Note:
This is a translation of the RSK Recommendation entitled
“Zulässigkeit von Prüf- und Instandhaltungstätigkeiten sowie Festlegung von Maßnahmen zur Ereignisbeherrschung bei Mitte-Loop-Betrieb”
In case of discrepancies between the English translation and the German original, the original shall prevail.

RSK Recommendation
(510th RSK meeting of the Reactor Safety Commission (RSK) on 05 June 2019)

Permissibility of inspection and maintenance activities and determination of measures for event control in mid-loop operation
RECOMMENDATION

1 Introduction (cause, objectives)

Discussions of the reportable event (*Meldepflichtiges Ereignis* - ME) 15/034 "Excitation of a reactor protection signal during the steam generator pressure test" of 20 June 2015 at the KKP-2 plant [1] among the RSK Committee on REACTOR OPERATION (*REAKTORBETRIEB* - RB) and among the RSK had raised the question of what kind of work should be avoided during mid-loop operation. On this basis, the RSK requested the RSK’s RB Committee at its 486th meeting on 21 September 2016 to prepare a statement on this topic.

In addition, questions arose in connection with the so-called extended safety review (*erweiterte Sicherheitsüberprüfung* - eSÜ) in Baden-Württemberg [2] regarding the event D3-13 "Failure of an operating train of the residual-heat removal system (RHR)" in various phases of low-power and shutdown operation (LP&S), as dealt with in Appendix 2 of the Safety Requirements for Nuclear Power Plants (*Sicherheitsanforderungen an Kernkraftwerke* - SiAnf) [3]. In this respect, the RSK Committee on PLANT AND SYSTEMS ENGINEERING (*ANLAGEN- UND SYSTEMTECHNIK* - AST) had specifically discussed the so-called Diablo Canyon scenario at its 118th meeting on 23 June 2016 [4a/4b/4c]. Thereupon, the AST Committee had asked the RB Committee for advice on the question of whether adequate regulations in this respect existed in the operating regulations or whether they needed to be added.

Within the framework of its discussions on the topic of "Inspection and maintenance activities in mid-loop operation", the RSK concentrated its focus on the specifications in the operating manual (*Betriebshandbuch* – BHB) regarding

- minimisation of the occurrence frequency of "loss of residual-heat removal" events in operating phases C and D (according to the phase definitions of the "Safety Requirements for Nuclear Power Plants"),
- procedures to control "loss of residual-heat removal" events in operating phases C and D, and
- minimum availability of systems/components to control the above events in low-power and shutdown operation (LP&S)

and asked the licensees for a corresponding report [5a/5b]. These reports were to include descriptions of how the results of GRS investigations on LP&S operation and of experiments performed at the RCS test facility, especially in connection with postulated events in mid-loop operation, are implemented and what general processes for the generic evaluation of research results for the improvement of plant operation are established. The licensee's approach

- to reduce the probability of occurrence of events leading to the loss of residual-heat removal in case of a reduced coolant inventory (mid-loop states), and
- to control such events

was also to be presented in this context.

2 Course of discussions

At the 247th RB Committee meeting on 15 December 2016, GRS had first reported on national and international operating experience in connection with events involving the loss or disruption of residual-heat removal in LP&S operation and on the currently existing requirements in the operating manuals of the German PWR plants in power operation for the minimum availability of the safety systems during the different plant operating states [6a/6b/6c]. Regarding the latter aspect, on the basis of the documents evaluated by GRS, sometimes significant differences were found with regard to the availability requirements existing in the individual plants for the respective trains of the residual-heat removal and emergency core cooling pumps, the accumulators, and the steam generators.

At the 258th RB Committee meeting on 15 March 2018, Framatome reported on the results of RCS tests with a focus on mid-loop operation [7]. Various relevant scenarios and primary system configurations (reactor coolant system (RCS) pressure-tight or not, hot-leg or cold-leg openings in the RCS) were dealt with.

At the 264th RB Committee meeting on 13 February 2019, VGB Powertech e. V. (VGB) reported on the handling of operation-relevant research results as well as on the development and implementation of a concept to avoid a loss of residual-heat removal in mid-loop operation and on how to control such a loss [8a/8b]. The RB Committee adopted the Statement at its 265th meeting on 09 May 2019; the RSK adopted the Statement at its 510th meeting on 05 June 2019.

