Note:
This is a translation of the RSK statement entitled
"Ausbildung und Auswirkungen eines Deionatpfropfens beim Dampferzeugerheizrohrleck"
In case of discrepancies between the English translation and the German original, the original shall prevail.

Statement of the RSK Committee on PLANT AND SYSTEMS ENGINEERING (AST)

11th December 2014

Formation and effects of an unborated water plug during a steam generator tube rupture event

1 Background

In a letter dated 19 February 2013 to the Chairman of the Reactor Safety Commission (RSK), Dipl.-Ing. Mayer from Energiebüro Gorxheimertal drew attention to the problem of the formation of an unborated water plug with subsequent recriticality of the core during a steam generator tube leak in a pressurised water reactor (PWR). This letter was answered by the RSK Chairman in a letter dated 5 March 2013. On 16 September 2013, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) submitted a statement on the above-mentioned letter from Mr Mayer [2]. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) agreed with this statement and made it available to Mr Mayer. The Vienna Institute of Safety and Risk Sciences (ISR) also addressed this issue and stated that the scenario described could possibly not be ruled out by corresponding safety analyses. The accident sequence described by Mr Mayer would therefore not be comparable with the available results from investigations conducted to date and would have to be reviewed.

Due to the differing views, the BMUB considered it necessary to refer the matter to the RSK Committee on PLANT AND SYSTEMS ENGINEERING. At its 465th meeting on 24 April 2014, the RSK requested the Committee on PLANT AND SYSTEMS ENGINEERING to consult on this matter. In response, Dipl.-Ing. Mayer (Energiebüro Gorxheimertal, EnBG) presented his considerations on the "risk due to unborated water plugs during a steam generator tube leak in a pressurised water reactor (PWR)" [1] [4] at the 97th meeting of the Committee on 8 May 2014 and formulated questions relating the accident sequence that are unresolved from his point of view. In addition, at this meeting and subsequently, the Vienna Institute of Safety and Risk Sciences (ISR) [3] [5] [7] commented on GRS's statement of 16 September 2013. In a further report at this meeting, GRS presented to the Committee the process of boron dilution following a steam generator tube leak and the analyses on the steam generator tube leak event conducted so far [6].

The Committee decided to carry out an assessment of the potential for the formation of an unborated water plug with subsequent recriticality.

In the following, after a brief presentation of the requirements in the regulations on the control of steam generator tube leaks, it is first explained (Section 3) which special aspects are to be taken into account with regard to steam generator tube leaks, which cases are treated as representative in the operating manual (BHB) of the plants and what sequences are considered for basic variants. Subsequently, the scenario outlined by EnBG and further analyses under conservative boundary conditions will be dealt with (Section 4).

2 Requirements of the applicable regulations

According to the “Safety Requirements for Nuclear Power Plants” (SiAnf), the failure of a steam generator tube corresponding to a leak cross-section up to a maximum of 2A is to be considered as an event of level of defence 3 (event D3-31 according to Annex 2 of the SiAnf) with regard to the fundamental safety functions K (fuel element cooling), B (confinement of radioactive materials) and S (compliance with radiological safety objectives).

Furthermore, according to event D3-19, Annex 2 of the SiAnf, the inadvertent injection from a system carrying unborated water or low-borated coolant in combination with a loss of function of the limitation system or other upstream measures (external boron dilution; homogeneous and heterogeneous) is to be considered, for this event with regard to the fundamental safety functions K (fuel element cooling) and R (reactivity control), in particular the feedwater injection during cooldown under loss of offsite power conditions after steam generator tube rupture.

3 Status: Concept for controlling a steam generator tube leak

The concept described below for the control of accidents involving steam generator tube leaks was presented to the Committee using a plant as an example, i.e. an up-to-date operating manual (BHB) for a pre-Konvoi plant. According to the Committee, this concept has been introduced uniformly for all pre-Konvoi and Konvoi plants, as well as the event variants dealt with in the BHB and the corresponding modes of plant operation. The Committee did not carry out any further reviews in this regard.

3.1 Introduction

A steam generator tube leak is a loss-of-coolant accident (LOCA) into the secondary circuit bypassing the containment, resulting in a connection to the atmosphere when main steam valves of the defective steam generator (SG) are opened. Therefore, fundamental safety function S (compliance with radiological safety objectives) and an accident management to be optimised in this respect are of primary importance.

Irrespective of this, the fundamental safety functions K (fuel element cooling) and R (reactivity control) are also affected since the steam generator tube leak is also a LOCA and has the potential for unborated water to enter the primary circuit from the secondary side.

Overall, the control of this scenario requires a more complex approach than for most other events.

Relevant for the potential of a large activity release (fundamental safety function S) is a persistent high pressure in the primary circuit, which leads to a high leak rate. This can be caused, for example, by the safety injection pumps or due to the unavailability of the reactor coolant pumps (RCPs). The accident procedures are thus aimed at limiting the decrease in the pressuriser level to such an extent that the actuation values of the reactor protection system for switching on the safety injection pumps are not reached and loss of offsite power as a result of the load reduction is avoided as far as possible.

