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# A realistic approach for the assessment of the consequences of heterogeneous boron dilution events in pressurized water reactors

**S. Kliem, A. Grahn, Y. Bilodid, Th. Höhne**

*Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany*

*Tel.: +49 351 260 2318*
*S.Kliem@hzdr.de*

**Abstract**

In order to compensate the excess reactivity over the fuel cycle in pressurized water reactors, boric acid is added to the reactor coolant. During certain accident conditions, the formation and the subsequent transportation towards the reactor core of a slug of coolant with reduced boron concentration can lead to a positive reactivity insertion. In this paper, a new approach dealing with such heterogeneous boron dilution scenarios is presented. This approach is based on the use of computational fluid dynamics methods for the whole reactor pressure vessel with direct coupling to a 3D neutron-kinetic model of the reactor core. The application of this approach is demonstrated on a main coolant pump start scenario for hot-shutdown conditions using the coupled ANSYS CFX/DYN3D code. The calculation results demonstrate the enormous influence of the coolant mixing on the reactivity behavior of the reactor core.

**Keywords:** Boron dilution, DYN3D, ANSYS CFX, neutron kinetics/thermal hydraulics coupling, PWR

# 1. Introduction

In order to compensate the excess reactivity over the fuel cycle in pressurized water reactors (PWR), boric acid is added to the reactor coolant. Forced coolant circulation during normal operation ensures that this boric acid is homogeneously distributed in the primary circuit. In this way, the boron concentration is practically uniform.

Hyvärinen described in his paper the possibility of the formation of slugs with reduced boron concentration in different parts of the primary circuit of PWR (Hyvärinen, 1993). The underlying scenarios can be divided into external dilution (injection of coolant with reduced boron concentration from outside) and inherent dilution (separation of coolant into highly and low concentrated parts). Subsequently, corresponding scenarios can lead to a homogeneous or a heterogeneous change of the boron concentration within the primary circuit. Depending on the amount and time duration of boron concentration reduction the criticality of the reactor can be affected. This requires a safety assessment of the consequences of boron dilution events. A discussion of the possible scenarios with a focus on the inherent dilution can be found in (Pointner and Wohlstein, 2003).

Experimental facilities have been built for the investigation of the creation and formation of slugs with reduced boron concentration (e.g. PKL test facility (Umminger et al., 2001; Hertlein et al., 2003) as well as the transport and mixing of such slugs towards the reactor core (BORA-BORA (Alvarez, D. et al, 1995), UMCP 2x4 Loop Test Facility (Woods et al., 2000), Vattenfall (Kliem et al., 2007), VVER-1000 Gidropress facility (Bucalossi et al., 2011) and Rossendorf Coolant Mixing Model (ROCOM) (Kliem et al., 2008)).

The transport and the mixing of such slugs with ambient usually higher borated fluid till the reactor core lead on the one hand to a considerable reduction of the deboration and on the other hand to a very heterogeneous distribution of the boron concentration at the core inlet. This coolant mixing has a considerable influence on power behavior even if a system code with point kinetics is being applied. Such findings were deepened during benchmark calculations for coupled 3D neutron kinetic/thermal hydraulics code systems starting with the TMI-1 benchmark (Ivanov et al., 2001). One of the outcomes of the benchmark activities was the necessity to connect or to implement adequate coolant mixing models at the interface between the system code and the core model for a best-estimate description of transients and accidents where coolant mixing is involved (boron dilution and steam line breaks).

The data obtained at the coolant mixing facilities has been used also for the validation of Computational Fluid Dynamics (CFD) codes in order to enable their use in safety analyses.

The paper is organized as follows: first the current approaches for the treatment of coolant mixing are described. In the next section the basic ideas of the new proposed approach are outlined. After the description of the involved codes and their coupling, the new approach is applied to an inherent boron dilution scenario.

# 2. New approach for the analysis of heterogeneous boron dilution events

## 2.1 Overview on approaches used so far

The analysis of boron dilution events is part of the design and safety assessment of PWRs. In the oversight practice, e.g. in Germany, this analysis is treated by defining a boron concentration target value. The design process for reactor core configurations should ensure that the reactor can become critical only, when the boron concentration homogeneously in the whole reactor core has been lowered to this value (RSK, 2014)[1]. In such a way, coupled neutron kinetic /thermal hydraulic calculations of specific postulated boron dilution events are not needed. Nevertheless, several approaches are discussed in the literature to treat boron dilution events by such coupled calculations. For the core response, typically core simulators consisting of a two- (or multi-) group nodal diffusion code and a thermal hydraulic core model equipped with a boron transport option are used. The same core simulators are being used for the assessment of reactivity-initiated-accidents like control rod ejection or group withdrawal. The main difference to those calculations is the necessity to provide adequate time-dependent boron concentration distributions at the core inlet. In all following examples, models have been developed which are dedicated to one specific reactor type and cannot be applied to other ones.

So, Ivanov et al. (1999) used an analytical model for the mixing of borated and unborated coolant from different loops in the downcomer and lower plenum of a Russian VVER-440 reactor (Ackermann and Draeger, 1987). Diamond et al. (2004) used also an analytical mixing model which was validated on experiments at the UMCP 2x4 Loop Test Facility (diMarzo, 2001) and conducted a boron dilution analysis of a Babcock&Wilcox PWR. Kliem et al. (2004) developed a semi-analytical mixing model which should be supplemented with transfer functions for specific reactors and scenarios and applied it to boron dilution scenarios during the start-up of the first main coolant pump or during natural circulation conditions (Kliem and Rohde, 2007). The corresponding transfer functions were derived from mixing experiments at the above mentioned ROCOM test facility. Velkov et al. (2009) divided the core inlet region into three radial rings and provided different time dependent boron concentration to those

[1] This document contains also recommendations on thermal hydraulic conditions and the poisoning state of the reactor.

rings. A similar approach was applied by Tietsch and Tischer (1999) to the boron dilution analysis for a Babcock&Wilcox PWR. The boron concentration in the different rings was derived from mixing experiments at the above mentioned UMCP 2x4 Loop Test Facility. The cases investigated by Kuopanportti (2015) are driven by the introduction of a slug of pure water of limited sized into the reactor core. No mixing with ambient higher borated coolant takes places so that the reactor becomes prompt-critical during the analysis. Zerkak and Ferroukhi (2011) defined mixing coefficients relating the values at the cold leg outlet of the loops with the core inlet positions considering in this way a predefined amount of coolant mixing and applied this approach to a main steam line break analysis in a Swiss PWR. In a similar way, Gandrille et al. (2000) applied the MANTA code to a main steam line break analysis of a French CPY reactor.

