Impact of Boron Dilution Accidents on Low Boron PWR Safety

Angel Papukchiev*[1], Yubo Liu[1], Anselm Schaefer[2]
[1]*Chair for Reactor Dynamics and Reactor Safety, Technical University Munich,*
Walther Meissner-Str. 2, 85748 Garching, Germany
[2]*ISaR Institute for Safety and Reliability,*
Walther Meissner-Str. 2, 85748 Garching, Germany

Abstract

In conventional pressurized water reactor (PWR) designs, soluble boron is used for reactivity control over core fuel cycle. As an inadvertent reduction of the boron concentration during a boron dilution accident could introduce positive reactivity and have a negative impact on PWR safety, design changes to reduce boron concentration in the reactor coolant are of general interest. In the framework of an investigation into the feasibility of low boron design, a PWR core configuration based on fuel with higher gadolinium (Gd) load has been developed which permits to reduce the natural boron concentration at begin of cycle (BOC) to 518 ppm. For the assessment of the potential safety advantages, a boron dilution accident due to small break loss-of-coolant-accident (SBLOCA) has been simulated with the system code ATHLET for two PWR core designs: a low boron design and a standard core design. The results from the comparative analyses showed that the impact of the boron dilution accident on the new PWR design safety is significantly lower in comparison with the standard design. The new reactor design provided at least 4,4% higher reactivity margin to recriticality during the whole accident which is equivalent to the negative reactivity worth of additional 63% of all control rods fully inserted in to the core.

KEYWORDS: PWR, low boron core design, boron dilution, improved safety

1. Introduction

Concerning the PWR inherent safety, a reduction of boron concentration in the reactor coolant might be of general interest regarding three aspects – improved reactivity feedback properties, lower impact of boron dilution scenarios on reactor safety and more flexible accident management strategies. Design changes to reduce boron concentration in the reactor coolant have been proposed in a number of R&D projects for new reactors [1,2]. This paper describes similar investigations regarding the feasibilities to introduce low boron design in current PWRs.

In the framework of an investigation into the feasibility of low boron design a PWR core configuration has been developed which permits to reduce the BOC boron concentration by approx. 50% compared to current standard PWR technology. The low boron design is based on fuel with higher Gd load along with an appropriate core loading strategy. The core meets German acceptance criteria regarding stuck rod, departure from nucleate boiling ratio (DNBR),

* Corresponding author, Tel. +49 89 289 12263, Fax. +49 89 289 13949, E-mail: apa@isar.tum.de

shutdown reactivity, and maximal linear power.

For the assessment of potential safety advantages of the new core, comparative analyses are being performed for two PWR core designs: a low boron design (case 1) and a standard design (case 2). The aim of this paper is to present the results of boron dilution accident calculations performed with the best-estimate, thermal-hydraulic system code ATHLET and to evaluate the impact of this event on PWR safety.

2. Boron Dilution Accidents

Boron dilution accidents are transients which could lead to an inadvertent reduction of the boron concentration in PWR primary circuit and eventually to reactivity and power increase. Two main categories of boron dilution accidents are presently discussed in Germany – external and inherent boron dilution scenarios. In external boron dilution accidents underborated or boron free water enters the primary circuit through connected systems and tanks. A hypothetical scenario is injection of boron free water in one or more loops due to malfunction in the chemical and volume control system (CVCS).

During the so called inherent scenarios a deborated slug is generated by evaporation and condensation of reactor coolant during a reflux condenser mode in the primary side. Later, when the natural circulation reestablishes, the underborated slug is forwarded to the reactor core where it could cause reactivity and power increase. A characteristic initiating event of such scenarios is a SBLOCA with the additional assumption that two of four safety injection systems (SIS) are unavailable due to maintenance and single failure [3].

In order to investigate the impact of boron dilution accidents on low boron PWR safety, a 35 cm^2 hot leg SBLOCA with two unavailable high pressure injection systems (HPIS) has been simulated with the ATHLET system code.