Irrespective of the high pressure difference to the secondary side, the unavailability of the RCPs during cooldown can lead to stagnant natural circulation conditions and thus no cooling of the coolant in the affected loop, resulting in vaporisation with large volume expansion during the further pressure reduction in the primary circuit.

In order to fulfil the fundamental safety functions, the measures for controlling the event consist of an upstream part (i.e. effectiveness of the limitations before actuation of the reactor protection system), which primarily serves to minimise radiation exposure, and a part for “leak control”.

The upstream part contains differentiated automatic measures, the actuation of which is not realised in the reactor protection system, and was implemented in 4-train limitation systems in accordance with safety standard KTA 3501, which are of a higher quality than the instrumentation and control equipment for normal operation. Due to this high-quality design, it can be assumed that the availability of this equipment is highly reliable.

Due to the loss of coolant caused by the leakage, the leak control part (fundamental safety function K) consists of actuation of the emergency core cooling criteria with the start of the safety injection pumps and thus uses the measures provided by the reactor protection system for loss of coolant accidents. With the exception of the reactor scram, the main steam (MS) activity signal does not trigger any further protective actions by the reactor protection system. The injection capacity of just one pump is so large that the leakage will be reliably compensated.

Further accident control measures consist of approvals in the reactor protection system so that the safety injection pumps can be switched off manually during the accident sequence.

Fundamental safety function R is taken into account insofar as leakage make-up is always highly borated in all variants and in this way, the highest possible boron concentration is present in the primary circuit at the end of the automatic measures. In addition, the manual measures specified in the BHB aim to prevent the transfer of low-borated coolant from the secondary side of the defective steam generator to the primary circuit when the RCPs are not running. The measures prescribed in the BHB during the waiting period in case of failed RCPs also result in the water on the secondary side being borated due to the persistent leakage.

For a more detailed description of the accident control concept, Sections 3.3 and 3.4 describe the event sequences, including the main measures provided for in the BHB, which represent the realistic sequence without and with loss of offsite power for minimising the release of activity. Sections 3.5 and 3.6 describe the cases, including the measures in the BHB, where a fault (not defined in detail) leads to the emergency core cooling criteria being reached causing the safety injection pumps to start. Thus, the most unfavourable variants are considered, both for activity release and for core cooling. Section 3.7 describes an event sequence as it occurs when only safety systems are taken into account.

3.2 Structure of the BHB

As described under 3.1, both cases (failed RCPs or running safety injection pumps) lead to higher pressures in the primary circuit. For this reason, in addition to the expected realistic sequences with and without loss of offsite power, for which upstream automatic measures are provided, the cases with actuated safety injection, also with and without loss of offsite power, are also considered.

Four event-based sequence variants are therefore described in the BHB:

a. without loss of offsite power, without emergency core cooling criteria (most probable case),
b. with loss of offsite power, without emergency core cooling criteria,
c. without loss of offsite power, with emergency core cooling criteria,
d. with loss of offsite power, with emergency core cooling criteria.

The high-pressure (HP) safety injection is always considered in the BHB chapters in connection with the actuation of the emergency core cooling criteria.

Class S fault alarms exist to quickly identify the variant and refer to the relevant sequences:

- Class S fault alarm: SG tube leak I (MS activity > 20 Imp/s **and** pressure difference Cont./Atm. < 30 mbar -> BHB Case a),
- Class S fault alarm: SG tube leak II (MS activity > 20 Imp/s **and** pressure difference Cont./Atm. < 30 mbar **and** rotation speed ≥ 2 RCPs < 94%-> BHB Case b),
- Class S fault alarm: SG tube leak III (MS activity > 20 Imp/s **and** pressure difference Cont./Atm. < 30 mbar **and** actuation of emergency core cooling criteria-> BHB Case c/d) (not in the case of Konvoi plants since there is an automatic pump head limitation).

The SG tube leak I fault alarm always refers to a SG tube leak, regardless of the variant. SG tube leak II fault alarm is always actuated if at least 2 RCPs have failed, regardless of the other variants. Finally, SG tube leak III refers to the running HP safety injection pumps.

The reason for this selection of variants is that for these variants differentiated measures and limit values are provided as well as correspondingly different manual measures in order to comply with the minimisation principle regarding fundamental safety function S. In particular, this involves taking into account failed RCPs and actuated safety injection pumps, as described under 3.1. Other sequences do not lead to significantly different measures than the variants mentioned above.

In addition to these four variants, the BHB contains another chapter on the SG tube leak, which describes a sequence without automatic actuation when reaching the activity limits. In this case, especially in the case of leakage sizes that cannot be compensated by the injection of the volume control system, the activity signal can be set manually on the reactor protection panel. This triggers all automatic measures and alarms, insofar as they can still take effect, and all authorisations to carry out manual measures are given. The transition to one of the four BHB chapters described above takes place via the Class S fault alarms that are also triggered.