## 2.2 Description of the new approach

Summarizing the needs of the analysis of the consequences of boron dilution events, the following three[2] problems have to be solved:

- 3D coolant mixing for deborated slugs at one or more cold leg outlets inside the reactor pressure vessel till the core inlet.
- Transport of the deboration front through and mixing inside the reactor core
- Adequate treatment of the neutronic behavior and feedback

As already outlined, the approaches available in the literature combine the application of a neutron kinetic/thermal hydraulic core model with a coolant mixing assumption for providing the boron concentration at the core inlet.

A CFD code is naturally the right tool to treat the first two problems in a realistic manner. Since several years, modern CFD codes in combination with sufficient computer power are more and more applied to hydrodynamic calculations in full light water reactor pressure vessel geometry. A comprehensive and impressive overview with about 30 different applications can be found in (Sheng and Seidl, 2015).

On the other hand, some years ago the coupling of 3D neutron kinetics with a CFD model of the whole reactor core was accomplished (Kliem et al., 2011) providing the correct neutron kinetic feedback during core transients.

The next logical step is the coupling of a model for the whole reactor pressure vessel with such a core model with 3D neutron kinetics. The first attempt was reported in (Grahn et al., 2017) using the TrioCFD code in coupling with the neutron kinetic code

[2] The formation of the deborated slugs and the corresponding transport in the loops is not included here.

DYN3D. This code system was applied to the calculation of a main steam line break event.

In the current paper this approach is accomplished using the CFD code ANSYS CFX in combination with the DYN3D code.

Blömeling and Schaffrath (2015) discuss the application of CFD codes in the regulatory practice. Single-phase applications of CFD codes reached a level of reliability which allow the use of these codes in the oversight procedure. Beside others, the coolant mixing within the reactor pressure vessel during boron dilution events is mentioned as one of the areas, where the results of CFD calculations are being used to support the supervising process.

# 3. Overview on the involved codes

## 3.1 CFD Code ANSYS CFX

### 3.1.1 Description of ANSYS CFX

ANSYS CFX (ANSYS, 2018) is a general-purpose fluid dynamics simulation software which has been applied across a wide range of CFD and multi-physics applications. Phenomena that can be simulated and that are relevant for conventional and nuclear power generation applications include turbulent multiphase flow, heat and mass transfer, and flow in rotating geometries such as pumps, fans, compressors and turbines.

ANSYS CFX is an element-based finite-volume method with second-order discretization schemes in space and time. It uses a coupled algebraic multigrid algorithm in order to speed up convergence. The discretization schemes and the multigrid solver are parallelized.

Although being a commercial software, ANSYS CFX provides a command language and a programming interface for the FORTRAN language that allow the user to extend its capabilities or to implement own models and couplings with other simulation software. This is one of the reasons, ANSYS CFX was chosen as the reference CFD code of the German CFD Network in Nuclear Reactor Safety. One of the goals of the co-operation inside this network is the development of CFD software for the simulation of multi-dimensional flows in reactor cooling systems. This includes the coupling of the CFD code ANSYS CFX with the 3D neutron kinetic core model of DYN3D, in order to extend the description of the coolant flow and of the convective heat transport to three dimensions.

### 3.1.2 Validation for one-phase coolant mixing

In the recent years, a comprehensive validation program was conducted in order to validate the ANSYS CFX code for one-phase coolant mixing in the reactor pressure vessel using experimental data from different test facilities. Beside others, the pro-

gram covered typical boron dilution conditions ranging from the restart of natural circulation till the switch-on of the first main coolant pump, both with and without the presence of density differences between deborated slug and ambient coolant. Tab. 1 provides a corresponding overview on the validation calculations.

Tab.1: Overview on the validation activities on one-phase coolant mixing for ANSYS CFX

| **Test facility** | **Scale** | **Reactor** | **Scenario** | **References** |
|---|---|---|---|---|
| ROCOM | 1:5 | German PWR KONVOI (1300 $MW_{el}$) | Start-up of the first main coolant pump/Steady-state operation | Rohde et al., 2007<br>Boumaza et al., 2014<br>Hoehne et al., 2018 |
| ROCOM | 1:5 | German PWR KONVOI (1300 $MW_{el}$) | Restart of natural circulation | Rohde et al., 2007<br>Kliem et al., 2010<br>Hoehne et al., 2018 |
| ROCOM | 1:5 | German PWR KONVOI (1300 $MW_{el}$) | Coolant mixing with presence of density differences | Hoehne et al., 2006<br>Hoehne et al., 2008<br>Hoehne et al., 2009<br>Bousbia Salah et al., 2018 |
| V-1000 | 1:5 | Russian PWR VVER-1000 | Start-up of the first main coolant pump | Kliem et al., 2007<br>Bucalossi et al., 2011 |
| V-1000 | 1:5 | Russian PWR VVER-1000 | Restart of natural circulation | Bykov et al., 2009<br>Bucalossi et al., 2011 |
| V-1000 | 1:5 | Russian PWR VVER-1000 | Coolant mixing with presence of density differences | Bykov et al., 2009<br>Bucalossi et al., 2011 |

| Test facility | Scale | Reactor | Scenario | References |
|---|---|---|---|---|
| UM 2×4 thermal-hydraulic loop facility | 1:5 | Babcock & Wilcox PWR | Coolant mixing with presence of density differences | Hoehne, 2002 |

The results of these validation calculations have been derived applying the Best Practice Guidelines for the use of CFD codes in reactor safety applications (latest release: Mahaffy et al., 2015).

