Note:
This is a translation of the RSK statement entitled "Empfehlungen zur maximalen zulässigen kritischen Borkonzentration zur Sicherstellung der Unterkritikalität nach „Reflux-Condenser-Betrieb" beim kleinen Leckstörfall".
In case of discrepancies between the English translation and the German original, the original shall prevail.

RSK Statement
(446th meeting on 05 April 2012)

Recommendations on the maximum permissible critical boron concentration to ensure subcriticality after operation in "reflux condenser mode" during a small-break loss-of-coolant accident

1 Cause of the discussion

The discussions among the PLANT AND SYSTEMS ENGINEERING Committee about maximum permissible critical boron concentrations on the basis of postulated boron dilution accidents with reflux condenser mode, which lasted for a longer period of time, were caused by the letter AG RS I4 of 11 July 2000 [1] in which the BMU asked the RSK to discuss the draft status report by GRS on the topic of "Prevention and control of inadvertent criticality or reactivity addition" [2].

In [3], the state of knowledge in 2003 was summarised. This document was used in the licensing and supervisory procedures that followed. The recent discussions were caused by new experiment results obtained at the Rossendorf research centre. They generated the need to review whether the statements made in the year 2003 continue to be valid.

2 Course of discussions

Upon the advisory request by the BMU, the PLANT AND SYSTEMS ENGINEERING Committee began discussing the topic of "Prevention and control of inadvertent criticality or reactivity addition" at its 6th meeting on 19 October 2000, thereby continuing the discussion that had been going on among the RSK Committee on LIGHT WATER REACTORS (for the last time at its 155th meeting on 30 September 1998) [4-9]. At its 9th meeting on 16 February 2001, the PLANT AND SYSTEMS ENGINEERING Committee heard reports by GRS, the utilities and the authorised expert TÜV Süddeutschland on the state of the analyses regarding small breaks [10-16]. At its 13th meeting on 15 November 2001, the Committee dealt with the state of the analysis regarding operation in reflux condenser mode during a small-break loss-of-coolant accident [17].

At its 9th meeting on 16 February 2001, due to the different presentations by GRS and the utilities, the Committee saw a need for clarification in connection with the reliability of the quantification of mixing processes and with the reverse flow of the HP injection presented by GRS. The Committee supported the proposal by GRS to carry out mixing experiments at the Rossendorf research centre.

At its 13th meeting on 15 November 2001, the PLANT AND SYSTEMS ENGINEERING Committee came to the conclusion that especially with regard to boration in the lower plenum, there was still a need for clarification due to the differences in opinion between GRS on the one hand and utilities and vendors on the other.

In a joint statement of 15 September 2003 on “Boron dilution in reflux condenser mode”, GRS and the Technical Inspection Agencies (TÜVs) summarised the state of their knowledge on the problem. According to this statement, it could be seen as assured at that time that in LOCAs with reflux condenser mode, the boron concentration at the core inlet would not sink below 800 ppm (plants with preferred cold-leg path for safety injection) and 850 ppm (preferred hot-leg path), respectively. It was recommended to apply the mentioned values for the definition of the so-called critical maximum boron concentration. Regarding the critical maximum boron concentration, it has to be shown as part of the core design that the reactor core will still remain subcritical under the assumption of a homogeneous boron distribution in the coolant as well as under the demonstration boundary conditions of a LOCA with reflux condenser mode. This ensures that there will be no recriticality during a LOCA with reflux condenser mode. Cores that require a higher boron concentration than the values mentioned above in order to maintain subcriticality should be examined case by case according to [3].

At the 21st meeting of the Committee on 15 October 2003, GRS reported on the state of the verification procedure regarding subcriticality during accidents with internal deboration [18]. At this meeting, the utilities reported on their method to clarify the “Boron dilution in reflux condenser mode during a small-break loss-of-coolant accident” issue [19, 20].

In current licensing and supervisory practice, the boron concentration value of 850 ppm is applied as a basic value in the safety demonstrations, following a corresponding definition by the BMU at the 41st meeting of the FARS on 22/23 October 2003. In the meantime, on the basis of experiments that were carried out after the GRS/TÜV statement was issued in 2003 [3], higher critical boron concentrations have been approved for several plants within the framework of the demanded case-by-case examinations.

In continuation of their presentation at the 21st meeting of the Committee on 15 October 2003, the utilities reported at the 39th meeting of the Committee on 08 May 2006 about the results of Series F of the PKL III test series on the reflux condenser problem as well as about ROCOM test results with the aim to determine the boration i. a. with the aim to verify the analyses carried out so far regarding the LOBI/GRS scenario that were also carried out to clarify issues that from the point of view of GRS had still been unresolved [21]. The utilities furthermore presented the results of the mixing experiments regarding the cold-leg break/cold-leg injection scenario. GRS supplemented the remarks made at the 21st meeting of the Committee on 15 October

2003 and reacted to the assessment of the ROCOM-, PKL III F1.2- and F1.4 experiments that had in the meantime been carried out by the utilities [22].