3.3 Event sequence without loss of offsite power, without safety injection (with upstream measures and with running reactor coolant pumps)

The failure of a steam generator tube (2A rupture) leads to a maximum leak mass flow to the secondary side of approx. 45 kg/s at full load. This results in the following sequence:

- Detection of the tube leak by diverse activity measurements (GM counter tubes and ionisation chambers) on the main steam line in the annulus by the reactor protection system.
- Automatic actuation of the 4-train limitation system with redundant and diverse upstream measures.
- Load reduction with 20%/min (boron injection and control rod insertion) to 30% power.
- This is followed by lowering the coolant pressure by pressuriser spraying. Spraying is carried out both via the operational spraying system and via the volume control system with emergency power backup and the extra borating system.
- In addition, to improve the spraying effectiveness and for coolant make-up, automatic start of the second pump of the volume control system and limitation of coolant extraction of the volume control system from the primary circuit also automatically down to the minimum quantity.
- Coolant make-up after the end of spraying by the volume control system with 2 pumps and reduced extraction quantity as well as by the extra borating system with 7,000 ppm boron concentration.

Reactor scram takes place either at a coolant pressure of 131 bar or 300 s after reaching the activity limits.

With these automatic measures, a stable plant state is achieved at a coolant pressure of approx. 90 bar and a secondary side pressure of 76 bar with the RCPs running.

During load reduction with 20%/min, the steam generator levels are automatically adjusted to a lower value by lowering set values and closing valves to create sufficient volume for taking up the leakage quantity transgressed from the primary side.

The interaction of the automatic measures was tested at each plant within the framework of their first start-up as a test from power operation.

After completion of the automatic measures mentioned above, the defective steam generator is manually isolated on the main steam and feedwater side of the secondary side in accordance with the specifications of the BHB so that further feeding of the defective SG is reliably prevented. In addition, the RCP in this loop is switched off and electrically disconnected. The further shutdown of the plant is then started manually.

Since the pressure in the defective and isolated steam generator remains almost constant, the coolant pressure drops below the secondary pressure during the cooldown. Secondary side water then flows from the defective steam generator to the primary side, where it mixes with the coolant flowing backwards in this circuit. The further flow path of the mixture of primary coolant and secondary side inflow runs via the upper plenum, a further forward-flowing loop, the reactor downcomer and the lower plenum. Along this path, the unborated water from the secondary circuit is largely mixed with the primary coolant so that there is no relevant reduction in the boron concentration when the coolant enters the reactor core.

The intact SGs are supplied by the start-up and shutdown pumps, which take hot feedwater from the feedwater tank. There is no further feed into the defective steam generator as it is isolated on the main steam and feedwater side.

Due to this shutdown mode, the water level in the defective SG drops and the SG tubes are being uncovered in the steam space. As a result of the cooldown, the entire primary coolant is cooled down, also in the defective steam generator due to the backward flow. As long as the heating tubes are covered with water, the secondary side pressure in the steam generator remains almost constant. If the level in the defective SG has decreased due to the leakage to the primary side such that the heating tubes are being uncovered in the steam space, the steam condenses on the cold U-tubes and the pressure in the steam generator decreases without steam having to be discharged. As a result, the pressures between the primary and secondary circuits equalise and the ingress of unborated water into the primary side is stopped. As a result, the level does not decrease any further and the emergency feedwater system is not challenged.

3.4 Event sequence with loss of offsite power, without safety injection pumps (with upstream measures, without running reactor coolant pumps)

In the event that in combination with the reactor scram / turbine trip a loss of offsite power occurs or the RCPs fail for other reasons, temperature difference across the reactor core rises by which the natural circulation is driven. The coolant with the higher temperature on the hot-leg side also flows directly under the reactor pressure vessel (RPV) closure head. As a result, the saturation pressure under the RPV closure head is already reached at a coolant pressure of approx. 100 bar. Further effective pressure reduction by spraying will then not be possible because the steam formation under the RPV closure head leads to a volume expansion and thus to a level increase in the pressuriser. When the level reaches 0.8 m above the automatically raised setpoint, which is regarded as an indication that the pressuriser level has reached saturation, spraying is switched off by the limitation system. The plant stabilises at a coolant pressure of approx. 90 to 100 bar and a secondary side pressure of 75 bar after partial cooldown under natural circulation conditions.

After isolation of the defective SG, the BHB requires leaving the plant in this state until the RCPs in the intact loops can be restarted. According to the BHB, the RCP in the loop with the defective SG will be deactivated also in this case. The permissible duration of this phase is limited by the available reserves of demineralised water, which are sufficient for injection over at least 10 hours. When the RCPs are available again, cooldown takes place as described in Section 3.3. In this case, the intact SGs are also supplied by the start-up and shut-down pumps from the feedwater tank. Feeding of the defective SG by the operational feedwater system is not necessary and also not possible, as it is isolated on the main steam and feedwater side as defined in the BHB. The emergency feedwater system will not be activated due to the water level in the defective SG.

During the phase with available demineralised water reserves, natural circulation continues in all loops, including the one with the isolated SG. The leakage to the secondary side – which decreases after isolation of the defective steam generator and the resulting pressure increase on the secondary side, but which is present in the defective SG until pressure equalisation – is made up by the injection of borated coolant from the volume control or extra borating system. This leads to the boration of both the entire primary circuit and the secondary side water in the defective SG.