3. Low Boron PWR Design Methodology

For the performance of these investigations a new low boron core configuration, based on existing German PWR technology has been designed. An innovative low boron core design methodology was developed combining a simplified reactivity balance search procedure with a core design approach based on detailed 3D diffusion calculations. Fuel cross sections needed for nuclear libraries were generated using the 2D lattice code HELIOS [4] and full core configurations were modeled with the 3D diffusion code QUABOX/CUBBOX [5]. For dynamic 3D calculations, the coupled code system ATHLET - QUABOX/CUBBOX [6,7] has been used. The next paragraphs give a brief overview of the main processes of core design methodology.

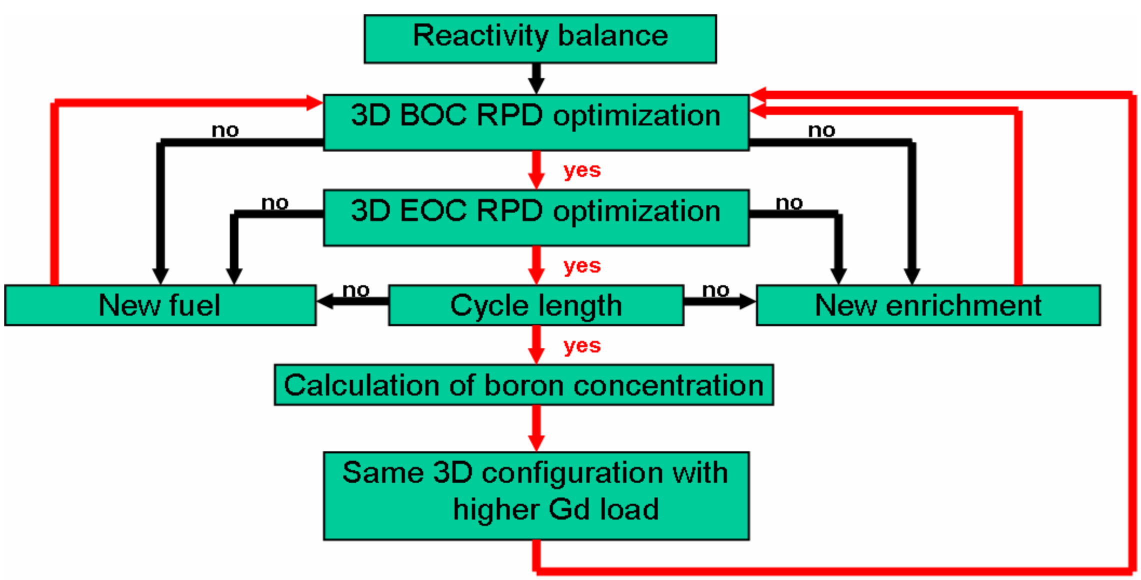
3.1 Fuel Assembly Design

Broad spectrum of 16x16 fuel assembly configurations have been designed and their cross section data were generated using validated HELIOS input data. The main parameters that were varied are number of Gd rods (8 to 116), Gd concentration (3 to 9%) and Gd rod positioning. The analyses showed that three factors have a strong influence on k_{inf} - number of Gd rods, Gd concentration as well as uranium enrichment of rods without Gd. The positioning of Gd rods has greater effect on power distribution within the fuel assembly.

3.2 Reactivity Balance Search and 3D Core Design Approach

In order to create a low boron PWR core configuration, a simplified and approximate core reactivity balance search was needed at the beginning for orientational calculations. A software tool (REBA) was developed, which finds in cell calculations' output data the appropriate k_{inf} value for each fuel assembly according to its type and burnup and calculates the average k_{inf} of all 193 assemblies for a specified configuration. Furthermore, an algorithm which searches for fuel assembly combinations with small excess reactivity at BOC (i.e. low boron concentration) has been developed and integrated in the program. The REBA program is suitable for the calculation of an approximate core reactivity balance, but can not determine the neutron multiplication factor of a real reactor core configuration. That is why an innovative approach for the low boron core design implementing the 3D diffusion model QUABOX/CUBBOX was developed. Fig. 1 shows a simplified scheme with the main steps of the design process. The fuel assembly combination identified by REBA as most promising for low boron core design was used as a basis for the first detailed 3D diffusion calculations. In the next step of the design process a radial power distribution (RPD) optimization for BOC is done. After performing the burnup calculation with QUABOX/CUBBOX, the end of cycle (EOC) RPD is optimized. If the BOC and EOC power peaking criteria are met, a detailed burnup calculation is performed to calculate the power density peaks during the cycle as well as its length. If one of these steps fails, either the assembly types or the enrichment of the fuel should be changed. In case that all conditions are fulfilled, the same configuration is being tested with fuel with heavier Gd load. The whole design cycle is then repeated to check if a lower boron concentration could be achieved. In order to optimize factors like power distribution, core criticality during cycle, cycle length etc., more than 1000 core configurations with reduced boron concentration have been generated and analyzed. A software tool (POWEROPT) has been programmed and utilized for automatic generation and evaluation of QUABOX/CUBBOX I/O data as well as for iterative control of the core depletion calculation.