3 Background

Regarding the monitoring and evaluation of operation-relevant findings and research results, the licensees state in [8a] that the German plants are subject to officially specified as well as their own, self-imposed requirements. New insights and research results are also evaluated and assessed on a higher level with the involvement of the plant manufacturer and coordinated by VGB. In this context, the following focal points are considered in particular:

- applicability assessment of the relevance of special events,

- early detection of weak points (administrative/in view of systems engineering),
- improvement of operational boundary conditions (administrative/in view of systems engineering) und
- recognition of special issues.

Regarding the possible loss of residual-heat removal during LP&S states, the licensees show that numerous RCS experiments have been carried out in the last ten years in co-operative efforts by manufacturers, research institutes/expert organisations and licensees to verify measures in connection with the handling of anticipated operational occurrences in the event of a loss of residual-heat removal in LP&S operation. Starting from plant states with a lowered RCS level, the effectiveness of various measures for coolant injection has been investigated.

As a result, the licensees conclude that processes for

- the plant-specific as well as generic evaluation of research results and
- an assessment of new insights from the checking of the applicability of events

with the aim to improve the level of safety of the plants are established and effective in German nuclear power plants.

Especially with regard to events in the LP&S operation, the licensees describe in [8a] the further development of the state of knowledge since the year 2000, taking into account

- GRS reports on the prevention and control of events in LP&S operation,
- updated or new requirements of the regulations (KTA Safety Standards, SiAnf), and
- results of RCS experiments relating to LP&S operation.

Starting from this further development of the state of knowledge, the licensees state that a basic concept for the control of events in LP&S operation was initially developed in the years 2000 to 2009, based i. a. on findings from the Probabilistic Safety Analysis (PSA) [9] of LP&S operation. They claim that in the period from 2010 to 2012, an assessment was carried out of new requirements and findings on the control of events during LP&S operation which had resulted from the SiAnf, KTA Safety Standards, GRS reports on the LP&S operation and RCL experiments. From this, a proposal was derived for the reorganisation/supplementation of the written operating rules, with the introduction of procedures for the control of events during LP&S operation in the operating manual and optimisation of the descriptions of the protection-goal-oriented management of design basis accidents in the operating manual and the emergency manual. Based on the requirements for LP&S operation and the evaluation of operating experience, the licensees and the plant manufacturer adopted the "Concept for controlling events during LP&S operation and its representation in the operating manual" in 2012. According to the licensees, the plant-specific implementation of the procedures stipulated in the concept for the management of design basis accidents during LP&S states took place in the period from 2012 to 2018.

According to the licensees, generic minimum availability requirements for the individual plant operating states (identical with operating phases according to the SiAnf) are part of the concept for controlling events during LP&S operation. If the required availabilities are not achieved, measures to restore them must be initiated immediately. If this cannot be ensured, the plant has to be taken - after the specified period at the latest - to a plant operating state in which there is either no or only a reduced requirement for the system in question.

Table 1: Generic minimum availability of selected systems regarding the maintenance of RHR in LP&S operation at mid-loop (source: [8a], excerpt)

Revaluation of availability requirements for LP&S operation[1]

System/System function	Shutdown		Start-up	
	C	D	D	C
Fuel pool cooling system trains	1+1	1+1	1+1	1+1
Reactor coolant system isolation (without RHR system)	1+1	1+1	1+1	1+1
Reactor coolant system isolation for RHR system	1+1	1+1	1+1	1+1
LP injection RHR trains	2+1	2+1	2+1	2+1
HP safety injection pump trains (isolation at coolant temperature < 180 °C possible)	-	-	-	-
Accumulators (isolation at coolant temperature < 180 °C possible)	6	-	-	6
RHR chains KA/TF-VE/PE (allocated to subsystems to be supplied in JN/TH+FA/TG)	2+1	2+1	2+1	2+1
Ventilation systems controlled area containment isolation containment ventilation	1+1	-	-	1+1
SG emergency feedwater system trains	2+0	-	-	2+0
Main-steam relief trains (incl. 100 K/h shutdown)	2+0	-	-	2+0
Annulus flooding protection (Level monitoring)	1+1	1+1	1+1	1+1
Electric power supply (allocated to the subsystems to be supplied)				
- emergency diesels	2+1	2+1	2+1	2+1
- uninterrupted (transformers, batteries)	2+1	2+1	2+1	2+1

2+1 Number of system trains/components (single-failure criterion covered; failures due to accidents are considered but not listed separately).

