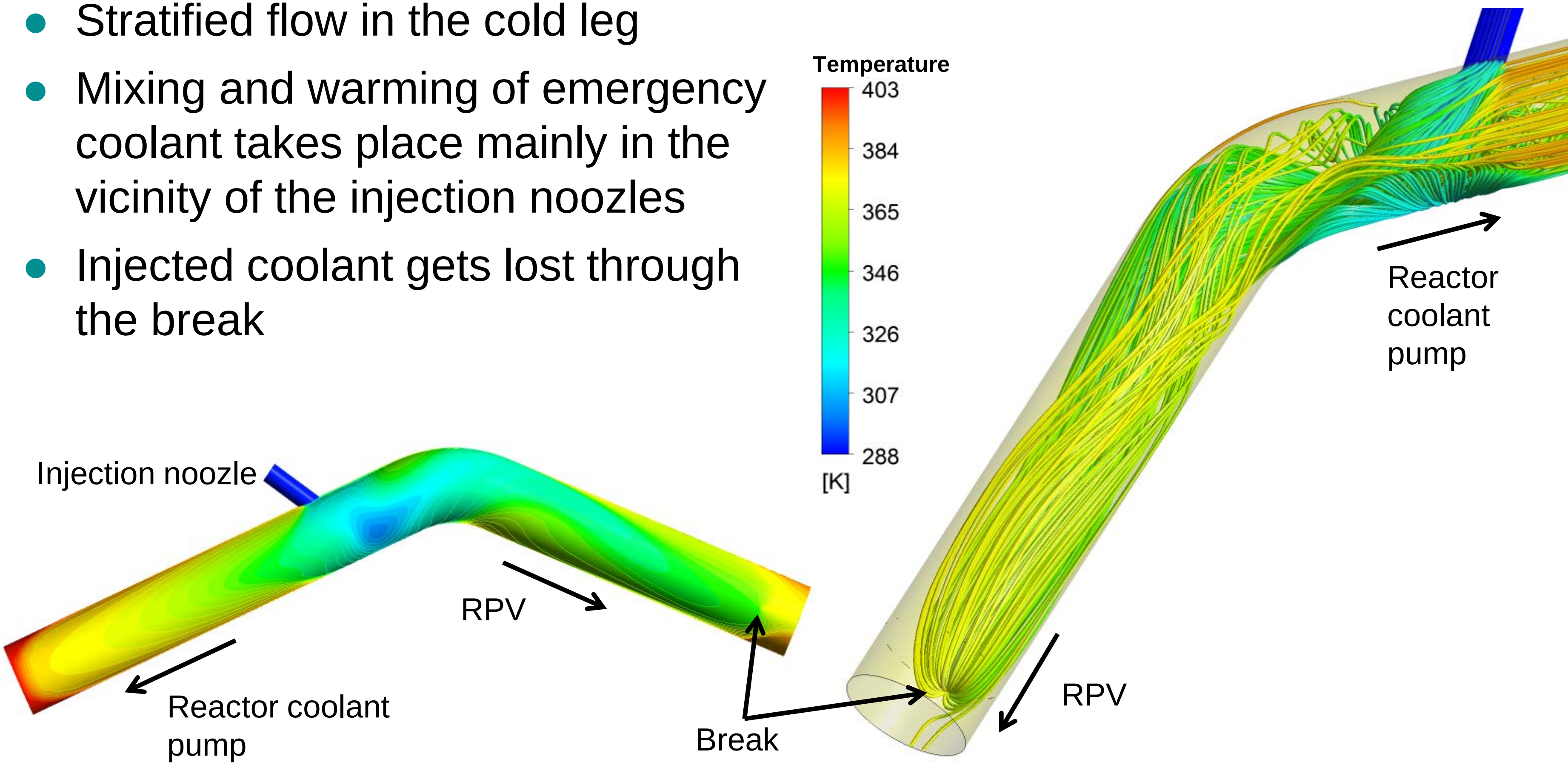
Cold water streaks in the downcomer:

- SB-LOCA
- Emergency coolant injection in two adjacent loops
- Continuous natural convection
- Lowest temperatures in the knees of the inlet nozzles