Generally spoken, the ANSYS CFX code reproduces very well the main phenomena observed during the experiments. A detailed quantitative comparison reveals that the ANSYS CFX solutions underestimates somewhat the coolant mixing inside the pressure vessel in experiments without density differences. So, comparing the data in the core inlet plane of the facilities, the calculated boron concentration is slightly lower than the measured one in the mentioned experiments without density differences. The calculated values belong mostly to the $2\sigma$ confidence interval of the experimental data (e.g.: Rohde et al, 2007).

### 3.2 Reactor dynamics code DYN3D

DYN3D is a 3D nodal reactor dynamic code developed at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), mainly for transients, but also for steady-state and fuel cycle analyses of LWR cores with hexagonal or square fuel assemblies (Kliem et al., 2016; Rohde et al., 2016). DYN3D couples the neutronic solution obtained using a nodal polynomial expansion method with internal thermal hydraulic and fuel rod behavior models. For the analysis of transient and accident scenarios, where both 3D neutronics and thermal feedbacks from other plant components and safety systems play an important role, DYN3D has been coupled to system codes such as ATHLET (Austregesilo et al., 2016; Kozmenkov et al., 2015) and RELAP5 (RELAP5, 2001; Kozmenkov et al., 2007). Recent developments of the DYN3D code are connected with the introduction of a new solver for the neutronics (Bilodid et al., 2018), hybrid microscopic depletion and decay heat models (Bilodid et al., 2016; Bilodid et al., 2018a).

Since several years, DYN3D is part of the European simulation platform NURESIM (Chanaron et al., 2015; Kliem et al., 2017).

## 4. Coupling of ANSYS CFX and DYN3D

The thermal hydraulic part of DYN3D is based on a one-dimensional representation of the coolant flow in the fuel assemblies. However, various accident scenarios of

nuclear reactors may involve asymmetric flow conditions in the reactor core, in particular if the coolant flow is driven by natural convection, in the case of pump failure, loss-of-coolant accidents and pump restart. As a consequence, the coolant flow may be deflected from its mostly axial direction that would prevail under normal conditions to form large scale vortices and even reverse flow.

As DYN3D's built-in one-dimensional thermal hydraulics is not able to reproduce such three-dimensional flow structures, it is replaced in this study by the CFD code ANSYS CFX, which solves the differential equations of momentum, energy and convective boron transport in three dimensions. However, a detailed spatially resolved modeling of the whole reactor core down to the fuel pin level in the CFD code is not feasible for practical applications. For acceptable computation times, it is necessary to approximate the reactor core as a porous region.

The code coupling was presented in (Kliem et al., 2011). Its implementation was verified by comparing test case results with reference solutions of the DYN3D standalone version (Grahn et al., 2015). The test cases covered mini and full core geometries, control rod movement and partial overcooling transients.

In a similar way, DYN3D was coupled with the open-source CFD solver Trio_U (Grahn et al., 2017) and used for the simulation of a Main Steamline Break in a PWR. Trio_U assumes constant coolant properties (density, viscosity and thermal conductivity), which lead to discrepancies of temperature and velocity fields obtained from the coupled simulation as compared to the standalone DYN3D results. Therefore, the coupling with ANSYS CFX is preferred for simulating the boron dilution scenario presented here.

The porous body approach of modelling the reactor core affects the interface for exchange of simulation quantities between the CFD code and the core simulator DYN3D. The neutron kinetics solver in DYN3D requires distributions of coolant density, boron concentration and fuel temperature as input parameters for calculating the core reactivity and power distribution. They depend on the heat transfer in the coolant at the fuel pin surface, which cannot be resolved by the CFD code in the case of a porous body representation of the reactor core. The thermal hydraulic part of DYN3D already implements a number of well tested models that account for the heat conduction in the fuel and in the pin claddings, and for the different heat transfer regimes on the coolant side of the pin surface based on coolant flow velocity and temperature. Therefore, the interface for data exchange was chosen to be at the level of the volumetric heat release rate to the coolant and sent from DYN3D to ANSYS CFX. It plugs directly as the source term into the energy transport equation solved by the CFD code. In the opposite direction, ANSYS CFX provides coolant velocity, pressure, temperature and boron concentration fields to DYN3D. The remaining feedback parameter coolant density is calculated from pressure and temperature inside DYN3D using the IFC-67 formulation of water properties (Grigull and Schmidt, 1989).

DYN3D and ANSYS CFX operate on computational meshes that both represent the reactor core, but which largely differ in spatial resolution. As a consequence, the bi-directional data exchange between both codes involves interpolation of field quantities. Interpolation routines are implemented in User-Fortran and dynamically linked to the ANSYS CFX executable. Care is taken to ensure conservation during interpolation. Conservation is verified and corrected locally on the level of the DYN3D node volumes. Also, in a parallelized environment, the mapping of the partitioned, refined CFD mesh onto the nodal DYN3D mesh is carried out by the User-Fortran library.

In the coupling set-up, ANSYS CFX acts as the master, which is responsible for time stepping and iteration control, while DYN3D is implemented as a set of subroutines statically linked to the User-Fortran library.

A typical transient analysis requires a stationary solution of the neutron-kinetic and thermal-hydraulic equations serving as initial conditions. This stationary solution is obtained in a separate, coupled simulation run. In a stationary calculation, DYN3D is called by ANSYS CFX once per coefficient loop in order to update the heat source distribution based on the currently available distributions of the feedback parameters. In the transient calculation, calling DYN3D and the exchange of data are carried out at the end of every time step. The time step size is dynamically adjusted by ANSYS CFX to ensure convergence of the solution.

As outlined above, reactor transients such as boron dilution and overcooling have their origin in a section of the coolant circuit, which is located upstream of the core inlet plane. Therefore, the core domain was connected with the computational domain of a reactor pressure vessel. The CFD meshes of the core and the RPV are connected using a CFX Domain Interface in the problem set-up. The simulation of the coolant mixing covers the flow region from the inlets of the cold leg nozzle, over the downcomer, lower plenum, up to the core outlet plane (Fig. 1).