In [8a], the licensees cite the following measures to reduce the probability of a loss of RHR at reduced RCS inventory:

- restrictions on jobs/testing during mid-loop phases,
- additional monitoring of the RCS inventory by means of coolant mass balances,
- plant-specific measures such as checklists, additional shift personnel (e.g. reactor operator) during shutdown/start-up,
- preparation of the staff for the overall maintenance inspection and refuelling outage (specific instruction of the operating personnel),
- ensuring of RHR via the secondary side with still pressure-tight RCS after loss of the RHR chains,
- provision of a reserve RHR train,

[1] n+1 means: There must be n redundant system trains available and one additional redundant system train to control the single failure.

- deactivation of reactor protection signals or no activation of relevant valves in the residual-heat removal system,

- verification of the functional capability (surveillance testing) of operational monitoring equipment and shut-off functions, and

- training of the responsible shift personnel.

Especially with regard to restrictions for jobs/tests during mid-loop phases, the licensees state that work on isolated safety equipment and engineered safety features must not be performed if the jobs and tests may influence residual-heat removal. No work may be carried out or tests be performed on safety equipment and engineered safety features that must be kept available.

In view of the relatively short grace periods in case of a loss of RHR in mid-loop operation, the "Concept for controlling events during LP&S operation and its representation in the operating manual" provides for the installation of a Class 1 signal at an exposed location with acoustic signal in the control room. In this way, the malfunction or loss of the residual-heat removal system, according to the licensees, can be clearly detected in the control room, taking into account the alarm image specific to the plant operating state. Thus there is a clear initial criterion for the procedure for controlling the event.

With regard to the necessary measures for the control of events during mid-loop operation, the licensees explain in [8a] that the following boundary conditions for handling incidents were derived from the RCS experiments:

- Short grace periods until boiling point is reached (after approx. 12-15 minutes). Necessity of quick detection of the malfunction.

- Limited availability of instrumentation in mid-loop operation.[2]

- Restoration of critical heat flux ratio before connecting the residual-heat removal system.

- The conditions for connection the RHR systems, provided that saturation in the RCL has already been reached, can only be reliably established and maintained for a relatively short period of time by injecting defined amounts of coolant (approx. 100 m³).

- Limitation of the injected coolant amount to approx. 100 m³ since with pressure-tight RCS the pressure increases with increasing coolant volume, if necessary up to the delivery head of the RHR pumps. This means that if too large a quantity of coolant is injected, there will be no more scope for any further injection that may be required.

- It is not possible to achieve sufficient subcooling in the core and the hot leg by injecting from individual accumulators.

[2] Although the measurement "KMT_{AUS}" (coolant temperature at pump outlet) is available, it does not provide representative information about the coolant temperature in the hot loop or at the suction point of the RHR line due to its positioning (near the SG inlet) and lack of immersion depth in mid-loop operation.

- Hot-leg and cold-leg flooding by means of the RHR pump (approx. 100 m³) is sufficient to ensure that the RHR system is connected again (maintain subcooling at the suction point).

In [8a] the licensees state that a procedure "Disruption of RHR" has been included in the operating documents. The following objectives and requirements apply to this procedure for restoring RHR in the case of a reduced RCS inventory:

- A quick introduction of the procedure should be possible (recognition on the basis of the new Class 1 signal).

- The procedure should consist of individual units of manual actions that can be carried out quickly and easily. Despite different initiating events causing the loss of residual-heat removal, it shall be possible to carry out the return to service effectively and purposefully.

- The procedure is to cover all process engineering states with level lowering to ¾-loop (RCS pressure-tight, RCS not pressure-tight).

- The procedure is also to be effective and applicable if only one RHR train is functional (train ready for flooding).