At its 40th meeting on 13 June 2006, the Committee stated its intention to continue its discussion of boron dilution scenarios and their safety significance once the information yet to be provided by GRS at the time [23] had been evaluated and following a meeting between GRS and the utilities to clarify unresolved issues. The Committee revisited the topic at its 64th meeting on 22 April 2010. At its 75th meeting on 24 November 2011, it heard a report by the utilities on boron dilution during reflux condenser mode [24] and concluded the discussion concerning this matter at its 77th meeting on 26 January 2012 with the preparation of a statement. The RSK discussed and adopted this statement at its 446th meeting on 05 April 2012.

3 Technical situation

In a PWR, reactivity control is achieved by the joint effects of the boron concentration in the coolant and the motion of the control rods. In operation, the boron serves for the compensation of the excess reactivity in the core. In hot operating condition (290 °C to 300 °C), there are no control rods in the core at the start of the cycle and the reactor is critical at a boron concentration of 1100 - 1300 ppm. Subcriticality is achieved by the control rods dropping into the core. If the operating temperature is maintained and the boron concentration is steadily reduced, the reactor will go critical again at a boron concentration of about 600 ppm even if the control rods are inserted.

If a small leak occurs in the primary system, there may be a decrease in the boron concentration in parts of the coolant during the course of the accident. This is the case if due to the reduction of the primary system inventory there is a sudden interruption in the single-phase natural circulation. Within a break spectrum of approx. 10 – 70 cm^2, part of the decay heat output will be removed through partial evaporation of the coolant in the core and through condensation of the steam in the steam generator tubes (reflux condenser mode). While the condensate forming in the rising u-tubes can flow back into the upper plenum of the reactor pressure vessel via the hot leg of the reactor coolant lines, the condensate forming in the falling u-tubes will flow into the steam generator outlet chambers and into the pump suction lines. After the refilling of the primary system and the renewed start of natural circulation, this low-borated coolant can reach into the reactor core.

In the case of breaks < 10 cm^2, there is a constant one-phase natural circulation flow; with breaks > 70 cm^2, the secondary system does not contribute to heat removal. In both cases, there is thus no formation and accumulation of low-borated coolant.

On the basis of this scenario, analyses were carried out for the following four combinations of break positions and emergency cooling injection location [27]:

- hot-leg break/hot-leg injection
- hot-leg break/cold-leg injection

- cold-leg break/hot-leg injection
- cold-leg break/cold-leg injection

It follows from the analyses that for plants with preferred cold-leg path for safety injection, the cold-leg break is the leading scenario when it comes to the amount of accumulated condensate and the ensuing minimum boron concentration at the core inlet. However, within the framework of the statement in hand, plants with preferred cold-leg path for safety injection are not considered any further as these plants are no longer in power operation.

For plants with preferred hot-leg path for safety injection, the largest amounts of low-borated coolant will form in the case of a hot-leg break. Here, however, two different scenarios have to be looked at, a) with a sudden interruption in natural circulation in all coolant loops and b) with natural circulation continuing in the two injected loops with a sudden interruption in natural circulation occurring in the other two loops. Both scenarios were studied in the different PKL experiments. In these experiments it turned out that there will be an early carryover of high-borated water via short steam generator u-tubes during the refilling process and that additionally a certain boration will occur in the pump suction line before the restart of natural circulation. Moreover, a limitation of the plug size was found. In the loops that were not injected, natural circulation set in with a delay and at lower start-up rates.

The result of the PKL experiment with a sudden interruption in natural circulation in all loops was a minimum boron concentration of approx. 1600 ppm at the RPV inlet prior to mixing in the downcomer [24].

The scenario in which natural circulation is maintained in the injected loops is restricted to a narrow break spectrum around 35 cm^2. It was first described by GRS on the basis of ATHLET calculations and referred to as “LOBI scenario” [26]. Due to the adverse conditions for coolant mixing within the reactor pressure vessel after the restart of natural circulation in the loops that are not injected, this is the leading scenario with regard to the minimum boron concentration occurring at the core inlet.