Example 2:
Protection of the RPV against brittle failure

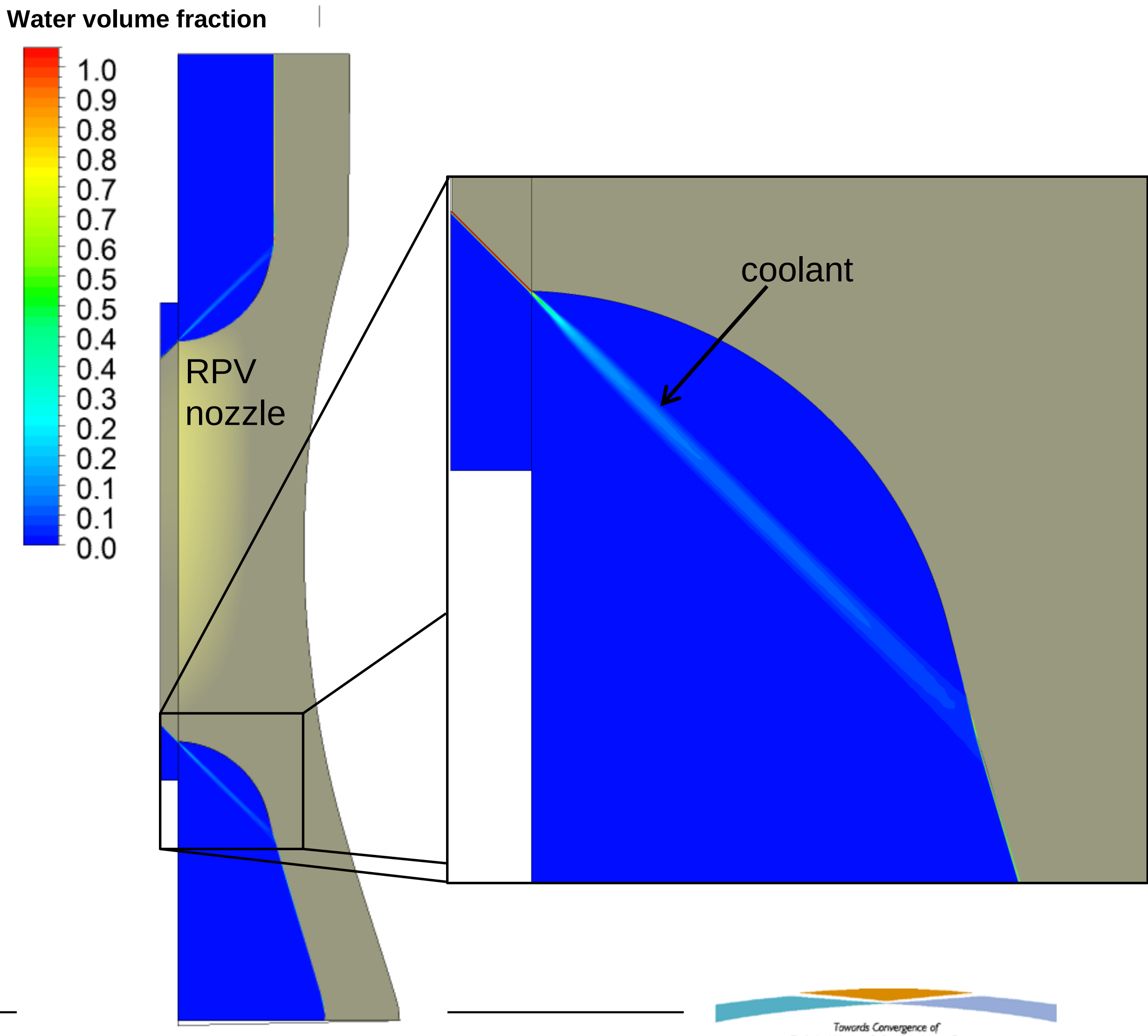
- Stratified flow in the cold leg
- Mixing and warming of emergency coolant takes place mainly in the vicinity of the injection noozles
- Injected coolant gets lost through the break



Example 2:
Protection of the RPV against brittle failure

Cooling at the outside:

- Annular shaped gap between guard pipes and nozzle
- Wetting of the RPV around the nozzle
- Water strap at the outer wall below the nozzle



Summary

- The nuclear technical rules and standards specify high requirements for
  - the application of numerical methods,
  - the validation,
  - the treatment of errors and
  - the determination of uncertainties.
- Today CFD analyses play only a secondary role in the regulatory practice
- Big progress is made regarding knowledge, experimental data, computing power and the determination of uncertainties

  ➡ The role of CFD analyses in nuclear safety issues will propably grow
- Typical application examples for CFD analyses:
  - Boron dilution transients after reflux condenser mode
  - Protection of the RPV against brittle failure