The restoration of RHR for the different plant operating states involving mid-loop level can be realised in principle via two possible operating modes:

- cold-leg and hot-leg injection with a flooding-ready residual-heat removal train (approx. 80-120 m³) and overlapping connection of a still available (reserve) residual-heat removal train in residual-heat removal function or

- cold-leg and hot-leg injection with a flooding-ready residual-heat removal train (approx. 80-120 m³) and subsequent switching of this train to residual-heat removal mode.

According to the licensees, these basic modes of operation were verified to be effective and applicable within the framework of the various RCL experiments with different primary system configurations (reactor pressure vessel pressure-tight/not pressure-tight, reactor pressure vessel (RPV) top head in place or lifted). They state that effectiveness of the measures is independent of the cause of the loss of RHR and that there is no need to change this firmly implemented mode of operation depending on the primary circuit configuration. The licensees have therefore decided to prescribe this mode of operation for all plants, which has been implemented by all plants in the meantime.

The licensees say that the establishment of the generic procedure has been implemented in different ways from plant to plant. Possible options have been, for example, the creation of a chapter on "Disruption of residual heat removal" in the operating manual or by supplementing or preparing new operating modes for LP&S operation that are protection-goal-/condition-oriented. In principle, the measures are established in the relevant operational regulations (operating manual, additionally emergency manual, and the company organisation manual (*Betriebliches Organisationshandbuch* - BOHB). Here, the licensees say, it should be noted that the individual plants have historically grown differences in terms of the structure and scope of their operating documents.

Regarding the so-called Diablo Canyon scenario,[3] the licensees state in [8b] that this scenario can be avoided by correspondingly limiting after-power in such a way that within an assumed maximum grace period of 30 minutes until effective countermeasures are initiated, there will be no departure from nucleate boiling (after-power of approx. 6 MW corresponds to a grace period of 30 minutes). Alternatively, a sufficient relief opening in the hot leg can be created before opening the cold leg. In this way, the steam produced during boiling can be released without pressure build-up in the reactor coolant system. Accordingly, when first mid-loop operation is reached, i.e., upon plant shutdown, no large cold-leg openings (steam generator manhole opened on the primary side, reactor coolant pump (RCP) shaft drawn, source isolating valve removed) would be created without an adequate hot-leg relief opening. A corresponding self-commitment declaration by the licensees has been in existence since 2009.

In [13], the operators add that coolant losses due to open SG manholes (and/or certain large cold-leg openings) are not dealt with by the procedure described in the chapter on "Disruption of residual-heat removal in low-power and shutdown operation". A loss of residual-heat removal in such plant states could only be controlled via sump recirculation mode, applying the protection-goal-oriented instruction manual (*Schutzziel-BHB*).

The largest possible openings in the RCS could be created by drawing a RCP shaft (NB 750), completely removing an SG primary manhole cover (NB 500) or removing a source isolating valve of the JNA/TH system (NB 225). Surveillance tests or maintenance measures planned in the outage which require such a complete removal of the above-mentioned components and for which errors and malfunctions would then have to be considered are generally not permitted or ordered in Phases C-E, i.e. as long as there are still fuel assemblies in the RPV.

4 Assessment criterion

Requirements with regard to measures to avoid a loss of residual-heat removal during mid-loop operation are derived from the corresponding state of the art in science and technology as it ensues e.g. from GRS studies of the corresponding plant operating states, see GRS-A reports 3114, 3523 and 3765 [10a/10b/10c].

Requirements regarding measures to control a loss of residual-heat removal in mid-loop operation arise with respect to

- the postulated events, the failure assumptions to be applied (single-failure concept) as well as the boundary conditions for verification from the SiAnf, in particular Appendices 2, 4 and 5 [11a/11b/11c],
- the effectiveness of measures to restore residual-heat removal from the RCS experiments for the mid-loop plant state [7], [8a].

[3] In the case of an opening exclusively in the cold leg, the void formation which starts after the loss of residual-heat removal leads to the expulsion of single-phase coolant from the opening. This is accompanied by a coolant displacement in the RCS and a lowering of the RPV level. Depending on the cold-leg opening area, core uncovery can occur much earlier than with the RCS opened in the hot leg.