To maintain the desired secondary- and primary-side pressure ratios as a result of pressuriser cooling due to heat losses, the load at the secondary side is to be reduced by a rate of 2 K/h as defined in the BHB. Natural circulation is also maintained in the loop with the defective SG.

If it is not possible to switch on the RCPs in the intact loops before reaching the minimum demineralised water inventory, the plant should be cooled down with 50 K/h under natural circulation conditions as defined in the BHB. Since the natural circulation in the loop with the defective SG will then stop, cooldown should be carried out according to the BHB in such a way that the main steam pressure in the defective steam generator is equalised to the coolant pressure by main steam relief via the warm-up line so that there is as little backflow as possible from the secondary side into the primary circuit.

The aim of this approach is to ensure that as little unborated water as possible can enter the undrained loop of the defective SG. If, however, backflow does occur, secondary water that has been borated from the primary circuit due to the long lasting leakage will flow to the primary side.

3.5 Event sequence without loss of offsite power, with safety injection (ineffectiveness of measures actuated by the limitation system)

If pressure reduction is postulated to be ineffective for the maximum tube leak to be postulated (equivalent to 2A), the pressuriser level drops due to the relatively high leakage such that a pressuriser level of < 2.28 m is reached. The reason for this is that the leakage cannot be compensated with the injection from the volume control system. As the level decreases, the pressure in the primary circuit also decreases. Reactor scram is triggered at a pressure of < 131 bar (if not already triggered by other criteria), and at < 110 bar and a pressuriser level of < 2.28 m, the emergency core cooling criteria are actuated, with starting of the safety injection. The pressuriser level limit also actuates switch-off of the RCPs and initiates the isolation of the primary circuit, which also results in the isolation of the volume control system.

The BHB defines that following the automatic measures, the pressuriser level should be raised by spraying with the extra borating system or the volume control system (after restart) and the safety injection pumps should be switched off manually. For this purpose, the emergency core cooling criteria can be partially reset on the reactor protection panel. In the case of the Konvoi plants, the head of the safety injection pumps is limited automatically so that they do not have to be switched off.

After resetting the remaining emergency core cooling signals and the primary circuit isolation and restarting the operational equipment, the RCPs in the intact SGs can be switched on again. All other measures and cooldown procedures are generally carried out as described in Section 3.3.

3.6 Event sequence with loss of offsite power, with safety injection (ineffectiveness of measures actuated by the limitation system, without running reactor coolant pumps)

If the loss of offsite power occurs additionally in a variant described in Section 3.5, the sequence essentially differs in that partial cooldown is actuated and steam is discharged to the atmosphere. As in Section 3.5, switching off the safety injection pumps has priority here too. This is followed by a plant state according to Section 3.4 with the related measures, such as reaching a stationary plant state in hot zero-power and the waiting phase until voltage recovery or cooldown under natural circulation conditions.

3.7 Event sequence without upstream measures, only with safety systems

In the case that all upstream measures from the limitation system are not taken into account, reactor scram through “activity high” remains as the first measure. The pressuriser level and the coolant pressure drop as a result of the leakage into the steam generator. At a pressuriser level of < 2.28 m, the emergency core cooling criteria are actuated. The safety injection pumps thereby started pressurise the primary circuit to almost the zero head of the safety injection pumps. In the case of also considering the loss of offsite power, this occurs with reactor scram / turbine trip.

The RCPs are also switched off when reaching the emergency core cooling criteria.

After 30 minute, according to the BHB, the pressuriser level should be raised by spraying into the pressuriser with the extra borating system and the safety injection pumps should be switched off manually if a level of more than 13.5 m is reached in the defective SG. The plant will then be stabilised to a state similar to the event sequence with failure of the RCPs described above (Section 3.4). Other manual measures are also provided for accordingly.

At Konvoi plants, in addition to the measures described above, an automatic limitation of the maximum pump head of the safety injection pumps is triggered by the reactor protection system when the level in an SG reaches > 15 m.

On the secondary side, the level in the intact SGs would drop to < 5 m in case of unavailability of the start-up and shutdown pumps. This would start the emergency feedwater system and these SGs would be refilled. Pressure adjustment of the isolated steam generator to the pressure of the primary side during cooldown is then carried out by the pilot valves of the MS isolation valve in accordance with the protection-goal-oriented part of the BHB to prevent the transfer of low-borated coolant from the isolated steam generator to the primary circuit and thus preventing the formation of an unborated water plug.

4 Worst-case analyses on scenarios with "steam generator tube leak" to determine an unborated water plug in the primary circuit with maximum reactivity supply when entering the core

4.1 Analysis on the EnBG scenario

To assess the safety-related effects of the event "Steam generator tube leak" under the assumptions made by EnBG, GRS carried out exemplary thermal-hydraulics analyses [2] and the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) reactor dynamics analyses [9] for one plant. The failures/operator errors were selected – in some cases going beyond the assumptions of EnBG – in such a way to reach maximum transfer of unborated water via the steam generator tube leak into the primary circuit at the lowest possible temperature and minimum boron concentration in the remaining regions of the primary circuit.

