Note:
This is a translation of the RSK recommendation entitled “Wasserstofffreisetzung aus dem Sicherheitsbehälter”.
In case of discrepancies between the English translation and the German original, the original shall prevail.

RSK recommendation
(475th meeting of the Reactor Safety Commission (RSK) on 15.04.2015)

Hydrogen release from the containment

1 Background

At its 458th meeting on 23.05.2013, the RSK was informed about the results of an ENSREG workshop in Brussels on the “National Action Plans” that were set up as a follow-up to the EU stress test. It was reported that in the German action plan, no statements have been made so far on the topic of hydrogen release from the containment, which is discussed as a consequence of the hydrogen explosions occurred in Fukushima.

In Fukushima,

- there was presumably a leakage of hydrogen during venting from Unit 3 into the reactor building of Unit 4, followed by hydrogen explosion in Unit 4, since the exhaust air systems used shared a common stack and gas flows into Unit 4 have not been prevented through appropriate provisions, and

- there were leakages of hydrogen from the containments of Units 1, 2 and 3 into the respective reactor buildings, in particular due to the high pressures and temperatures generated in the containments, which led to hydrogen explosions in Units 1 and 3 (in Unit 2, an accumulation of hydrogen has presumably been prevented through openings at the reactor building).

Background of dealing with this issue is therefore the concern that hydrogen leakages from the containment may enter rooms outside the containment, these rooms may not be monitored for hydrogen and/or no hydrogen management measures are installed there.

At its 458th meeting on 25.05.2013, the RSK requested the Committee on PLANT AND SYSTEMS ENGINEERING (AST) to consult on the topic of “hydrogen release into rooms outside the containment” on a generic level. The RSK discussed and adopted the statement prepared by the Committee AST at its 475th meeting on 15.04.2015.

2 Current situation

Hydrogen outside the containment

- may occur during filtered venting of the containment in the vent pipes, on other exhaust ducts possibly used, or in the stack, and
- in case of leakages from the containment into the reactor building and possibly into adjacent buildings.

Below, these two aspects are dealt with in separate sections.

Scenarios directly leading to beyond design basis release of hydrogen from the containment, such as a multiple failure of containment isolation valves and containment bypass scenarios, have not been considered due to their low frequency of occurrence. Furthermore, accident sequences during low-power and shutdown operation where the containment cannot be isolated in time have not been considered either.

Scenarios for a large-scale failure of the containment caused by core melt impact have not been considered due to the immediate hydrogen explosion in the reactor building (annulus) to be postulated.

2.1 Filtered containment venting

The actions required for initiating and conducting preventive and mitigative severe accident management measures, the latter include filtered containment venting, are generally specified in the severe accident management manual (*Notfallhandbuch* – NHB). In addition, since 2013, manuals containing mitigative severe accident management guidelines (SAMGs) (*Handbuch Mitigativer Notfallschutz* – HMN) have now been introduced in all German plants, serving to support the work of the on-site crisis management team. These take up again the mitigative severe accident management measures already existing and described in the severe accident management manuals (NHB) of the plants and are structured, among other things, according to various hazard states of the containment.

The requirements for filtered depressurisation (venting) are shown in summary form in Positional Report KTA-GS-66 [1]. At its 218th meeting on 17.12.1986, the RSK adopted a related recommendation on the design for PWRs and at its 222nd meeting on 24.06 1987 for BWRs. The final statement with requirements for the filter capacity (retention factors) was published in the minutes of the 263rd RSK meeting on 24.06.1991 as Annex 6. The systems were then implemented in different designs with dry filter systems or venturi scrubbers and with different piping layout for discharge to the environment. An overview was drafted within the framework of the ENSREG stress test, and requirements for the review of the systems are specified in [5.17].

Furthermore, on the topic of hydrogen release during venting of the containment, GRS Information Notice (*Weiterleitungsnachricht* – WLN) 2012/02 [5] is available, prepared in the wake of the Fukushima accident, which specifies additional requirements for the review of the venting systems. According to this WLN, the system for filtered containment venting should be analysed to determine whether potential H_2 combustion processes during containment venting can also be excluded in vent pipes and possibly in commonly used exhaust air chamber or in other reactor building areas. In addition, according to the WLN, effective precautions are to be taken against direct impacts on a neighbouring unit e.g. by transfer of hydrogen or radionuclides through shared systems or pipes. According to the RSK statement (450th meeting), the filtered venting system is to be designed such that pressure relief can also be repeatedly performed during or after natural external design basis hazards and in the event of a station blackout.

Depressurisation of the reactor containment (venting) is necessary if preceding accident management measures have not been successful during a beyond design basis event and there is a pressure build-up in the containment or may occur which endangers the integrity of the containment. General objectives of the venting are to prevent containment failure due to continuing pressure increase and to minimise radioactive release through filtered discharge. The procedure necessary for performance is described in the severe accident management manual (NHB) of the plant and can be interrupted or repeated as far as required. Criteria for the preparation and completion of the action are also specified. They will be extended with the introduction of the manual for mitigative severe accident management (HMN) if required.