KTA Safety Standard 1201 [12] contains requirements regarding the establishment of measures in the operating manual and the design of procedures.

Altogether, based on the requirements contained in these documents, the RSK concludes that a concept should be implemented in the PWR plants to prevent events contributing to the loss of residual-heat removal in case of a reduced coolant inventory ("mid-loop states") and to control such events if they nevertheless occur. This concept should in particular cover the following points:

- Measures to avoid the "loss of RHR" at reduced RCS inventory.
- Measures to control the events in the respective operating phases with consideration of further relevant boundary conditions, e.g. the configuration of the primary system (closed, various openings and their location in the RCS).
- Appropriate establishment of the measures in the operating documents of the plants. The stipulations regarding the availability of the safety equipment to be provided in the different plant states to control a mid-loop event should be laid down in the safety specifications (SSP).

5 Assessment

Based on the licensees' presentation [8a] and in knowledge of the regulations in the operating manuals of different PWR plants, the RSK comes to the following conclusions:

A generic concept for the management of events with loss of RHR was developed by the licensees with participation of the plant manufacturer in the years 2000 to 2012. This concept considers

- the state of the art in science and technology regarding event prevention and control during mid-loop operation (based, among others, on relevant GRS reports and on the results of RCS experiments), and
- currently valid requirements of the nuclear regulations (KTA Safety Standards, SiAnf).

The concept contains

- specifications in the written operating rules regarding measures to avoid a loss of residual-heat removal in mid-loop operation,
- specifications in the written operating rules regarding the minimum availabilities of relevant systems required for event control during the individual plant operating states,
- the establishment of a Class 1 signal for fast and reliable detection of disruptions in residual-heat removal operation and
- procedures in the operating manual to control disruptions in residual-heat removal operation.

The concept presented by the licensees is regarded by the RSK as meeting the requirements.

The individual measures mentioned by the licensees in [8a] for the prevention of a loss of RHR during mid-loop operation are also regarded by the RSK as meeting the requirements. As concerns the work and inspection bans referred to by the licensees, the RSK is of the opinion that the SSP should regulate which individual systems are affected and to what extent. Furthermore, special aspects for mid-loop operation with regard to monitoring measures or special availabilities should be laid down in the SSP. To what extent this is the case in the different plants is not known to the RSK. Hence the following recommendation:

Recommendation 1:

With a view to avoiding a loss of residual-heat removal in mid-loop operation, the SSP should list individually the systems subject to a prohibition of work and testing and should also establish special aspects for mid-loop operation, e. g. regarding additional monitoring measures or special availability requirements.

As regards the minimum availabilities of relevant equipment during mid-loop operation mentioned by the licensees in [8a] (see columns C and D in Table 1), the RSK has not performed its own examination on the extent to which these are sufficient for event control under the boundary conditions specified in the SiAnf [3]. Regarding the plant-specific implementation of the minimum availabilities listed in Table 1, an evaluation of plant-specific requirements in the operating manuals [6a/6b/6c] performed by GRS shows that there are deviations from the information given in this Table. Hence the following RSK recommendation:

Recommendation 2:

It should be verified plant-specifically that the minimum availabilities listed in Table 1 of this Statement are covered by the availabilities listed in the SSP.

The RCS experiments to investigate the effectiveness of measures for restoring RHR in mid-loop operation show that temporary subcooling can be achieved in the suction area of the residual-heat removal trains by hot-leg and cold-leg injection of approx. 100 m³ of coolant by means of a flooding-ready residual-heat removal train after a period of approx. 30 minutes (30-minute criterion). This assertion applies initially irrespective of the primary system configuration (RPV pressure-tight/not pressure-tight, RPV top head tensioned, resting de-tensioned on the RPV, or lifted). The available time period can be used to put a possibly still available train into operation in residual-heat removal mode or to switch the train used for flooding to residual-heat removal mode after injection has been completed.