4.1.1 Analysis carried out by GRS

The analysis was carried out in accordance with EnBG's assumptions. In order to be able to carry out a concrete analysis for the EnBG scenario, additional boundary conditions had to be set and further unfavourable assumptions had to be selected for the worst-case consideration. The following points therefore contain both EnBG assumptions and additional GRS assumptions:

- Cold-leg side break of a steam generator tube above the tube sheet (most unfavourable leak position for formation of unborated water plug) directly at the start of the fuel cycle (highest requirement for boron concentration).
- Postulation of errors that lead to a primary-side pressure reduction beyond the target value in the initial phase of the event sequence and thus to a shutdown of the RCPs (due to incorrect operation of the spraying from the volume control system or several technical errors or due to drifting of 4 pressure measurements (CCF effect) in the limitation system).
- Postulation that the shift team, when deciding on the procedure of the BHB to be applied after automatic cooldown,
    - Case A: steam generator tube leak without loss of offsite power, without emergency core cooling criteria (RCPs available),

- Case B: steam generator tube leak with loss of offsite power, without emergency core cooling criteria (RCPs not available),

decides in favour of Case A despite RCPs are not running, even though

- the Class S fault alarm “SG tube leak II” indicates that the RCPs have failed while a steam generator tube leak has occurred, and
- the BHB requires cooldown to operational conditions of the residual heat removal system via intact SGs and 3 out of 4 RCPs.

- Postulation that, after the manually triggered secondary shutdown, the shift team recognises that no automatic pressure reduction is actuated in accordance with the characteristic curve for cooldown (due to the RCP failure), but then does not clarify the cause of this and manually reduces the pressure to the switchover conditions for the residual heat removal system.
- Postulation that the shift team not only reduces the pressure to 32 bar (target value for automatic shutdown in Case A), but far beyond that to 8.5 bar (assumption, so that the natural circulation is restarted in the analysis and thus the plug enters the RPV).
- Postulation that the shift team allows the level in the defective SGs to decrease so low as a result of failure to equalise pressure that the emergency feed starts automatically.
- Assumption that in the emergency core cooling and residual heat removal system, the safety injection pump in the train with the defective SGs is unavailable.

<u>Impact of the assumptions and postulations on the event sequence:</u>

Under the unfavourable boundary conditions mentioned above, the secondary side of the defective steam generator is initially cooled via the primary-side natural circulation after isolation. In the medium term, however, natural circulation will break off during cooldown with 50K/h since the pressure difference available to drive the natural circulation via the reactor pressure vessel is not sufficient to transport the coolant cooled by the intact steam generators via the U-tube bends of the defective steam generator.

If cooldown takes place according to Case A and the pressure reduction on the primary side is initiated manually and no pressure equalisation is carried out, a pressure difference occurs between the defective steam generator (pressure largely constant) and the primary circuit (pressure reduction) resulting in a backflow into the primary circuit, which leads to a pronounced level drop in the isolated steam generator, ultimately with actuation of the emergency feedwater system. As a result, the coolant on the secondary side of the isolated defective steam generator, which was borated by primary coolant via the leak at the start of the accident, is borated again via the emergency feedwater system. However, the injection also causes the secondary pressure in the defective steam generator to decrease due to condensation, thus reducing the leakage mass flow again.

The injection of the cold emergency feedwater leads to rapid condensation of the vapour in the tubes of the defective SG and thus to a pressuriser level drop to < 2.28 m. This results in primary circuit isolation with the volume control system being switched off, the emergency core cooling criteria being actuated and the safety injection being started (but no injection into the train with the defective SGs due to the assumed unavailability of the corresponding safety injection pump). Due to the safety injection capacity, the primary circuit is quickly filled up.

As a result of the backflow, a low-borated coolant plug forms in the cold leg of the isolated steam generator (assuming that the tube has broken on the cold side) since natural circulation has come to a standstill. Depending on the boundary conditions in the primary circuit, the low-borated coolant plug can now enter the reactor pressure vessel and reactor core via natural circulation. Natural circulation restarts when the driving pressure difference across the reactor pressure vessel becomes greater than the forces acting against the natural circulation in the defective steam generator and pump elbow. For restart of natural circulation, the primary pressure had to be reduced to 8.5 bar in the analysis.

Result of the GRS analysis with the postulated failures

The GRS analysis shows that, under the specified boundary conditions, a low-borated coolant plug of approx. 8 t (minimum boron concentration 88 ppm, average boron concentration approx. 440 ppm, density 3.0% lower than the density of the primary coolant) flows into the RPV downcomer with a mass flow of 100 kg/s and into the intact cooling circuits with mass flows of approx. 60 kg/s. The boron concentration in the primary circuit is 2,200 ppm. The GRS analyses using a point kinetics model yield a subcriticality of approx. 6% under the above conditions with ideal mixing in the downcomer and a coolant temperature of 135 °C.