In the German PWR plants in operation, two filter systems have been retrofitted alternatively: a combination of metal fibre fleece filter and molecular sieve, or a combination of sliding pressure venturi scrubber and metal fleece filter. The design pressure of the venting system is above the design pressure of the containment. In the BWRs in operation, the filter system shared by the two units consists of a combination of sliding pressure venturi scrubbers and metal fibre fleece filters. In BWRs, the filtered venting system is filled with nitrogen under overpressure during operation and monitored for leak tightness.

In the BWR, the discharge of the gas mixture downstream of the filter takes place through a separate clean gas line into the environment, while in the PWR this is different specific to the plant and takes place through connection of the clean gas line with exhaust air systems of the building near the stack or directly into the stack [11].

Estimate of hydrogen release during venting and potential combustion processes

Until about 2001, GRS carried out exemplary studies for the KONVOI PWR within the framework of a PSA Level 2 as to whether combustible gas mixtures can occur in venting systems during filtered venting [11, 16]. With the postulation made there that the ventilation systems of the buildings cannot be operated during containment venting, these studies indicated that there is a risk of hydrogen combustion in that part of the venting system of PWRs where the vent pipe is integrated into the exhaust system of the plant upstream the stack inlet.

As part of a current project of the BMUB, GRS analyses the radionuclide retention by venturi scrubbers in containment venting systems of KONVOI PWRs (reference plant GKN-2) and of boiling water reactors SWR-72 (SWR = *Siedewasserreaktor* (boiling water reactor)) using two characteristic severe accident sequences each. Here, analyses on the H_2 situation in the clean gas line are no separate work item according to [11] so that the findings presented below are based so far on a just rough modelling of the conditions for PWRs.

Here, GRS’s preliminary finding for a PWR venting system (taking the example of reference plant GKN-2) is that at the beginning of depressurisation, combustible gas mixture conditions may occur in the shared exhaust air chamber and in the stack for a limited period of time when there is no ventilation system in operation. Ventilation systems in operation whose operation requires power supply prevent the formation of combustible gas mixtures in the shared exhaust air duct including stack. From the current perspective of GRS [11], combustion conditions for the case without ventilation systems are to be expected particularly in the upper part of the stack since reverse flows are possible due to the low gas velocity at the stack outlet and the relatively large diameter of the stack; thus, combustible mixtures may occur after completion of the depressurisation in major areas of the stack since hydrogen from the completed depressurisation process may still be present there.

According to GRS, such conditions are not to be expected for boiling water reactor SWR-72 since a separate clean gas line exists from the outlet of the scrubber to the stack outlet, which, with DN350, has a much smaller diameter of than the stack used for PWRs for discharging gases during containment venting. Furthermore, with the clean gas line, a passive flow (comparable to the natural draft in a stack) is prevented by the closure of valves downstream the venturi scrubber. In addition, direct impacts on the neighbouring unit due to the shared system, e.g. by transfer of gases, are excluded by the administrative and system design conditions according to [20].

2.2 Leakages from the containment

- **Boiling water reactor SWR-72**

According to [15], the following applies to boiling water reactor SWR-72:

Design features

The design of the containment for events up to the third level of defence is based on the design specification. The components necessary for ensuring the leak tightness and integrity of the containment, such as loading cover, assembly openings and airlocks, are designed to meet the requirements in terms of strength in conjunction with the selection of materials. The fracture toughness and strength requirements for the material in conjunction with the stress limitation correspond to nuclear safety standards KTA 3401.1 and 3401.2.

The design pressure of the containment is 3.3 bar(g), the test pressure 3.6 bar(g), and the failure pressure was calculated in the licensing procedure with 10 bar(g). The maximum permissible leakage rate at design pressure is 1 vol%/day; measurements conducted during in-service inspections showed an average leakage rate of 0.5 vol%/day. Boiling water reactor SWR-72 has a redundant leakage exhaust system with emergency power backup, which returns any leakages occurring at airlocks and ventilation flaps into the containment in case of accidents.

The reactor building is equipped with a redundant subatmospheric pressure build-up system with emergency power backup, which extracts and filters a gas volume of 4,600 m^3/h if required and discharges it through the stack.

A hydrogen monitoring system is installed to measure the hydrogen and oxygen concentration in the containment.

In addition to the combustible gas control system (2 x 100 %) of the BWR designed for design basis accidents, the wetwell is inertised during power operation for beyond design basis events, and 78 autocatalytic, passively operating recombiners are installed in the containment with a hydrogen recombination rate of 37 g/s, corresponding to 133.2 kg/h, of which 12 are located in the wetwell. The design was based on the scenarios of station blackout (loss of main feedwater supply, failure of all active injection systems) with initial steam and hydrogen release into the wetwell and the main steam line break with the release of steam and hydrogen directly into the drywell. According to estimates, about 350 kg of hydrogen can be recombined in the entire containment [14] due to the limited amount of oxygen in the drywell and the inerted wetwell until the oxygen is used up and hydrogen accumulates in the containment.