In further studies towards the clarification of unresolved issues regarding the size of demineralised-coolant plugs and with respect to mixing processes, the utilities have assumed the most adverse conditions of the LOBI scenario regarding boron for reasons of conservativeness, even though this scenario is considered by the utilities as not typical of this kind of reactor. According to the utilities, the ROCOM experiments carried out in this context were performed under conservative boundary conditions regarding a minimum boron concentration at the core inlet. The minimum concentration that resulted from the ROCOM experiments under boundary conditions that were derived from the PKL experiments was a local minimum value of 1200 ppm boron at the core inlet. This concentration was observed only for a short period of time and only in individual fuel element positions in the outer area of the core inlet level. Further ROCOM experiments in which the boundary conditions were derived from an ATHLET analysis of GRS showed a minimum boron concentration of 1280 ppm (again in the outer area of the core inlet level) and thus confirmed the minimum boron concentration of 1200 ppm [24]. This ATHLET calculation had resulted in higher starting mass flows and a greater density difference, which were used as boundary conditions for the above-mentioned ROCOM experiments [26].

In contrast to the utilities, GRS sees the LOBI scenario as typical of this reactor type, albeit at a limited load spectrum. For this reason, the assessment by GRS of the safety margin of the LOBI scenario is different. From the point of view of GRS, the verification process for this scenario has to be on the basis of assumptions for design basis accidents of level of defence 3 [25].

GRS furthermore explained that

- if there was a critical boron concentration near (only) one bundle at the core inlet, subcriticality was high from the points of view of the utilities and GRS.

- GRS as well as the utilities confirmed that recriticality could be controlled even under conservative boundary conditions.

From the point of view of GRS, the limit value to be applied for the maximum critical boron concentration in the LOBI scenario is 1100 ppm if the variance of different ROCOM experiments is applied or 1200 ppm boron if sufficient subcriticality can be demonstrated at a local boron concentration of 1100 ppm boron at the core inlet.

Neutron-kinetic/thermal hydraulic analyses of the deboration event showed that whenever the low-borated coolant amount entered the core, there was always a minimum shutdown reactivity of 9 % (e.g. [28]), even though for a short while the boron concentration fell short of 1100 ppm upon entry into individual fuel elements in these ATHLET analyses of GRS.

4 Conclusion

The boron concentration values mentioned in the following refer to coolant temperatures under LOCA conditions. The verifications regarding reflux condenser mode for the scenario of hot-leg injection/hot-leg break are currently based on a value of 850 ppm boron for the maximum critical boron concentration [3].

From the point of view of the RSK, this value has to be considered as very conservative due to the analysis results that have been presented.

From the point of view of the RSK, based on the established state of knowledge, a value of 1200 ppm can be applied as the limit for the maximum critical boron concentration for plants with preferred hot-leg path for emergency injection.

5 Documents

[1] Beratungsauftrag des BMU- Schreiben AG RS I 4 vom 11.07.2000

[2] Vermeidung und Beherrschung von unbeabsichtigter Kritikalität oder Reaktivitätszufuhr
GRS, Statusbericht- ENTWURF, 6. AST-Sitzung am 19.10.2000

[3] TÜV Hannover/Sachsen.Anhalt e.V., 17.09.2003
Gemeinsame Stellungnahme von GRS und TÜV

[4] Vermeidung und Beherrschung von unbeabsichtigter Kritikalität oder Reaktivitätszufuhr
6. Sitzung des RSK-Ausschusses Anlagen- und Systemtechnik
Folienkopien, 6. AST-Sitzung am 19.10.2000

[5] Vermeidung und Beherrschung von unbeabsichtigter Kritikalität oder Reaktivitätszufuhr
Deborierungspotential nach dem Ausfall der Nachwärmeabfuhr bei Mitte-Loop-Betrieb
W. Pointner, GRS, Folienkopien, 6. AST-Sitzung am 19.10.2000

[6] Vermeidung und Beherrschung von unbeabsichtigter Kritikalität oder Reaktivitätszufuhr
Entborierungs-Vorgänge im ´Reflux-Condenser´ Betrieb und Wiederanlaufen des Naturumlaufes bei kleinen Lecks
B. Pütter, GRS, Folienkopien, 6. AST-Sitzung am 19.10.2000

[7] Vermeidung und Beherrschung von unbeabsichtigter Kritikalität oder Reaktivitätszufuhr
Thermohydraulische Phänomene im Zusammenhang mit Deborierung
H.G. Sonnenburg, GRS, Folienkopien, 6. AST-Sitzung am 19.10.2000

[8] Vermeidung und Beherrschung von unbeabsichtigter Kritikalität oder Reaktivitätszufuhr
Zur Reaktivitätsbilanz von Deborierungsstörfällen
S. Langenbuch, GRS, Folienkopien, 6. AST-Sitzung am 19.10.2000

[9] Vermeidung und Beherrschung von unbeabsichtigter Kritikalität oder Reaktivitätszufuhr
Deborierungen durch Einbringen von Deionat bei Nicht-Leistungsbetrieb
D. Müller-Ecker, GRS, Folienkopien, 6. AST-Sitzung am 19.10.2000