4.1.2 Result of the HZDR's 3D analysis of the scenario dealt with by GRS

To validate the point kinetics analyses of GRS, the HZDR carried out transient 3D analyses on the reactivity effect when an unborated water plug determined according to 4.1.1 or [2] enters the reactor core [9]. The boundary conditions of plug size, coolant temperature in the core at entry, xenon concentration in the fuel corresponding to full load equilibrium conditions (i.e. without taking into account xenon build-up after reactor scram) and reactor scram with all control rods were adopted from [2]. The difference in the critical boron concentration between the core of the above-mentioned analysis and the one considered here was taken into account. An additional assumption in the sense of a worst-case analysis , however, was a boron concentration in the plug at entry into the RPV with 0 ppm (in 4.1.1 average boron concentration 440 ppm) and neglecting the increased B-10 enrichment in the extra borating tanks.[1]

The coupled 3D neutron kinetics/1D thermal-hydraulics analyses were carried out according to defined time-dependent boundary conditions of the boron concentration at the core inlet in each of the 193 fuel assemblies. These boron concentrations were determined on the basis of ROCOM experiments on the mixing under natural circulation conditions in all four loops using the plug size specified in [2], so that an inhomogeneous entry of differently borated coolant into the reactor core was modelled in accordance with the ROCOM test results. The ROCOM experiments on which the analyses were based were carried out with the same coolant density in all loops. The density difference of 3.0% in [2] could not be taken into account in this approach. A difference in density between the coolant from the different loops is in any case favourable for mixing and leads to further

[1] In the HZDR analysis, it was assumed that the B-10 enrichment of the coolant contained in the primary system when the plug enters the core is 30% for all proportions (primary water of power operation, injection via volume control system and extra borating system). In some plants, however, the B-10 enrichment of the coolant proportion injected by the extra borating system is 50%. Therefore, the overall boron worth of the coolant is also higher than with a value of 30%. If this would be taken into account in the HZDR analyses, the subcriticality would be higher than the calculated value.

boration of the low-borated plug that entered the reactor pressure vessel (see e.g. [14; 15]). For this reason, too, the results of the HZDR are to be regarded as a worst-case analysis.

These conditions led to a minimum subcriticality of 7.7% in the 3D core calculation.

4.1.3 Summary of the EnBG scenario

For the analysis of the EnBG scenario, covering boundary conditions were chosen that led to a maximisation of the size of the low-borated plug and to a minimisation of the boron concentration in the plug. By completely filling the cold leg in the cooling circuit of the defective steam generator with almost pure unborated water (as a result of injecting emergency feedwater into the defective steam generator), the maximum plug size confirmed in tests at the primary coolant loop test facility (Primärkreislauf-Versuchsanlage – PKL) was calculated.

In a 3D core calculation, the minimum subcriticality was calculated at 7.7%. In this calculation, the addition of negative reactivity as a result of the transient xenon build-up was neglected, just as the increased B-10 enrichment in the extra borating tanks. In addition, the mixing-promoting effect of the density difference between the plug water and the surrounding coolant was neglected.

4.2 Worst-case analysis only considering safety systems for boration

In another analysis [8], GRS examined a fictitious scenario under the boundary conditions that

- only safety systems are considered for boron injection (in the EnBG scenario also the injection of boron via the volume control system was considered),
- manual interventions are only carried out after 30 minutes and thereafter only manual interventions specified in the BHB, and
- no pressure equalisation is carried out between the defective SG and the primary circuit.

<u>GRS results</u>

In the first half hour after initiation of the steam generator tube leak, the reactor protection system starts the extra borating systems and the safety injection pumps, which inject borated coolant into the primary circuit. After half an hour, the manual measures defined in the BHB are initiated (supply to the primary circuit from the borating tank, switch-off of the safety injection pumps, isolation of the defective steam generator, lowering the pressure of the intact steam generators to 70 bar). During this time period of up to one hour after leak opening, approx. 80 t of borated coolant are injected into the primary circuit, and the primary circuit is borated to 1,550 ppm and the defective steam generator to approx. 1,000 ppm (boron concentration at full load and beginning of cycle (BOC): 1,150 ppm).

Further boration depends on the strategy used by the shift team to maintain the level in the pressuriser:

a. level maintenance by injection into the primary circuit with the extra borating system
b. level maintenance by pressuriser spraying with the extra borating system

As to a.):
In the analysis, it was assumed that the level is maintained by injection into the primary circuit with the extra borating system. With this strategy, the primary circuit is borated to approx. 2,000 ppm and the defective steam generator to approx. 1,600 ppm. When applying this strategy, it is not possible to reduce the pressure in the primary circuit to the switchover conditions of the residual heat removal system after cooldown via the intact steam generators.

Pressure reduction measures on the primary side could lead to a reduction in the fill level and supply via the emergency feedwater system in the defective steam generator. The break mass flow to the primary circuit would reduce the boron concentration in the primary coolant only insignificantly due to the already very high boron concentration in the defective steam generator. It is not to be expected that the concentration in the primary circuit and the reactor pressure vessel will fall below 1,800 ppm. In this case, the formation and transport of a less borated plug as in the previously considered scenario (Section 4.1) is to be expected.