All previous studies that used the ANSYS CFX/DYN3D coupling considered only the reactor core and did not take into account the coolant mixing in the upstream parts of the reactor pressure vessel, that is, in the downcomer and in the lower plenum.

In this study, ANSYS CFX is used for the first time to establish the coupling of two flow domains (pressure vessel and reactor core) with the core simulator DYN3D.

# 5. Analysis of a boron dilution scenario

## 5.1 Input data description and boundary conditions

The analysis is conducted for a German KONVOI PWR with 193 fuel assemblies. For the calculations, a generic core-loading pattern for such a reactor containing one third MOX elements was used (Kliem et al., 2004). The burn-up state of this core cor-

responds to the beginning of an equilibrium fuel cycle. A wide-range macroscopic cross-section library generated using the lattice code HELIOS (Wemple, 2008) was connected to DYN3D. The reactor is assumed to be in a hot sub-critical state with all control rods inserted.

The computational domain, as shown in Fig. 1, comprises the pressure vessel with its four inlet nozzles, the downcomer, the lower plenum up to the core inlet plane, and the reactor core up to the core outlet plane. The pressure vessel is discretized into 1,906,272 tetrahedral and the reactor core into 405,300 hexahedral cells. The nodalisation of the reactor core, used by DYN3D, is shown in Fig. 2. It consists of 2,132 nodes.

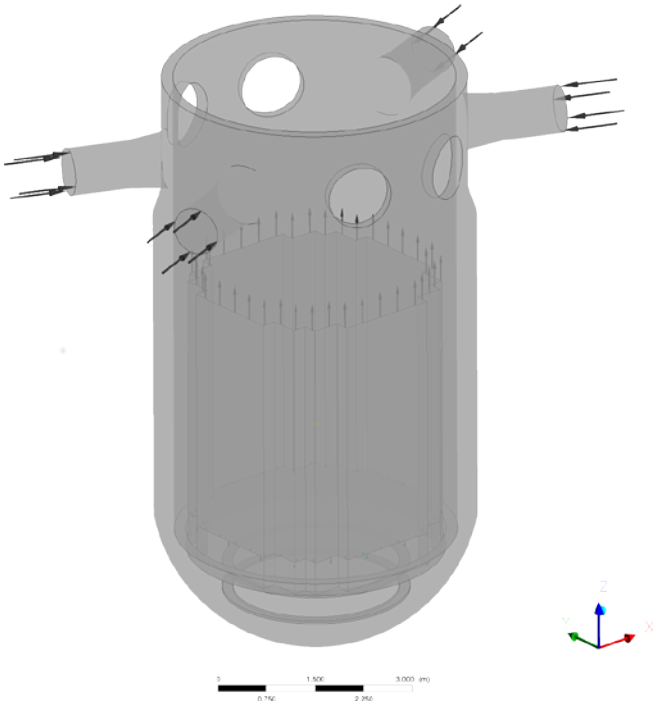


Fig. 1: Flow geometry for coupled ANSYS CFX/DYN3D simulation

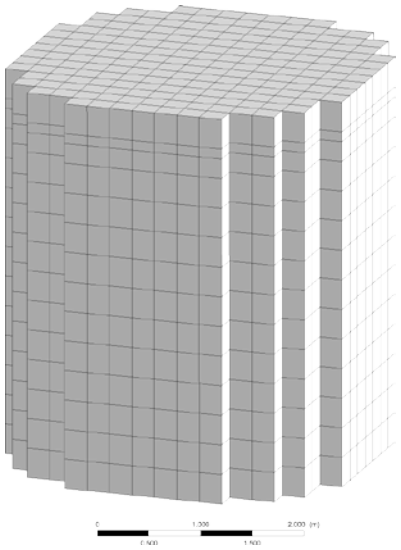


Fig. 2: DYN3D nodalisation of the reactor core

The underlying scenario is based on an unrecognized steam generator tube rupture (Reinders, 1998). It is assumed that a slug of unborated coolant has accumulated in the loop due to this tube rupture during outage, when the secondary side pressure was higher than that in the primary side. The size of the slug corresponds to the volume of the steam generator outlet chamber and the connected loop seal and is equal to 10 $m^3$. Switching on the main coolant pump in the affected loop drives the slug towards the reactor pressure vessel. The pump reaches its full mass flow rate about 14 s after start-up, in the three other loops a reverse flow establishes of about 5% of the nominal loop flow rate. (Fig. 3).