Figure 1: Simplified scheme of the core design process



3.3 Low Boron Core

Based on these calculations and analyses, an optimized low boron core configuration was designed which has 518 ppm boron concentration at BOC. The core utilizes two fuel types: fuel assemblies with low and with high Gd concentration. This concept is based on the different Gd burnout times of both fuels. The main advantages are lower power density peaks and a smaller excess reactivity permitting to reduce the boron concentration at BOC by about 50% compared to current PWR practice. Furthermore the core configuration complies with PWR acceptance criteria concerning shutdown safety margin, DNBR, stuck rod and maximal linear power density. The cycle length is comparable to standard designs. A summary of the most important physical parameters of the new core design is given in Tab. 1.

Table 1: Most important parameters of the low boron core.

Parameters of the Low Boron Core	Value
Critical boron concentration at BOC [ppm]	518
k_{eff}(BOC), hot full power, Bor=0 ppm, Xe equil.	1.04767
k_{eff}(EOC), hot full power, Bor=0 ppm, Xe equil.	1.00111
k_{eff}(BOC), hot zero power, Bor=518 ppm, all rods in	0.92551
k_{eff}(BOC), hot zero power, Bor=518 ppm, all rods in except stuck	0.93887
Cycle length [FPD]	331
Minimum DNBR, Channel 61, Node 6	2.83
Max. linear power density at BOC [W/cm]	442
Max. linear power density at EOC [W/cm]	340
Max. linear power density during the cycle [W/cm]	449
Rod worth (most effective control rod) [%]	1.4
Core mean burnup at BOC [MWd/kgU]	18
Core mean burnup at EOC [MWd/kgU]	29.8

4. Description of ATHLET Modeling

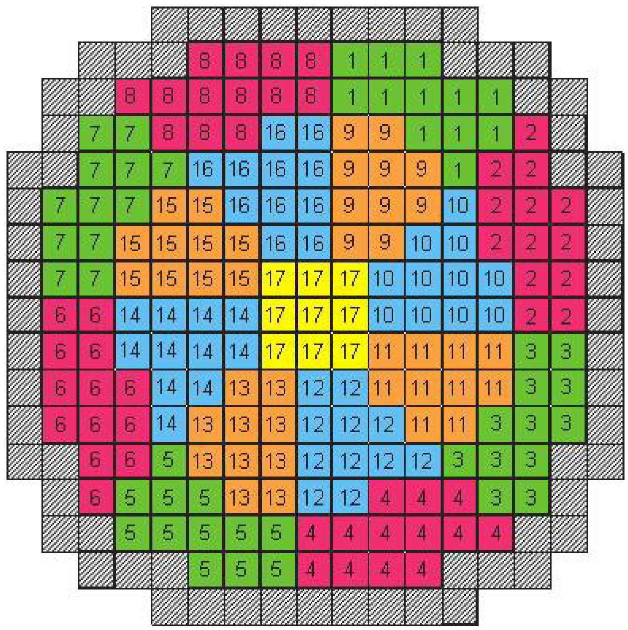
The specific ATHLET input deck used for the boron dilution analyses described in this work is based on a detailed ATHLET simulator model of a standard PWR. It consists of 46 branches, 263 pipes, 762 control volumes and has been extended for the calculation of the boron dilution accident.