As to b.):
For further boration of the primary circuit above the 1,550 ppm in the strategy of maintaining the pressuriser level at nominal value by pressuriser spraying, no mathematical analysis was carried out by GRS. Instead, the HZDR carried out a 3D criticality analysis with a boron concentration of 1,500 ppm (rounded down) in the primary cooling circuit.

HZDR results

A 3D core analysis was carried out for these conditions in the same manner as described in Section 4.1.2. Size and boron content of the postulated plug correspond to those from the analysis in Section 4.1. The minimum subcriticality for these conditions was calculated at 1.0%.

To assess the conservativeness of this value, a CFD (computational fluid dynamics) analysis of the mixing within the reactor pressure vessel was carried out at the HZDR under the above-mentioned boundary conditions, but taking into account the difference in density between the low-borated plug and the surrounding water. From this CFD analysis, as in a ROCOM experiment, time-dependent boundary conditions at the entry into each fuel assembly were extracted as boundary conditions for a 3D core analysis using the DYN3D computer code. With otherwise identical boundary conditions, this 3D core analysis results in a value of 4.9% for the minimum subcriticality. This difference to the above-mentioned value of 1.0% shows the conservativeness of the approach without taking the density difference into account.

5 Assessment by the Committee

Energiebüro Gorxheimertal (EnBG) and the Vienna Institute of Safety and Risk Sciences (ISR) submitted a number of statements and questions to the Committee on the event “Steam generator tube leak up to a maximum of 2A”. These relate to the occurrence of the event, its handling in the operating manual (BHB), various event sequence variants and the control of the event with regard to the entry of unborated water into the reactor core. In this Section 5, the Committee assesses the following three aspects, which it considers to be essential:

- Frequency of occurrence of 2A steam generator tube rupture
- Descriptions of event handling in the operating manual (BHB)
- Control of the event with regard to the entry of unborated water into the reactor core

5.1 Frequency of occurrence of a 2A steam generator tube rupture

In the past, steam generator tube degradation occurred in particular with heating tubes made of Inconel 600. In German PWR plants, only the material Incoloy 800 is used, which is considered to be significantly more corrosion resistant. In addition, the restrictive approach in Germany, which provides for very early plugging of the tubes in the event of degradation due to corrosive attacks, is to be taken into account. The determination of the frequency of occurrence of a 2A steam generator tube rupture in German PWRs is therefore not to be based on worldwide experience, but on experience specific to German steam generators. Since no 2A rupture has occurred in German PWRs to date, the expected value for the frequency of occurrence based on zero-failure statistics is approx. $1.5 \cdot 10^{-3}$/a, which was used in the probabilistic safety analyses (PSAs) as part of the periodic safety reviews. Taking into account the plugging strategy practised for defective steam generator tubes, the water chemistry and testing strategy, a significantly lower value is actually to be expected (see also RSK statement from the 447th meeting [12]).

For the small leak on the primary circuit with 2-25 cm², a comparable frequency of occurrence of $1.4 \cdot 10^{-3}$/a is assumed in the PSA. EnBG's assumption that there is an increasing probability of tube leaks so that these are more likely than any other small leak in the primary circuit is therefore incorrect according to the current state of knowledge for German PWRs.

5.2 Descriptions of event handling in the operating manual (BHB)

The following statements are based on an exemplary event-based BHB presented to the Committee.

The event-based BHB has the task of providing the shift team with instructions on how to proceed to control an event that has occurred for a representative sequence. In the event of a steam generator tube leak, leakage of the contaminated coolant must first be prevented or limited by isolating the defective steam generator and heat removal be ensured via the intact steam generators. The load must then be reduced to the switchover conditions of the residual heat removal systems and residual heat removal be ensured.

The occurrence of an event is indicated to the shift team via Class S fault alarms and other displays at the control room. Based on this information, the shift team must identify the corresponding chapter in the event-based BHB and proceed accordingly.

Due to the Class S fault alarms, the chapter relating to SG tube leak with response of the MS activity measuring points is to be referred to for steam generator tube leaks. Various operating sequences are provided in case of additional alarms “SG tube leak I to III”, which depend on the boundary conditions of the steam generator tube leak that has occurred.

Four sequences are described in the event-based part of the BHB on which the Committee’s consultations were based:

a. without loss of offsite power, without safety injection
b. with loss of offsite power, without safety injection
c. without loss of offsite power, with safety injection
d. with loss of offsite power, with safety injection

This describes four representative variants that differ in terms of certain effects that are essential for event control. Together with the protection-goal-oriented approach, these four variants provide a framework for event control. Against this background, the Committee is of the opinion that the four variants defined in the event-based part of the BHB are appropriate.

However, as with all the event sequences described in the event-based BHB, there is the fundamental problem that deviations from the described sequences can occur. This is the case, for example, if additional functional failures are postulated (e.g. unavailability of limiting measures in the initial phase of an SG tube rupture). In these cases, the shift personnel must select and implement appropriate measures on the basis of the available information, taking into account the protection-goal-oriented approach defined in the BHB. The Committee is of the opinion that the determinations made in the written operating rules are suitable for event control.