In the individual RCS experiments, it has been shown that the length of time during which subcooling is maintained depends for the individual primary system configurations on whether cold- or hot-leg or hot- and cold-leg injection is carried out. The plant manufacturer explained that it was decided deliberately not to include case-specific specifications for a preferred direction of injection in the procedure. Instead, the procedure should be designed in a simple and uniform manner, be sufficiently effective for all primary system configurations, and therefore be able to do without the need for case distinctions. The RSK agrees with this argumentation, especially as the specified combined injection for the configuration with pressure-tight RCS is the most effective option. The pressure-tight RCS represents the least favourable case with regard to the repeated application of the procedure.[4]

It furthermore follows from the RCS experiments [7] that in the event of a loss of residual-heat removal with

- pressure-tight RCS, the residual heat can be permanently removed via the steam generators that are ready to blow off (provided there are sufficient secondary coolant supplies) and with

- hot-leg opened RCS, due to the continuous loss of coolant, core uncovery without any countermeasures will only occur after considerably more than one hour.

Significantly less favourable conditions arise with large cold-leg opening cross-sections without hot-leg openings in the RCS. In this case, the formation of voids in the RCS leads to the expulsion of single-phase coolant from the opening, which is accompanied by a coolant displacement and a lowering of the RPV level. As a result, core uncovery can occur much earlier than with the RCS opened in the hot leg. Furthermore, the return to residual-heat removal operation requires a more extensive use of the residual-heat removal systems than in the other two cases (RCS pressure-tight or hot leg opened RPV) [7]. Such plant states should therefore be avoided.[5]

To control a loss of residual-heat removal in case of large cold-leg openings, the creation of sufficient hot-leg relief openings would be necessary. It has to be taken into account that, depending on the position of the cold-leg opening and/or the hot-leg relief openings, the supply of the RCS with approx. 100 m³ of coolant cannot be realised because the coolant will flow off via the opening(s) (e.g. at open SG manholes). The procedure "Disruption of residual-heat removal in low-power and shutdown operation" in the operating manual is therefore not applicable. Such plant states would therefore require operating modes using sump recirculation mode.

Hence the following RSK recommendation:

Recommendation 3:

Larger openings in the cold leg (with the exception of small opening cross-sections as in the case of RCP seal replacement) and larger, low-lying openings in the hot leg (e.g. SG manholes) in the RCS should only be made when the core is unloaded.

If in justified individual cases such openings are generated during mid-loop operation with the core loaded, a safety-related individual case analysis has to be performed. At least the following aspects have to be considered:

- *availability of the redundant residual-heat removal trains,*
- *after-power and grace period until boiling in the case of a loss of residual-heat removal,*

[4] Only a limited volume is available for the taking-in of injected amounts. This results in a pressure increase in the RCS.

[5] According to VGB, a self-commitment declaration by the operators has existed since 2009.

- *sufficient hot-leg relief areas in the event of cold-leg openings,*
- *positions of the openings,*
- *amount of coolant that can be injected into the RCS without discharge into the sump,*
- *necessity of sump recirculation mode upon loss of residual-heat removal.*

The need for such case-by-case considerations has to be established in the SSP.

5 Compiled recommendations

Recommendation 1:

With a view to avoiding a loss of residual-heat removal in mid-loop operation, the SSP should list individually the systems subject to a prohibition of work and testing and should also establish special aspects for mid-loop operation, e. g. regarding additional monitoring measures or special availability requirements.

Recommendation 2:

It should be verified plant-specifically that the minimum availabilities listed in Table 1 of this Statement are covered by the availabilities listed in the SSP.

Recommendation 3:

Larger openings in the cold leg (with the exception of small opening cross-sections as in the case of RCP seal replacement) and larger, low-lying openings in the hot leg (e.g. SG manholes) in the RCS should only be made when the core is unloaded.

If in justified individual cases such openings are generated during mid-loop operation with the core loaded, a safety-related individual case analysis has to be performed. At least the following aspects have to be considered:

- *availability of the redundant residual-heat removal trains,*
- *after-power and grace period until boiling in the case of a loss of residual-heat removal,*
- *sufficient hot-leg relief areas in the event of cold-leg openings,*
- *positions of the openings,*
- *amount of coolant that can be injected into the RCS without discharge into the sump,*
- *necessity of sump recirculation mode upon loss of residual-heat removal.*

The need for such case-by-case considerations has to be established in the SSP.

6 Sources

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