Rate of leakage into the reactor building

By periodic leak rate tests of the containment it is ensured that the leakage rate is below the design leakage rate. The underlying assumption that the maximum leakage rate corresponds to the design leakage rate presupposes that the tightness of the installed containment seals is neither significantly affected by temperature increases in the containment induced by accident sequences nor by chemical impacts.

With regard to the impact of increased temperatures on the containment seals, it was calculated in studies on the behaviour under maximum load of the loading cover and the assembly openings, conducted within the framework of the licence procedure, that in the long term a temperature of about 160°C is reached with a containment pressure of 10 bar(g) and a containment temperature of 200°C at the sealing area. This is within the range of the design temperature of the seals, but the sealing surfaces of the airlock doors, of the loading cover and the assembly openings are sealed by polymer sealing rings inserted in grooves. When under pressure, the metal surfaces of the sealing areas and flanges are pressed together and the seal is in its groove, then there exist no open contact surfaces exposed to the containment atmosphere. The resistance of polymer seals used in BWRs has also been confirmed by tests for sealing materials in the installed state with a model of the loading cover of the containment up to 400°C.

With respect to the chemical resistance of seals and airlocks in the containment, it is noted that

- for cable penetrations, compression glass seals are used,
- for polymer seals, the design temperature, as stated above, will not be exceeded so that the chemical resistance is maintained, and
- otherwise chemically resistant metal seals and expansion joints are used.

In conclusion, this means that no significant impacts on the maximum leakage rate specified due to increased temperatures in the containment or chemical agents have to be postulated.

Estimate of hydrogen concentration in the reactor building

In core meltdown scenarios with accident sequences leading to pressure build-up in the containment, hydrogen may be released from the containment into the reactor building through leakage paths without containment failure. Scenarios that proceed comparatively slowly in which containment venting is initiated at a relatively late stage lead to correspondingly long lasting leakage times. This approach is covered best by the core meltdown scenario “wetwell temperature > 150°C due to loss of residual heat removal”. Here, the containment pressure increases continuously after the onset of the accident, after about eleven hours containment venting takes place at 6 bar(g), then the containment pressure stabilises at approximately 3 bar(g) and the temperature at about 150°C.

Since the reactor building consists of several separate room areas, the spatial layout of containment penetrations and the volume of the adjacent component rooms are also to be considered. Hydrogen releases would mainly occur in component rooms which are largely adjacent to the containment and which have a large number of containment penetrations. For boiling water reactor SWR-72, these are primarily the room areas above the 40-meter level and the room area above the 18.5-meter level. In these room areas, there are about half of all containment penetrations (incl. loading cover, mounting lid, transport shaft, main airlock and upper airlock).

Taking into account the large volume of the rooms above the 40-meter level of about 31,000 m³ (without transport shaft), the further estimation is limited to the hydrogen leakage from the containment into the room area above the 18.5-meter level with a free volume of about 7,500 m³.

With the conservative assumptions that

- the maximum amount of hydrogen of about 2,300 kg (about 1,150 kg due to the zirconium-water reaction, corresponding to a core oxidation of about 35 % and 1,150 kg due to molten core concrete interaction) is present from the onset of the accident,
- no hydrogen is recombined by the 78 recombiners in the containment,
- the pressure in the containment corresponds to the design pressure already from the onset of the accident,
- the leakage rate corresponds to the design leakage rate from the onset,
- 50 % of the design leakage enters the room area above the 18.5-meter level, and
- there is a total loss of the ventilation system, the subatmospheric pressure build-up system and the leakage exhaust system in the reactor building,

there will be hydrogen inflow of about 0.5 kg per hour (corresponding to 5.8 m³ per hour at 1.013 bar atmospheric pressure) into the room area above the 18.5-m level. Postulating a homogeneous mixing of the leakage flow, a hydrogen concentration of about 0.85 vol% will be reached after 11 h (at the time of containment venting initiation) in this room area. The ignition limit of 4 vol% hydrogen will not be reached with these postulations.

With the same assumptions, the hydrogen concentration in the room area above the 40-meter level would be lower by a factor of about 4.

Hydrogen distribution in the rooms of the reactor building

Analytical studies on the distribution of hydrogen in the reactor building from containment leakages have not been conducted for the BWR.

In the room area above the 40-meter level, thermal stratification is not to be expected since the heat and the leakage sources are located below this level.

The room areas above 18.5 m are connected with each other without major structural obstacles up to a level of 28.5 m, and thermal stratification resulting from temperature distributions in the containment is not to be expected for the BWR in these areas from an engineering point of view due to the circulation in the containment and the wall thicknesses of the prestressed concrete containment and the spatial conditions of the reactor building. In addition, there are no dead-end zones in the above-mentioned room areas in which combustible hydrogen mixtures could accumulate.