[10] Bericht der GRS
Analysen von Deborierungs-Ereignissen
GRS, Folienkopien, 9. AST-Sitzung am 16.02.2001

[11] Analysen von Deborierungsereignissen
Neutronenkinetik
S. Langenbuch, K.-D. Schmidt, K. Velkov
GRS, Folienkopien, 9. AST-Sitzung am 16.02.2001

[12] Analyse von Deborierungs-Ereignissen
– Thermohydraulische Untersuchungen –
G. Herbold, W. Pointner, B. Pütter, H.G. Sonneburg
GRS, Folienkopien, 9. AST-Sitzung am 16.02.2001

[13] Analysen von Deborierungsereignissen
Stand der Arbeiten und Ausblick
GRS, Folienkopien, 9. AST-Sitzung am 16.02.2001

[14] Untersuchungen zum kleinen Leck mit „Reflux-Condenser-Mode“
G. Sgarz, H. Hertlein
E.ON Kernkraft, Folienkopien, 9. AST-Sitzung am 16.02.2001

[15] Minimale Borkonzentration am Kerneintritt nach unterstelltem kleinen Leck
R. Hertlein, FRAMATOME ANP, NDS1, Folienkopien, 9. AST-Sitzung am 16.02.2001

[16] Stand der Begutachtung zu Störfällen mit lokaler Borverdünnung im Primärkreislauf einer DWR-Anlage
TÜV Süddeutschland, Folienkopien, 9. AST-Sitzung am 16.02.2001

[17] Stand der Analysen zur Deborierung bei kleinen Lecks
Bewertung der Annahmen und Ergebnisse des Betreibers und begleitende Untersuchungen der GRS
W. Pointner, H.-G. Sonnenburg
Bonn, 15. November 2001, GRS, Folienkopien, 13. AST-Sitzung am 15.11.2001

[18] Stand der Nachweisführung zur Unterkritikalität bei Störfällen mit interner Deborierung
W. Pointner, GRS, 15. Oktober 2003, Folienkopien, 21. AST-Sitzung am 15.10.2003

[19] Vorgehen der Betreiber zur Klärung der Thematik „Borverdünnung durch Reflux-Condenser-Betrieb beim kleinen Leck“
R. Wohlstein, E.ON Kernkraft Zentrale, Folienkopien, 21. AST-Sitzung am 15.10.2003

[20] Minimale Borkonzentration am Kerneintritt bei kleinem Leck mit „Reflux-Condenser“-Betrieb unter Berücksichtigung von PK III- und ROCOM-Versuchsergebnissen
R. Hertlein, Framatome ANP NGPS1, Erlangen, Folienkopien, 21. AST-Sitzung am 15.10.2003

[21] Deborierung
38. Sitzung des RSK-Ausschusses Anlagen und Systemtechnik am 08.05.2006
EnBW ZS/Schwarz 02.05.2006, Folien, 39. AST-Sitzung am 08.05.2006

[22] Nachweisführung zur Unterkritikalität bei Störfällen mit interner Deborierung
W. Pointner, GRS, 38. Sitzung des RSK-Ausschusses Anlagen und Systemtechnik, Bonn, 8. Mai 2006, Folien, 39. AST-Sitzung am 08.05.2006

[23] Bewertung der Randbedingungen des Versuchs PKL III E2.3
GRS, Mai 2006, 40. AST-Sitzung am 13.06.2006

[24] Deborierung
Borverdünnung bei Reflux-Condenser-Betrieb in Anlagen mit vorrangig heißseitiger Einspeisung
VGB PowerTech, Präsentation, 75. AST-Sitzung am 24.11.2011

[25] GRS-Anmerkungen zur Borverdünnung bei REFLUX-Condenser-Betrieb in Anlagen mit vorrangig heißseitiger Einspeisung
W. Pointner, GRS, Präsentation, 75. AST-Sitzung am 24.11.2011

[26] M. Burwell, W. Pointner, “ATHLET-Analysen zur Ermittlung der minimalen Borkonzentration bei kleinen Lecks im Primärkreislauf“, TN-BUR-02-1, GRS 2002

[27] R. Wohlstein, W. Pointner, „Auslösende Ereignisse und Ablaufszenarien bei Borverdünnungstransienten“, Jahrestagung Kerntechnik 2003, Fachsitzung: „Experimentelle und theoretische Untersuchungen zu Borverdünnungstransienten in DWR“

[28] P. Dräger et al., “Ermittlung des Standes von Wissenschaft und Technik bei der Durchführung und Bewertung von Störfallanalysen und der Verwendung von Analysesimulatoren“, GRS-A-3635, GRS 2011