5.3 Control of the event with regard to the entry of unborated water into the reactor core

The Committee did not refer to plant-specific analyses within the framework of its consultations on the assessment of the potential for the formation of an unborated water plug with subsequent recriticality following a 2A steam generator tube rupture. The Committee rather pursues the approach of carrying out an exemplary analysis under worst-case boundary conditions on the basis of basic considerations on the technical processes [16], exemplary thermal-hydraulics analyses carried out by GRS [2], [8] and neutron kinetics 3D core calculations carried out by the HZDR [9] (see sections 4.1 and 4.2). The aim of this approach is that the decisive boundary conditions are estimated sufficiently enveloping, taking into account physical-technical conditions, such that no less favourable results have to be postulated under the analysis conditions to be assumed for an event of level of defence 3.

This analysis under worst-case boundary conditions essentially comprises the following four conditions:

1. Determining the size and boron content of an unborated water plug to be used:
   The size and boron content of an unborated water plug to be used is determined on the basis of the GRS analyses described in Section 4.1. This results in a plug size which, taking into account the existing thermal-hydraulic boundary conditions, approximately corresponds to the maximum geometric possibility (approx. 8 t)[2] due to the conditions in the pump elbow and cold leg, with a minimum boron concentration of approx. 100 ppm. The average boron concentration when entering the reactor pressure vessel is approx. 440 ppm.

   The Committee holds the view that, in the case of such an analysis under worst-case boundary conditions, detailed considerations of possible variations in the event sequence (e.g. with regard to variations in operator errors or system unavailability or time of occurrence) are not necessary regarding the determination of the size and boron content of an unborated water plug to be applied.

2. Determining the boron content in the primary system:
   The boron content in the primary system is determined by exclusively crediting the boration by safety systems on the basis of a simple mass balance in accordance with [16]. In the sense of the analysis under worst-case boundary conditions, it is postulated that a total of approx. 67 t of borated coolant are injected by safety injection pumps and extra borating pumps. These are made up of:

   - 60 t from the flooding tanks with 2,200 ppm and 30% B-10 content. This corresponds to the mass injected as given by the technical processes up to the isolation of the steam generator (postulating 30 minutes after start of the event).
   - approx. 7 t of coolant from the extra borating tanks with 7,000 ppm and 50% B-10 content. This corresponds to a share of approx. 30% of the total minimum inventory in the extra borating tanks of 4x6 t = 24 t. By limiting the injection from the borating tanks, the potential for boration of the plug by the surrounding coolant and the margin to criticality is minimised.

[2] The pump elbow and cold leg including the RCPs comprise around 12 m^3 and the SG outlet plenum around 6 m^3. This results in a maximum volume of up to 18 m^3 for a maximum unborated water plug. Since the SG outlet plenum is only partially filled during the formation of the unborated water plug (confirmed by PKL tests), this volume is reduced to approx. 14 m^3. The low-borated plug of about 8 t determined in [2] (see Fig. 7 therein) has a volume of 9 m^3 when taking into account the density. The reduction of the plug size from approx. 14 m^3 to 9 m^3 results from a partial flow-off of the low-borated plug to the secondary side of the defective SG when it is pushed past the break location twice (when refilling the U-tubes and when natural circulation starts, also confirmed by PKL tests) and the formation of flatter flanks during the time-delayed start-up of the natural circulation in the individual U-tubes and the flow of the plug through the SG outlet plenum (also confirmed by PKL tests).

3. Mixing of the unborated water plug until it reaches the reactor core:
   The mixing of the plug on its way to the reactor core is carried out using the covering boundary conditions experimentally determined at the ROCOM test facility. Covering with regard to the resulting distribution of the boron concentration at the core inlet are: neglecting the initial boron concentration in the plug by setting this value to 0 ppm and not taking into account the difference in density between the plug and the surrounding water. Both effects lead to lower boron concentrations at the core inlet, whereby the difference in density has a much stronger influence. The latter is due to the fact that if there is an initial difference in density, the mixing of the unborated plug on the way to the core inlet leads to a significantly greater reduction of the perturbation. From the Committee's point of view, the application of this approach is suitable for the intended analysis under worst-case boundary conditions.

4. Reactivity effect when the low-borated coolant enters the reactor core:
   For the maximised unborated water plug mentioned above (see 1.), its three-dimensionally modelled mixing-up until core entry on the basis of the most unfavourably selected ROCOM test results (see 3.) and a minimised boron concentration in the reactor core when low-borated coolant enters (see 2.), the 3D reactor dynamics calculations carried out by the HZDR with the DYN3D calculation code for an exemplary reactor core (for the most unfavourable cycle time (BOC reactivity state of the reactor core), neglecting the transiently favourable xenon build-up and a coolant temperature of 140 °C) [9] show a minimum subcriticality of 1%.

Overall, from the Committee's point of view, it can therefore be concluded that with the described analysis under worst-case boundary conditions sufficient margin to criticality will remain.

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