The introduced manual for mitigative severe accident management measures (SAMGs = HMN) recommends containment venting for progressive core melt scenarios at an early stage (before reaching 6 bar(g)), which also leads to a limitation of hydrogen leakage. In addition, the subatmospheric pressure build-up system is to be taken into operation again after failure, as stipulated in the manual for mitigative severe accident management measures (HMN). This leads to the mixing of leaked hydrogen with the room atmosphere in the entire reactor building and the discharge of the hydrogen via the exhaust air path.

- **PWR**

Design features

According to [6, 7], the spherical containment of a KONVOI PWR with a diameter of 56 m diameter has an annulus between containment wall and external wall of the reactor building with an average width of about 1.6 m. There are passages leading through the containment at different levels, such as the personnel airlock about along the horizon, the equipment airlock, two emergency airlocks, about 120 pipe penetrations and about 475 cable penetrations. The design pressure of the containment is about 5.3 bar(g), the design temperature of the steel shell 145°C and the design leakage rate 0.25 vol% per day. During commissioning, the containment was tested for leak tightness at design pressure. The cyclic monitoring programme for the containment includes leakage tests on penetrations, functional tests on the airlocks and dampers, the determination of the total leakage of the containment at 0.5 bar(g) following the plant outage for refuelling and revision, and the determination of the quality condition of pipe penetrations, cable penetrations and airlocks.

Probabilistic analyses have shown that the failure pressure of the containment is approximately twice as high as the design pressure [6, 12]. Furthermore, expansion of the containment vessel due to pressure build-up and thermal stresses with respect to a contact of the containment wall with components in the annulus were analysed and a failure excluded. According to these analyses, the failure probability for expansion joints, seals and airlocks increases only at a pressure of more than 10 bar and a temperature of about 145°C.

In the event of a release of hydrogen into the containment, the following systems are available within the design basis framework:

- hydrogen monitoring system to determine the spatial and temporal distribution of hydrogen in the containment,
- hydrogen mixing system for mixing of the containment atmosphere to prevent hydrogen concentrations above the ignition limit,

- hydrogen recombination system for recombination in the exhaust gas system by means of thermally operating recombiners.

For beyond design basis events with accidental hydrogen release into the containment or in the containment, the following systems are available:

- The hydrogen recombination system installed in the containment consisting of about 58 autocatalytic, passively working recombiners of different sizes with a hydrogen recombination rate of integrally about 200 kg H_2/h (at an average of 4 vol% H_2 and 3 bar(a)).

Rate of leakage into the annulus

By periodic leak rate tests of the containment it is ensured that the leakage rate is below the design leakage rate. The assumption, on which the following estimate is based, that the maximum leakage rate corresponds to the design leakage rate postulates that the tightness of the installed containment seals is neither significantly affected by temperature increases in the containment induced by accident sequences nor by chemical impacts.

With regard to the impact of increased temperatures on the tightness of the containment seals, it is estimated in [6, 12] that the maximum temperatures in the containment reached in the area of the dome are about 150°C and thus are in the range of the design temperature of the seals (polymer seals: 145°C). Since, however, the sealing surfaces of the airlock doors are sealed by polymer sealing rings inserted in grooves and, when under high pressure, the metal surfaces door and seats are firmly placed together and the seal is in its groove so that there are no open contact surfaces exposed to the containment atmosphere, it is to be expected that the temperature at the seal is well below the maximum containment temperature.

With respect to the chemical resistance of seals and airlocks in the containment, it is noted in [6] that

- for cable penetrations, compression glass seals are used,
- polymer seals have a design temperature of 145°C which, as stated above, will not be exceeded so that the chemical resistance is maintained, and
- otherwise chemically resistant metal seals and expansion joints are used.

In conclusion, this means that according to [6], no significant impacts on the maximum leakage rate specified due to increased temperatures in the containment or chemical agents have to be postulated.

Estimate of hydrogen release into the annulus

For estimating the hydrogen release, generic considerations for a scenario “total loss of the three-phase power supply (station blackout)” [7] were submitted to the RSK. In this scenario, the pressure in the containment shows an initial rise after opening the rupture discs at the pressure relief tank. After about10 ½ hours, there would be RPV failure. After about 2 ½ days, the criterion for filtered containment venting of 7 bar(a) would be reached. With the beginning of filtered containment venting, the pressure in the containment drops continuously.

According to [6], there are only a few penetrations beneath the embedded area of the containment, all of them being cable and pipe penetrations that have a high degree of robustness due to their design [12]. A relevant leakage of hydrogen into the lower, separated rooms of the annulus is to be assessed as negligible. In addition, it is pointed out that according to the results of the “German Risk Study Nuclear Power Plant Phase B”, the ventilation ducts leading through the annulus, for which ventilation isolation exists under these conditions, have been reinforced in order to prevent any hydrogen leakages into the annulus.