4.1 Primary Circuit

The primary side of the PWR plant is represented with four separate loops, four main coolant pumps (MCP) and all major operational and safety systems such as CVCS, extra borating system (EBS), high and low pressure injection systems, accumulators, etc. The pressurizer (PRZ) has been simulated with 6 nodes and connected via the surge line to the hot leg of loop 3. Fine nodalization scheme with three different heat exchanger U-tube bundles (short, medium and long) has been developed for the modeling of steam generator (SG) U-tubes (Fig. 11). Each bundle has 15 nodes and represents over 1300 tubes. This simulation technique has been chosen as a result of additional sensitivity analyses on the influence of SG tubes nodalization on transient progression.

A relatively fine nodalization scheme has been developed for the reactor pressure vessel (RPV). The core consists of 17 pipe channels (each one with 26 nodes) arranged in two radial rings and one central zone, according to the subdivision shown in Fig. 2.

Figure 2: Channel subdivision of PWR core



The aforementioned nodalization scheme was also used for the lower and upper plena. The downcomer has been represented with 8 parallel fluid channels. All flow paths among the thermal hydraulic objects were simulated with cross connection pipes which are essential for the more realistic simulation of coolant mixing in RPV.

4.2 Secondary Circuit

The secondary side as well as balance-of-plant model have been represented with control signals, which were arranged in logical control blocks. The SG downcomer, riser, separator and dome were separately modeled with thermal-hydraulic objects.

5. Initial and Boundary Conditions

- 35 cm^2 break in the hot leg of loop 1, after break opening loss-of-offsite power occurs
- Reactor power - 3850 MWe (102%)
- Primary pressure - 15.8 MPa
- PRZ level - 7.46 m
- Initial boron concentration - 518 ppm (case 1) and 1250 ppm (case 2)
- HPIS in loops 2 and 4 unavailable due to start up failure and maintenance assumptions on two emergency diesels

6. Transient Progression

At 0 s simulation time a 35 cm^2 SBLOCA is open in the hot leg of loop 1 and almost at the same time SCRAM, TURBINE TRIP and MCP OFF signals are actuated by the reactor protection system due to the loss-of-offsite-power (Fig. 3). 21 s later, a 100 K/h cooldown is initiated in the secondary side which additionally contributes to the pressure drop in the primary circuit (Fig. 4). When pump speed reaches 100 rpm a pump stall is assumed because of the increased shaft friction. About 80 s after accident begin the primary pressure drops below 11.0 MPa and HPIS starts to inject 2200 ppm borated water in the hot legs of loops 1 and 3. Fig. 5 shows the SIS injection rate which is representative for loops 1 and 3 and Fig. 6 displays the injection rate for loops 2 and 4. Because of the temperature and density differences in primary system as well as spacial arrangement of system components, one phase natural circulation establishes in all loops. It removes part of the produced decay heat and the rest is removed through the break. When the saturation pressure in the primary system is reached, reactor coolant in the core starts to evaporate. The steam flows to SG U-tubes where it condenses and interrupts the one phase natural circulation in loops 2 and 4 (without HPIS). The mass flow in the affected loops starts to oscillate around 0 kg/s (Figs. 7 and 8). This mode of operation is called reflux-condenser. Since the steam could transport upto 50 ppm boron or less, a deborated coolant accumulates in the U-tubes of SG 2 and SG 4 (Fig. 11, T=2050 s). When primary pressure drops below 2.6 MPa (~ 2600 s), all four accumulators connected to the hot legs start injecting borated water in the primary system. Together, HPIS and accumulators feed more water than is lost through the break and refill the primary system. When the one phase natural circulation reestablishes first in the long (Fig. 11, T=2830 s) and then in the other two U-tube bundles (Fig. 11, T=3140 s), the accumulated boron free coolant is shifted towards cold leg and RPV inlet. Fig. 9 and Fig. 10 show the boron concentration at RPV entrance in loops 2 and 4. On its way to the core, the condensate is further mixed with the highly borated water in the downcomer and lower plenum, which significantly increases its boron concentration. Table 2 gives an overview of the minimal boron concentration calculated by ATHLET at core inlet for some representative core channels as well as the difference between minimal and initial concentrations.