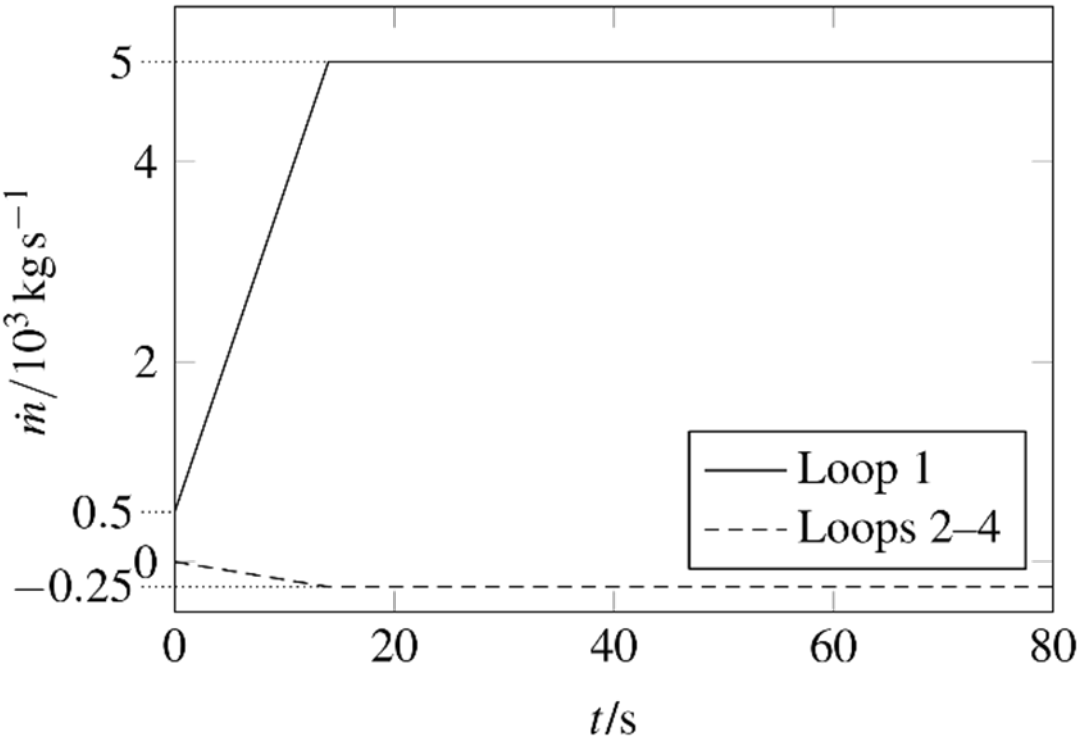


Fig. 3: Coolant mass flow boundary conditions at the inlets

## 5.2 Discussion of the coolant mixing

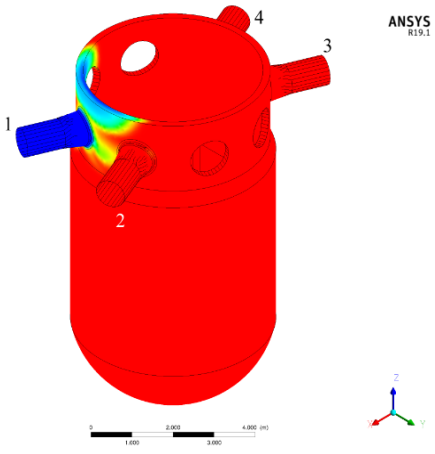
Figures 4 and 5 show the spreading of the deborated slug of coolant which enters the pressure vessel during the first 5.8 s. The duration results from the given slug volume and the increasing coolant flow rate after pump restart.

The coolant jet that is formed by the nozzle of loop 1 has enough momentum to split up and flow around the core barrel after impacting on it. At the same time, coolant leaves the vessel through loop nozzles 2, 3 and 4, according to the boundary conditions. This has an additional entrainment effect on the coolant inventory within the pressure vessel, and a part of the deborated coolant exits through these loops.

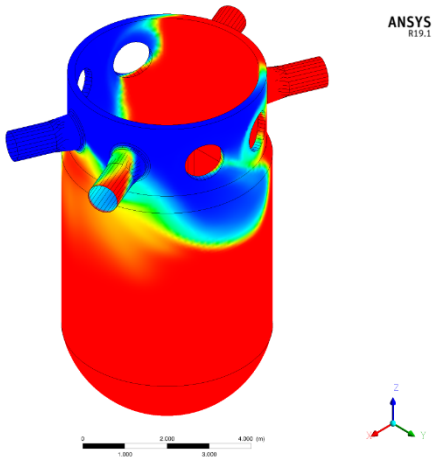
The horizontal movement of the deborated plumes is overlaid by the vertical flow towards the lower plenum. Figure 7 shows the minimum boron concentrations at different locations in the vessel. Coolant with zero concentration is detected in the orifice, where the loop 1 nozzle is attached to the outer cylindrical wall. While the coolant travels through the downcomer, the deborated slug is increasingly mixed with the surrounding, borated coolant. The zero-concentration front has vanished at about the half of the downcomer height, which is located at $z$=3.135 m above the core inlet plane ($z$=0 m). Here, a concentration of almost zero is detected only for an instant. Further down the flow path, the minimal concentration continues to increase. At the lower end of the downcomer at $z$=0 m, the minimal concentration is about 260 ppm and occurs at $t$=8 s, at the perforated drum surface of the lower plenum, the minimal concentration of 810 ppm is reached at $t$=10 s, and at the core inlet plane at $t$=11 s with a value of 1290 ppm.

At the core inlet, Fig. 6, the zone with minimal boron concentration is located in the lower left quandrant of the x/y plane, which corresponds to the loop 4 position. Initially, the zone of minimum concentration covers about one quarter of the core inlet and extends azimuthally to form the quarter of an annulus. As time advances, the core inlet plane is almost entirely covered with underborated coolant, apart from a central zone. In Figure 7 it can be seen that the low-concentration slug takes about 20 s to pass the core inlet plane. At $t$=30 s of simulation time, 90% of original boron concentration is reached. Afterwards, it approaches this value asymptotically.

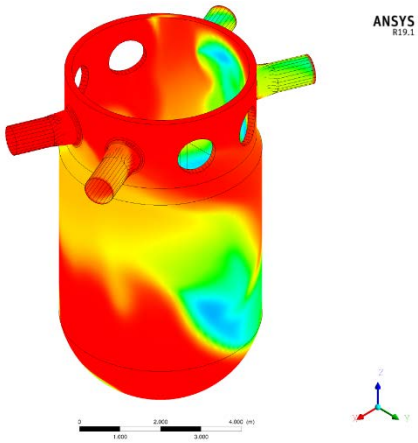
The lowest concentration and its time-dependency in the core region is identical to the one found in the core inlet plane. In addition to that, Fig. 8 plots the volume-averaged boron concentration in the reactor core against simulation time. Its minimum, 2840 ppm, is reached at $t$=17 s.