The further considerations on hydrogen accumulation in the annulus are limited to the upper half of the spherical shell of the annulus. Here, the hydrogen recombination rate by the recombiners (in the containment) has been taken into account in the computational estimates under consideration of the amount of oxygen in the containment. With the conservative assumptions that

- an amount of hydrogen of about 2,240 kg (about 1,120 kg due to the zirconium-water reaction, corresponding to a core oxidation of about 80 % and 1,120 kg due to molten core/concrete interaction) is present from the onset of the accident,

- the pressure in the containment corresponds to the design pressure already from the onset of the accident, and

- the leakage rate corresponds to the design leakage rate (0.25 vol%/day) from the onset,

there will be a hydrogen leakage mass of approximately 6 kg per day (equivalent to 67.25 m^3 per day at 1.013 bar, atmospheric pressure). For the case of failure of the annulus air extraction system (due to lack of three-phase current), it is to be postulated that the hydrogen concentration will slowly rise. It is estimated that under the assumption of a homogeneous mixing of the leakage flow in the spherical segment of the annulus, a hydrogen concentration of 4 vol% will not have been reached in the annulus yet after about four days.

In addition, it is stated that a currently planned adjustment of the venting procedures in the manual for mitigative severe accident management measures (HMN) would lead to a more favourable performance and would not affect the conservative nature of the above estimate.

Hydrogen distribution in the annulus

In this respect, GRS refers to experiments at the Battelle Model Containment facility (BMC) which included basic experiments that started in 1979 on the distribution of hydrogen in interconnected, mostly vertically superposed rooms under various conditions prevailing after a loss of coolant accident [9]. Within this framework, an experiment was carried out on thermal stratification (upper room hot, lower room cold) and on hydrogen feed into interconnected rooms in the lower room with a temperature analogous to this room. It showed that thermal stratification impedes the rise of hydrogen to the upper room. In theory, the following applies: the higher the temperature difference, the greater the barrier effect. The BMC experiments verified this theory qualitatively. Applied to the conditions in the annulus of a PWR under accident conditions, this means that at leakage of hydrogen in the lower area from the containment into the annulus caused by the thermal stratification to be expected under accident conditions also impedes the rise of hydrogen to the upper annulus.

Furthermore, GRS states that global convection processes in the containment are event-dependent and e.g. also depend on whether a larger number of rupture discs at the steam generator towers fail during the event and further openings in the missile protection wall are created. A limited or good convection inside the containment is an important boundary condition for distribution processes of vapour and gases and, ultimately, also for energy releases into the annulus and resulting temperature distributions there.

According to [9], there may be thermal stratification in the annulus under accident conditions. The temperature differences depend on the processes taking place in the containment. The conditions in the annulus and the released amount of hydrogen and other gases from the containment via leakages depend on

- the mass of hydrogen generated during the severe accident sequence and being present inside the containment and, in the long term, the duration of the hydrogen release from the molten core concrete interaction,

- the location and size of the leakage from the containment into the annulus and thus also on the temperature of the leakage mass flow,

- the function of the annulus air extraction system in the event of an accident,

- the time of venting and thus the discharge of hydrogen from the containment, and

- inward leakage from the surrounding area or the auxiliary building, respectively, and its location in the annulus, provided that the annulus air extraction system can maintain a negative pressure during the accident sequence.

The formation of a combustible gas mixture in the annulus depends both on the rate of leakage from the containment into the annulus and the location of the leakage [9]. From the available documents, the following is concluded:

- If the containment leakage rate is limited to the design leakage rate, the results [6, 9] show that the formation of combustible conditions in the annulus in the time range of a few days after beginning of the accident is not to be expected. This is also shown by the results when taking into account thermal stratification in the annulus [9,10] where thus there is no homogeneous mixing of the leakage flow into the annulus, as it is assumed in [6, 7].

- If at the equipment airlock a containment leakage rate is postulated that is 10 times higher than the design leakage rate and stratification behaviour is taken into account in the analyses, calculations show [9] that combustible conditions may occur in the annulus in the room areas above the postulated leakage location [9].

The analyses performed by GRS [21 – 24] were related to the development of recombiner concepts for PWRs and comprise various scenarios of uncontrolled loss of coolant accidents and transients which, according to GRS, can be considered to be “representative” with regard to the formation of hydrogen in the containment, the pressure gradients and the maximum temperatures (according to Section 3.1). This implies that the analyses were carried out under “realistic” boundary conditions, taking into account the function of the recombiners installed in the containment. In the analyses described in [21 – 24], different positions of the containment leakage and boundary conditions with respect to the annulus air extraction system were postulated, and the analyses were carried out for only a limited time span after the start of core damage and in each case terminated prior to containment venting to be expected after a few days. The analyses from [21 – 24] do not represent a systematic study on the conditions to be expected for different containment leakages into the annulus and an assessment of potential countermeasures which takes into account all aspects.