Figure 3: Break mass flow

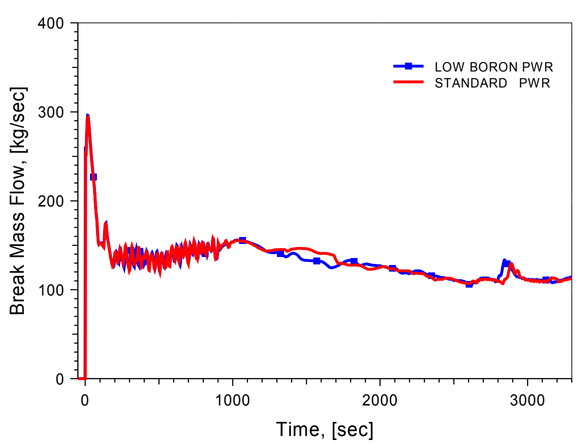


Figure 4: Primary pressure

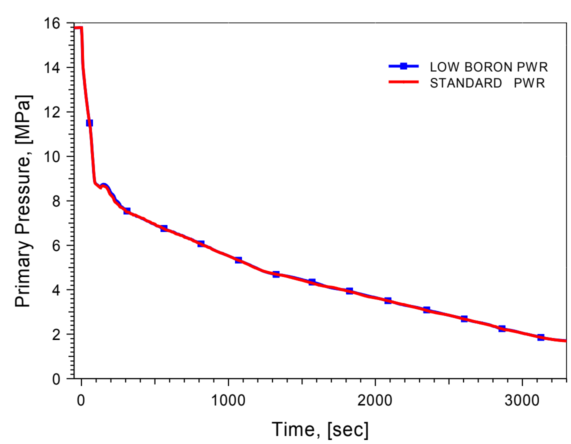


Figure 5: SIS mass flow, loops 1 and 3

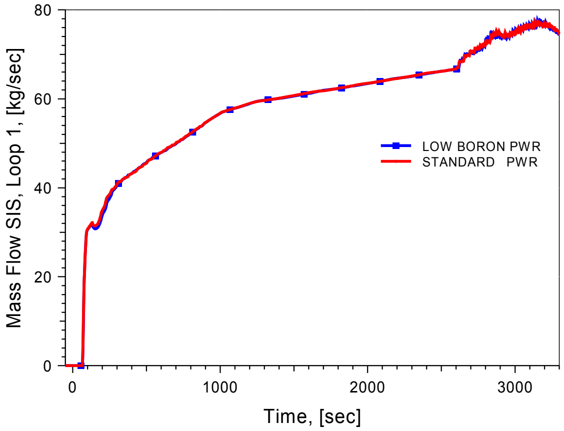


Figure 6: SIS mass flow, loops 2 and 4

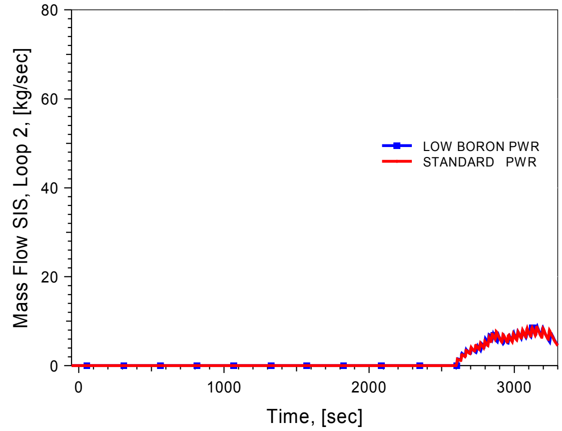


Figure 7: Mass flow in cold leg 2

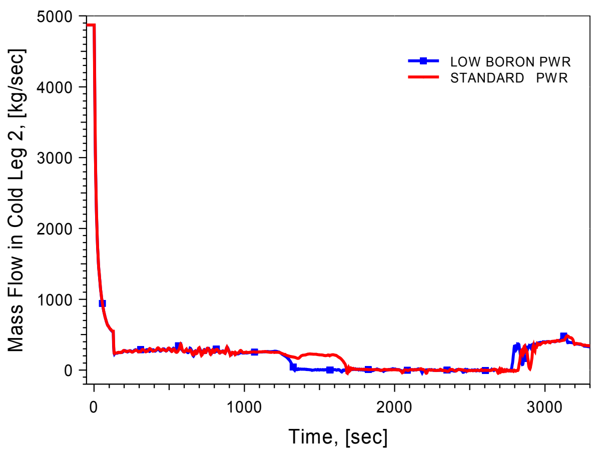


Figure 8: Mass flow in cold leg 4

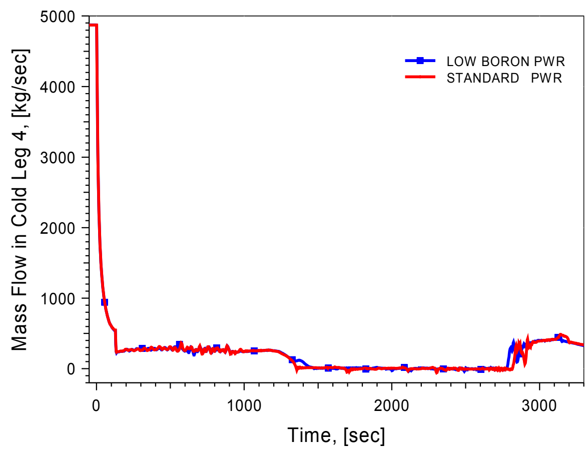


Figure 9: Boron conc. in cold leg 2