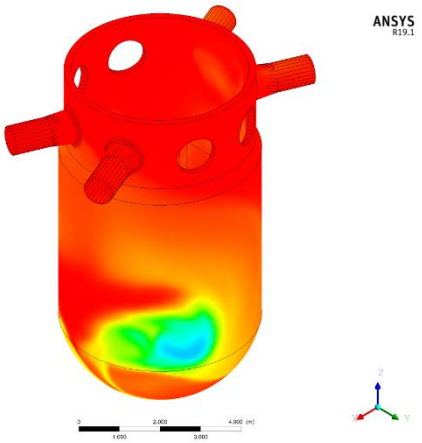

t = 2 s



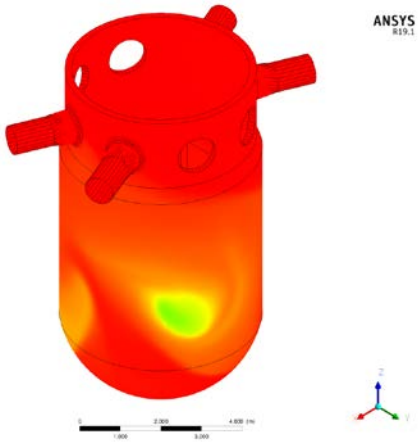

t = 5 s

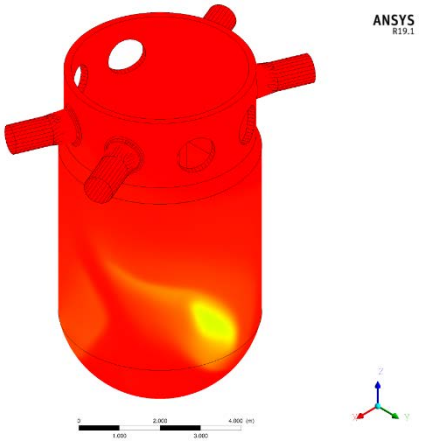



t = 10 s




t = 15 s



t = 25 s

t = 35 s

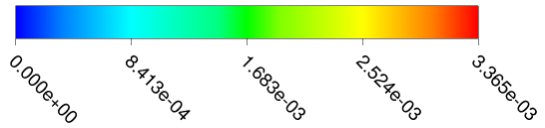
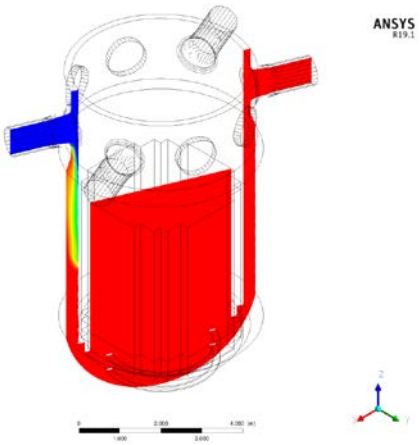
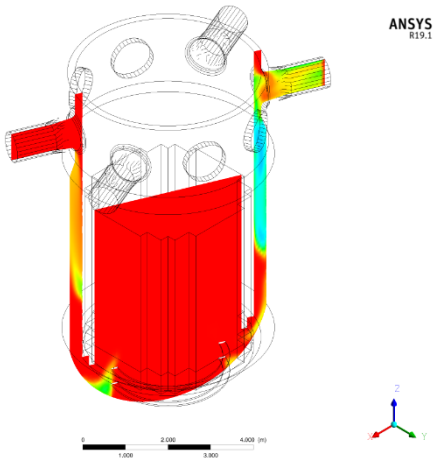


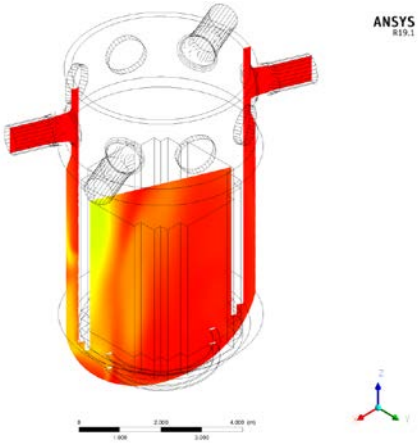

Fig. 4: Spreading of the deborated slug in the vessel (boron mass fraction; no unit)




*t* = 5 s

*t* = 10 s





*t* = 20 s

*t* = 30 s

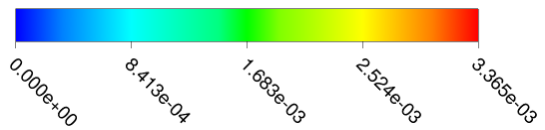
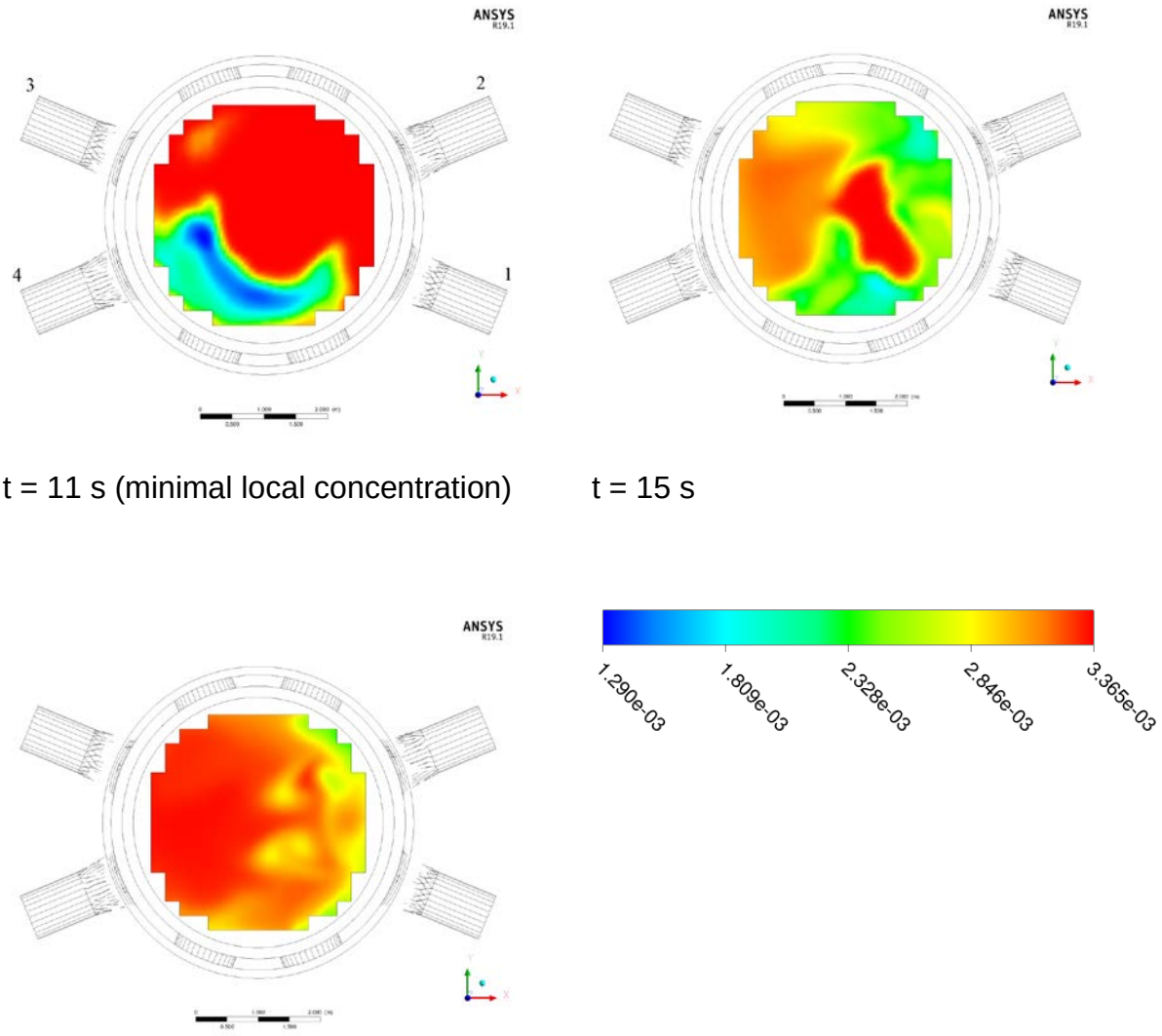