3 Assessment

3.1 Assessment basis

For an assessment of the hydrogen release and potential challenges resulting from it in case of the above processes, it is necessary to decide on which severe accident scenarios and assumptions the considerations are to be based. From the perspective of the RSK, it is sufficient for these considerations if the selection of the scenarios to be considered takes place in a way similar to that for the design (number and spatial layout) of the autocatalytic hydrogen recombiners in the containments of PWRs and BWRs of construction line 72.

Therefore, the RSK refers to the RSK statement “Threat to the containments of PWRs due to hydrogen reactions caused by the ignition effect of passive autocatalytic recombiners” [13] for the assessment of scenarios relating to “hydrogen release from the containment” and to the approach formulated therein for deriving scenarios to be considered. This approach is also applied for BWR construction line 72.

According to [13, 17] and [26], the primary objective regarding the effectiveness of a system of recombiners for mitigation of beyond design basis events is to prevent extensive hydrogen combustion due to a core melt accident that could threaten containment integrity. To this end, “representative event sequences” are to be defined that should cover the dominating event paths in terms of their frequency and a wide range of characteristic states and conditions that are relevant for the processes considered. When selecting the representative event sequences, both qualitative and quantitative findings from probabilistic analyses may be referred to.

Therefore, the RSK holds the view that with regard to the release of hydrogen from the containment those event sequences should be referred to that cover the relevant conditions and processes in the containment representatively as described above.

These conditions and processes are, in particular,

- the concentration of hydrogen under accident conditions and its distribution in the containment,
- the time-dependent pressure history in the containment (relevant with respect to the leakage rate from the containment) until venting,
- the peak temperatures in the area of the containment penetrations respectively their distribution in the containment being relevant for the maintenance of leak tightness of the containment penetrations apart from the pressure,
- the vertical temperature distribution in the containment, which is possibly relevant for the issue of formation of thermal stratification in rooms outside the containment.

Regarding the leakages from the containment, a distinction is to be drawn between potential leakage locations that may lead to different conditions in adjacent buildings.

For the event sequences being representative with respect to the above conditions and processes, it should be examined whether the formation of an ignitable mixture in rooms outside the containment must be postulated.

Insofar as the examinations show that ignitable mixtures outside the containment must be postulated, it is to be investigated which preventive measures could be implemented, or it is to be demonstrated that hydrogen combustions that may be caused by it can be controlled.

3.2 Hydrogen release during filtered containment venting

As regards the issue of "hydrogen release into rooms outside the containment during venting", the RSK points out that in GRS Information Notice WLN 02/2012 [5], the requirements for the venting system were formulated such that potential hydrogen combustion processes related to containment venting also have to be excluded in vent pipes and any shared exhaust air chamber, the stack or in other areas of the reactor building affected during venting. In addition, according to this Information Notice, effective precautions have to be taken against direct impacts on a neighbouring unit e.g. by transfer of H_2 or radionuclides via shared systems or pipes.

According to current exemplary investigations of GRS [11], combustible gas mixture conditions have to be expected for the analysed PWR reference plant GKN-2 in the exhaust air chamber and in the stack for a limited period of time when there is no ventilation system of the plant buildings in operation at the beginning of containment venting. According to these investigations, ventilation systems in operation, for which power supply is needed, prevent the formation of combustible gas mixtures in the exhaust air chamber and the stack due to the dilution of the gases caused by it.

For the SWR-72 boiling water reactor, such conditions are not to be expected since a separate clean gas line exists from the outlet of the scrubber to the stack outlet. According to [20], direct impacts on the neighbouring unit due to the shared system, e.g. by transfer of gases, are excluded by the administrative and system design conditions. The RSK is not aware of any information that might call this assessment into question.

With regard to PWR plants, the RSK recommends that it should be examined on the basis of representative analyses in accordance with the approach outlined in Section 3.1 which severe accident measures to prevent combustible conditions during containment venting in shared exhaust air systems, such as in the exhaust air chamber and the stack, can be provided or, alternatively, to demonstrate that hydrogen combustion will not lead to safety-relevant impacts. To what extent these measures are actually realised in an appropriate manner is to be shown on a plant-specific basis.

3.3 Hydrogen release into rooms outside the containment

- **Boiling water reactor SWR-72**

According to [15], the design of the recombiners installed in the containment is based on the scenarios of station blackout (total loss of the three-phase power supply, loss of main feedwater supply, failure of all active injection systems) with initial steam and hydrogen release into the wetwell and the main steam line break with the release of steam and hydrogen directly into the drywell. For an estimate on “hydrogen release into rooms outside the containment”, a scenario that proceeds slowly with regard to pressure build-up in the containment where containment venting is initiated at a relatively late stage is assessed to be dominating in [15] since it leads to correspondingly long lasting leakage from the containment. The estimate was based on the core meltdown scenario “wetwell temperature > 150°C due to loss of residual heat removal” (see Section 2.2) where it takes 11 hours until reaching the venting criterion.