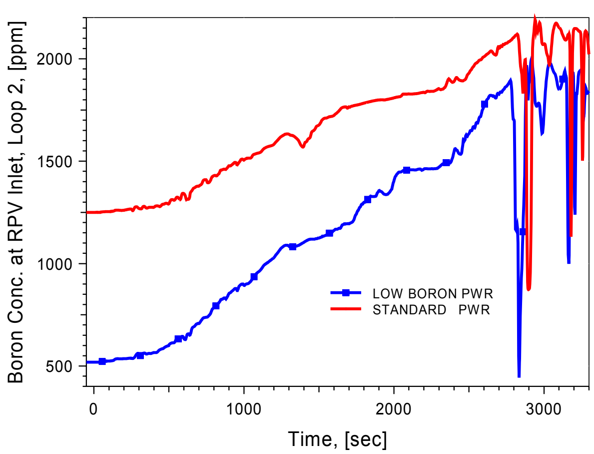


Figure 10: Boron conc. in cold leg 4

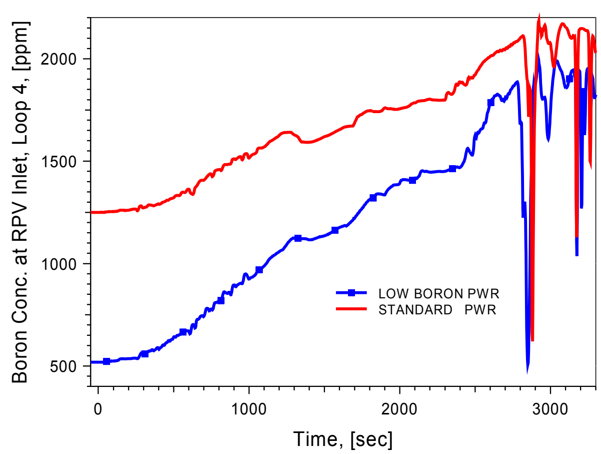
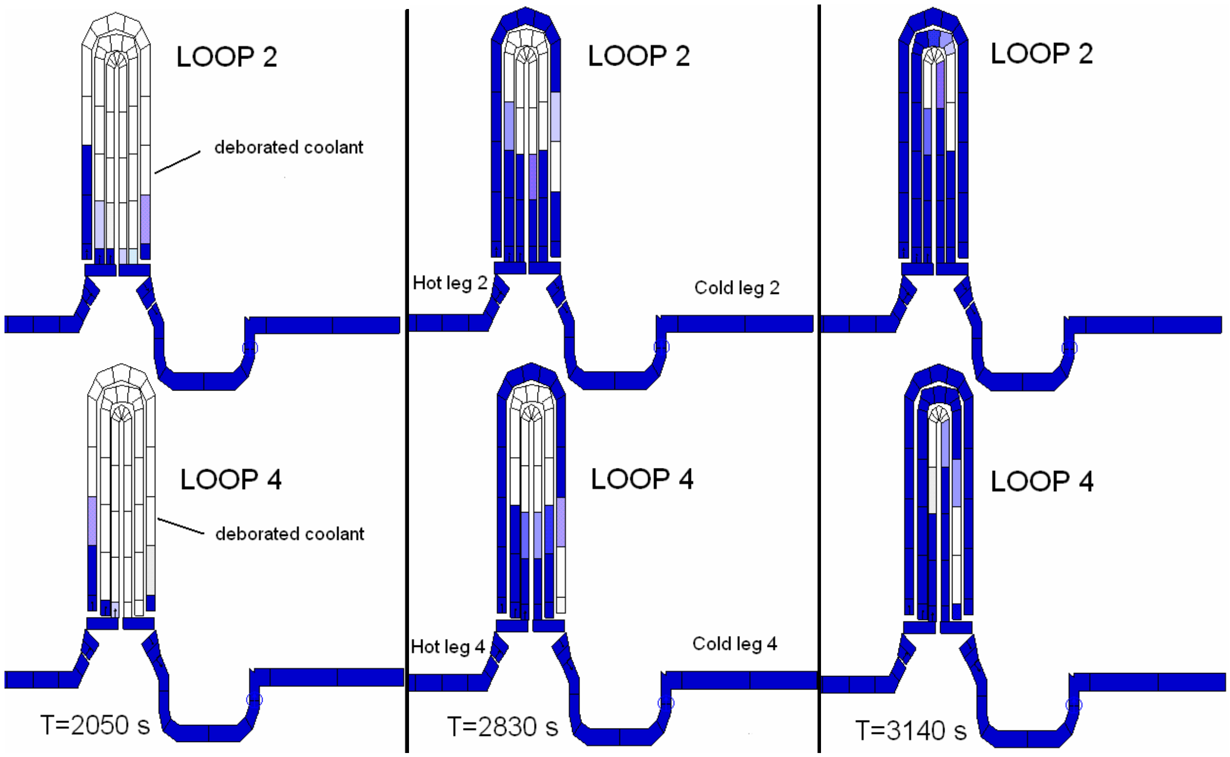


Figure 11: ATHLET representation of the of the boron concentration distribution in loops 2 and 4 during the different accident phases. White color depicts 0 ppm and dark blue 1000 ppm or higher boron concentrations.



Reflux-condenser mode *Restart of nat. circulation and deborated slug shifting towards hot legs and RPV*