Fig. 5: Sectional view of the boron distribution (mass fraction)




t = 11 s (minimal local concentration)  t = 15 s

t = 20 s

Fig. 6: Boron distribution (mass fraction) in the core inlet plane at different simulation times

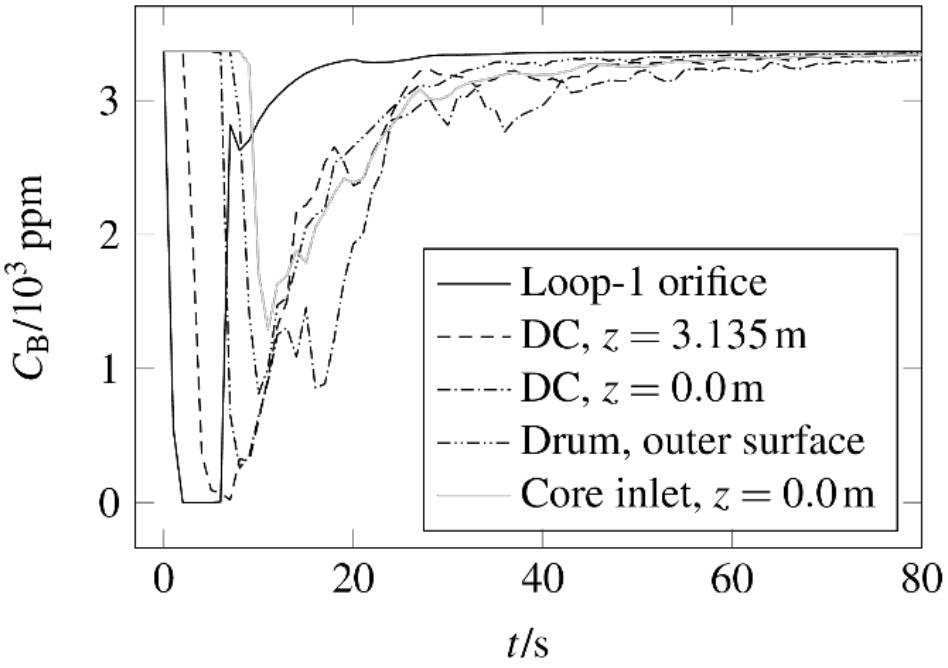



Fig. 7: Minimum boron concentrations at various locations in the RPV

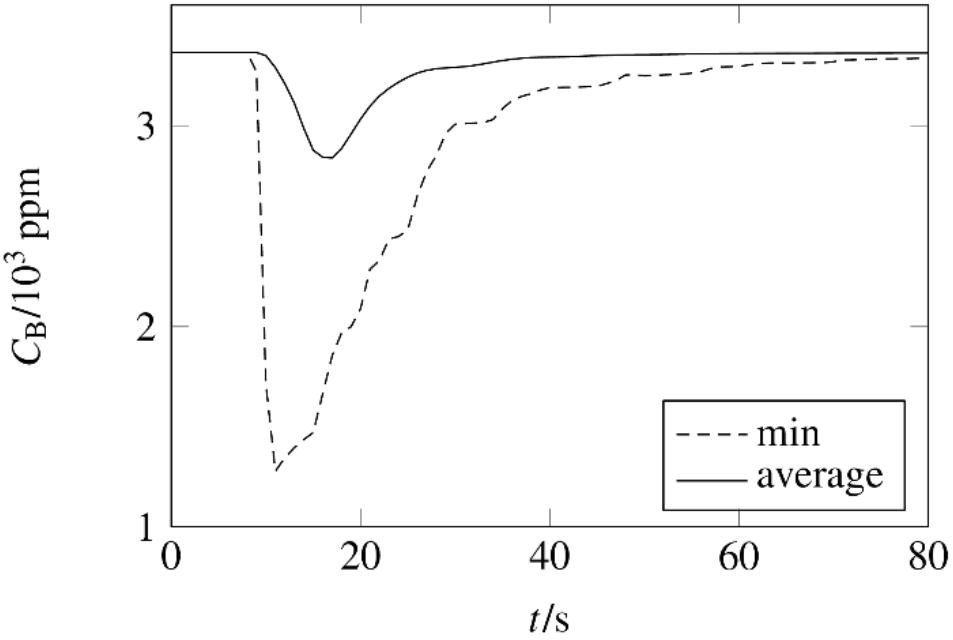



Fig. 8: Boron concentration in the reactor core

### 5.3 Reactivity behavior of the reactor core

Fig. 9 shows the reactivity of the reactor core. According to the specified boundary conditions, the simulation starts from a subcritical state. The corresponding value is -43.1$ which is due to the inserted control rods and the high boron concentration.