Based on the explanations on the design of the containment seals in Section 2.2 and the peak temperatures reached accordingly in representative scenarios in the area of the containment penetrations, the RSK concludes that for the assessment to be performed here according to Section 3.1 and the scenarios to be referred to, no leakage rate larger than considered in the design has to be postulated.

The RSK holds the view that the core meltdown scenario “wetwell temperature > 150°C due to loss of residual heat removal”, in [15] taken as a basis for estimating the hydrogen release into rooms outside the containment, together with the above postulations can generally be regarded as sufficiently representative in terms of Section 3.1. The PSA Level 2 for the SWR 72 boiling water reactor does not indicate any need for using additional representative scenarios.

According to [15], the estimate on hydrogen release into rooms outside the containment results in a hydrogen concentration of about 0.85 vol% at the time of initiation of venting for the room area above the 18.5-m level. The ignition limit of 4 vol% hydrogen will not be reached until then.

Since the formation of hydrogen does not end with the venting and there will still be a pressure gradient between the containment and reactor building, the leakage will be reduced with containment venting, but not terminated. Without countermeasures in the reactor building – with postulated hydrogen leakage into this room volume and the same leakage rate – it can be assumed that the ignition limit will be reached within two to three days.

Based on the above explanations, the RSK confirms that the formation of ignitable mixtures within a few days has to be postulated. Therefore, the RSK recommends the introduction of measures in the manual for mitigative severe accident management measures (HMN) to remove the air-hydrogen mixture from the rooms of the reactor building in which an ignitable mixture may be formed. In this respect, the possibilities of activity retention are to be taken into account.

- **PWR**

With [9], GRS presented results from [21 – 24] to the RSK in which the formation of combustible mixtures was analysed, taking into account the potential for vertical stratification of the gas mixture in the annulus for different scenarios of uncontrolled loss of coolant accidents and transients. According to GRS, these scenarios and the underlying boundary conditions include the event sequences on which the design of the recombiners is based. They cover the conditions of pressure and temperature development that are characteristic in connection with the release of hydrogen into rooms outside the containment as well as the temperature distribution in the containment representatively in terms of Section 3.1. However, the analyses from [21 – 24] do not represent a systematic study on the conditions to be expected and the potential countermeasures.

For a leakage rate that is limited to the design leakage rate, the analyses of GRS do not show ignitable hydrogen concentrations in the stratified zones within the first 4 days for a leakage in the upper containment part either.

Based on the explanations on the design of the containment seals in Section 2.2 and the peak temperatures reached accordingly in representative scenarios in the area of the containment penetrations, the RSK concludes that for the assessment to be performed here according to Section 3.1 and the scenarios to be referred to, no leakage rate larger than considered in the design has to be postulated.

According to further analyses of GRS [25], for an unchanged rate of leakage into the annulus and without countermeasures it cannot be excluded that combustible conditions are reached in the annulus after about five days. Stratifications in the annulus atmosphere may lead to locally increased hydrogen concentrations.

To prevent the formation of combustible gas mixtures in such scenarios, the RSK recommends developing and implementing a measure within the framework of mitigative accident management measures for the recirculation of the atmosphere in the annulus (break-up of stratification) and controlled ventilation (limiting the increase in H_2 concentration) in a timely manner. For the annulus air extraction required for it, it is to be assessed whether measures to reduce the release of radioactive substances into the environment can be used here (e.g. filtering, discharge via stack). Alternatively, measures for hydrogen recombination can be provided.

4 Recommendations

As a result of its consultations, the RSK makes the following above-mentioned recommendations:

Recommendation 1:
With regard to the hydrogen release during filtered venting of the containment it is to be examined for PWR plants (see Section 3.2) on the basis of representative analyses in accordance with the approach outlined in Section 3.1 which emergency measures to prevent combustible conditions during containment venting in shared exhaust air systems, such as in the exhaust air chamber and the stack, can be provided. Alternatively, it is to be demonstrated that hydrogen combustion will not lead to safety-relevant impacts. To what extent these measures are actually realised in an appropriate manner is to be shown on a plant-specific basis.

Recommendation 2:
With regard to the release of hydrogen into rooms outside the containment of the SWR-72 boiling water reactor (see Section 3.3), measures are to be introduced in the manual for mitigative severe accident management measures (HMN) to remove the air-hydrogen mixture from the rooms of the reactor building in which an combustible mixture may be formed. In this respect, the possibilities of activity retention are to be taken into account.