Table 2: Min. boron concentration and difference between min. and initial concentrations at the inlet of some representative core channels.

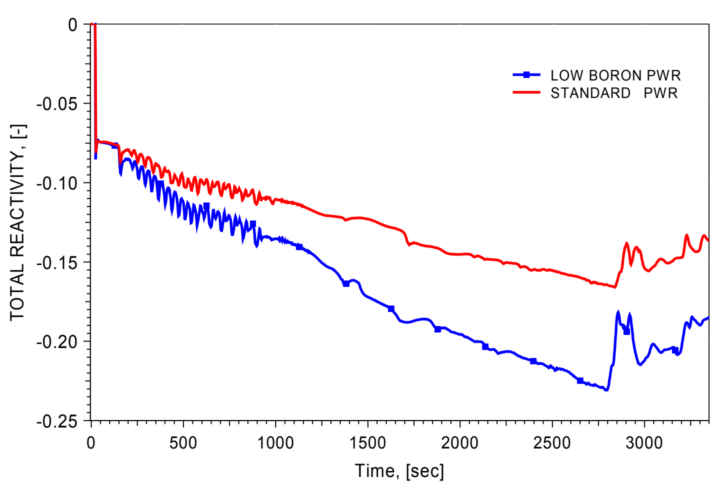
Core Channel	**Core Design**	**C_{min}, ppm**	**$C_{min} - C_{init}$, ppm**
6	standard	1301	51
	low boron	1103	585
7	standard	1356	106
	low boron	1061	543
8	standard	1744	494
	low boron	1269	751
10	standard	2010	760
	low boron	1787	1269
12	standard	1949	699
	low boron	1687	1169