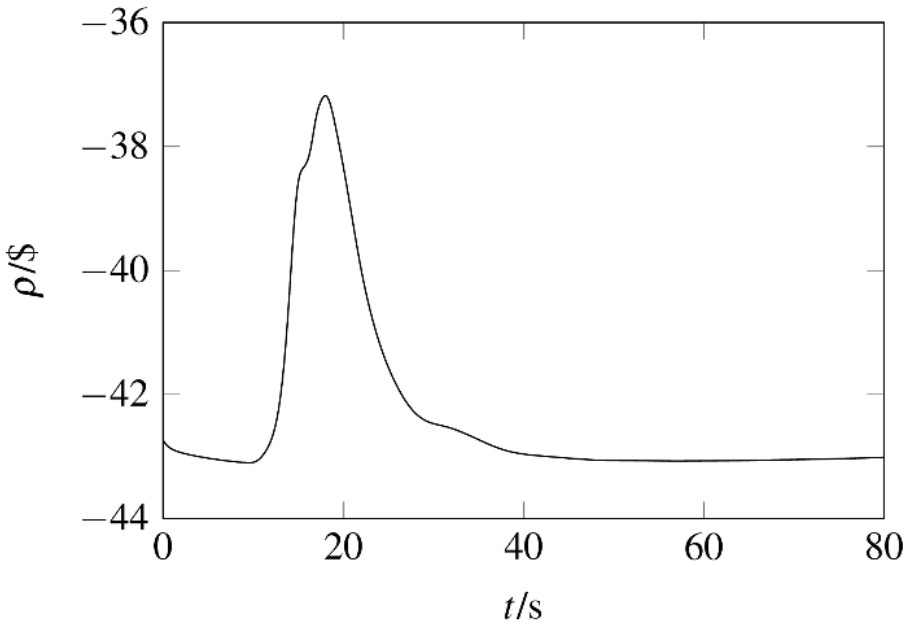



Fig. 9: Reactivity

As described above the deborated slug mixes on the way through the reactor pressure vessel with the ambient borated water. The resulting boron concentration in the reactor core is very far from the zero-concentration of the slug in the loop. For that reason the increase of reactivity during the transport through the reactor core is moderate, the maximum increase reaches 5.8$ resulting in a maximum reactivity value of -37.2$.

In order to evaluate such a result, typically, the reactivity curve obtained in a calculation with realistic mixing approach is compared to homogeneous (ideal) mixing and a case without mixing (e.g. Zerkak and Ferroukhi, 2011; Grundmann and Kliem, 2003). In mixing scenarios with involvement of coolant flow from different loops in the homogeneous mixing case, the flow from all loops is mixed completely before entering the core. In the no-mixing case, the flow from the loops is guided separately to corresponding sectors of the core.

For flow conditions like in the investigated scenario, where the flow from one loop is involved, only, the selection of the homogeneous and the no-mixing cases requires additional assumptions. Here, the no-mixing case is set-up in a way that the effective slug volume is transported of the whole core inlet cross section into the core with the resulting downcomer flow rate observed in the CFD calculation. For the determination of the effective slug volume, the part of the slug which is transported to the inactive cold legs due to reverse flow is subtracted from the initial slug volume. The assumption for the homogeneous mixing case specified here was to mix completely the effective slug volume with the volume of the coolant in the downcomer and lower plenum. The resulting coolant volume is transported into the core with the flow rate determined for the no-mixing case.

For both cases, stand-alone time-dependent DYN3D calculations have been conducted using the reactor core model form the coupled calculation equipped with the described above thermal hydraulic boundary conditions. Tab. 1 contains the results of all three calculations.

Tab. 1: Influence of the coolant mixing assumptions on the reactivity behaviour

| **Mixing approach** | **Minimal boron concentration in the core [ppm]** | **Maximum reactivity [$]** |
|---|---|---|
| Realistic (ANSYS CFX/DYN3D) | 2843 | -37.2 |
| Homogeneous mixing | 2958 | -36.6 |
| No mixing | 0 | +2.1 |

In the no-mixing case, the unborated slug covers roughly 40 % of the core volume starting from the inlet. Such a deboration leads to the insertion of a big amount of positive reactivity. The initial subcriticality is compensated and the core becomes critical and even super-prompt critical with a maximum reactivity of +2.1 $. The power peak induced by such a reactivity insertion is 150 GW with a half width of 10 ms. The reactivity increase is stopped by fuel temperature increase and later on by coolant boiling. According to the calculations, there is no violation of safety criteria like occurrence of DNB or cladding overheating.

As expected, the homogeneous mixing case provides a higher minimal boron concentration than the realistic case. But the maximum value of the reactivity reached during the calculation is higher than the value of the realistic calculation. This can only be explained by a so-called longitudinal mixing of the deborated water in the realistic case, which is not considered in the applied homogeneous case. It seems that the 3D flow pathes in the downcomer and lower plenum which clearly can be seen in the figures in section 5.2, are responsible for stretching the perturbation before entering the core.

## 6. Conclusions

CFD codes have recently been included into the oversight procedure of nuclear power plants. The main focus are currently single-phase applications. In the present work, a CFD model of a PWR reactor pressure vessel has been equipped with a 3D neutron kinetic core model and has been applied successfully to the calculation of the consequences of an inherent boron dilution scenario.

Such coupled code systems are not restricted to one specific reactor type, which is one of their biggest advantages. A tool is available which can be applied to any mixing scenario and in such a way eliminates the need of the development of simplified coolant mixing models.

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