Recommendation 3:
With regard to the release of hydrogen into rooms outside the containment of the PWR (see Section 3.3), a measure for preventing the formation of combustible gas mixtures is to be developed and implemented within the framework of mitigative severe accident management measures (HMN) for the recirculation of the atmosphere in the annulus (break-up of stratification) and controlled ventilation (limiting the increase in H_2 concentration) in a timely manner. For the annulus air extraction required for it, it is to be assessed whether measures to reduce the release of radioactive substances into the environment can be used here (e.g. filtering, discharge via stack). Alternatively, measures for hydrogen recombination can be provided.

References

[1] Sachstandsbericht KTA-GS-66
Zusammenstellung anlageninterner Notfallschutzmaßnahmen und die Prüfung ihrer Regelung im KTA
Salzgitter, June 1997

[5] Weiterleitungsnachricht zu Ereignissen in ausländischen Kernkraftwerken (WLN 2012/02)
Auswirkungen des Tohoku-Erdbebens an den japanischen Kernkraftwerksstandorten Fukushima Dai-ichi (1) und Dai-ni (11) am 11.03.2011 und des Niigataken Chuetsu-Oki-Erdbebens am japanischen Kernkraftwerksstandort Kashiwazaki-Kariwa am 16.07.2007
Kö1n, 15.02.2012

[6] Dr. Frank Sommer
H_2-Austrag in Räume außerhalb des SHB
Presentations, 93.and 94. AST meeting on 24.10.2013 and on 28.11.2013

[7] Dr. Frank Sommer, Carsten Ahrens, EKK Hannover
Wasserstoffeintrag in Gebäude außerhalb des SHB
Presentation, 96. AST meeting on 13.03.2014

[9] M. Sonnenkalb, GRS
Wasserstofffreisetzung in Räume außerhalb des Sicherheitsbehälters – Analysen für DWR
Presentation, 96. AST meeting on 13.03.2014

[11] M. Sonnenkalb, S. Schwarz, GRS
Wasserstofffreisetzung in den Kamin bei der gefilterten Druckentlastung
Presentation, 96. AST meeting on 13.03.2014

[12] U. Klapp, F. Sommer
Dichtigkeit des SHB bei schweren Störfällen
Presentation, 09.05.2014

[13] Reaktor-Sicherheitskommission, Stellungnahme der RSK "Gefährdung des Sicherheitsbehälters von DWR durch Wasserstoffreaktionen infolge der Zünderwirkung von passiven autokatalytischen Rekombinatoren", 03.09.2009 (419th meeting of the RSK)

[14] GRS, Kernkraftwerk Gundremmingen II (KRB II, Block B und C), Gutachterliche Stellungnahme zur Nachrüstung eines Wasserstoffabbausystems mit katalytischen Rekombinatoren im Sicherheitsbehälter, July 1999

[15] Reichenbach, Trobitz, 06.11.2014
Sachstand, Gefilterte Druckentlastung des Sicherheitsbehälters für SWR

[17] Reaktor-Sicherheitskommission, Empfehlung “Maßnahmen zur Risikominderung bei Freisetzung von Wasserstoff in den Sicherheitsbehälter von bestehenden Kernkraftwerken mit Druckwasserreaktor nach auslegungsüberschreitenden Ereignissen”, 17.12.1997 (314th meeting of the RSK)

[20] KGG Gundremmingen
Notfallhandbuch Teil 3, Kap 7, Druckentlastung SHB (Venting),

[21] M. Sonnenkalb
“Unfallanalysen für DWR mit dem Integralcode MELCOR 1.8.3”, June 1998, GRS-A-2579

[22] M. Sonnenkalb
Unfallanalysen für DWR vom Typ KONVOI (GKN-2) mit dem Integralcode MELCOR 1.8.4, Bericht zum Vorhaben SR 2306: „Bewertung von Maßnahmen des anlageninternen Notfall-schutzes zur Schadensbegrenzung für LWR“, December 2001, GRS-A-2954

[23] M. Sonnenkalb
„Bewertung von Maßnahmen des anlageninternen Notfallschutzes zur Schadensbegrenzung für LWR, Abschlussbericht zum Vorhaben SR 2306“, September 2001, GRS-A-2921

[24] S. Band, Schwarz, S., Sonnenkalb, M.
“Nachweis der Wirksamkeit von H2-Rekombinatoren auf der Basis ergänzender analytischer Untersuchungen mit COCOSYS für die Referenzanlage GKN-2, Vorhaben 3609R01375, Anforderungen an den Nachweis der Wirksamkeit von H_2-Rekombinatoren auf der Basis ergänzender analytischer Untersuchungen”, March 2012, GRS-A-3652

[25] M. Sonnenkalb, Wasserstofffreisetzung in Räume außerhalb des Sicherheitsbehälters – Fortsetzung von Analysen für DWR (siehe Basisvortrag 96. Sitzung des RSK Ausschusses AST), 104th meeting of the RSK Committee on Plant and Systems Engineering (AST), 12.2.2015

[26] Sicherheitsanforderungen an Kernkraftwerke
3 March 2015, BAnz AT 30.03.2015 B2