7. Evaluation of Results

The calculations presented here demonstrate the dependence of the results on both core designs used in the boron dilution calculations. The main differences between case 1 and case 2 can be summarized as follows:

- In general, a similar transient progression is observed in both simulations concerning break mass flow, primary pressure and system behavior.
- For both cases, the minimal boron concentration at core inlet remains higher than the initial boron concentration during the whole accident.
- Both designs are far from criticality due to the SCRAM and the intensive borating of the primary circuit by the SIS and EBS (Fig. 12).
- The size of the deborated slug in loop 2, case 2, is smaller in comparison with case 1. The reason for that is the shorter time of the reflux condenser mode in this calculation.
- Nevertheless, the difference between minimal and initial boron concentrations at RPV and core inlets is significantly larger for the low boron design.
- This effect is explained by the fact that the low boron core is more rapidly borated. The difference between initial and injected (2200 ppm) boron concentration is essential for the primary circuit borating dynamics.
- Finally, the more rapid borating of the low boron PWR coolant leads to larger negative reactivity insertion. During the whole accident, the new reactor design provided 4,4% or even higher reactivity margin to recriticality in comparison with the standard PWR (Fig. 12). This is equivalent to the negative reactivity worth of approx. 63% of all control rods fully inserted into the core.

Figure 12: Total Reactivity



8. Conclusions

A reduction of boron concentration in the reactor coolant might be of general interest regarding improved reactivity feedback, lower impact of boron dilution scenarios on reactor safety as well as increased flexibility of accident management strategies. In order to investigate the impact of boron dilution accidents on low boron PWR safety, an optimized low boron core which permits to reduce the natural boron concentration by 50% compared to current PWR technology has been designed. The developed low boron core design methodology combines a simplified reactivity balance search and a 3D approach based on detailed diffusion calculations. For the assessment of the impact of boron dilution accidents on PWR safety, boron dilution accident simulations have been performed with the system code ATHLET for two PWR designs – low boron and standard design. The analyses showed that both reactors are far from recriticality during the whole accident. Nevertheless, the low boron reactor is more rapidly borated due the larger difference between initial and injected water. It provided at least 4,4% larger reactivity margin to recriticality during the boron dilution accident, which indicates the lower impact of these events on the inherent safety of the new PWR design.

This paper deals exclusively with potential safety advantages of low boron core design. Supplementary investigations will be carried out to assess the drawbacks of higher Gd loads in PWR fuel.

Acknowledgements

The presented work was performed within a project funded by the German Federal Ministry of Economics and Technology. The authors would especially like to thank the experts from GRS, E.ON Kernkraft, AREVA NP and TUEV Sued for their valuable cooperation.

References

1) J.-P. Deffain, P. Alexandre and P. Thomet, "Feasibility Studies of a Soluble Boron-Free 900-MW(electric) PWR, Core Physics-II: Control Rod Follow, Load Follow, and Reactivity-Initiated Accident Linked to RCCAs", Nuclear Technology, 127, 267 (1999).
2) J.-Ch. Kim et al., "Nuclear Design Feasibility of the Soluble Boron Free PWR Core", Journal of the Korean Nuclear Society, 30, 342 (1998).
3) F.-P. Weiss and S. Kliem, "Study of Boron-dilution Transients in PWRs", The 2003 FJOH Summer School in Reactor Physics, 20-29.08.2003, Forschungszentrum Karlsruhe, Germany
4) HELIOS 1.8 User's Manuals, 2003, Studsvik *Scandpower.*
5) QUABOX/CUBBOX - HYCA User's Manual, 1993, GRS.
6) A. Papukchiev et al., "Coupled Thermal-Hydraulics – 3D Kinetics Analysis of ATWS" Proc. of the Annual Meeting on Nuclear Technology, Nuremberg, Germany, May 10-12, 2005, 155 (2005).
7) S. Langenbuch, K.-D. Schmidt and K. Velkov, "Analysis of the Pressurized Water Reactor Main Steam Line Break Benchmark by the Coupled Code System ATHLET-QUABOX/CUBBOX", Nuclear Technology, 142, 124 (2003).