RSK recommendation
(476th meeting of the Reactor Safety Commission (RSK) on 24/06/2015)

# Demonstration of residual ductility/residual strength by means of an ECR limit curve

Note:
This is a translation of the RSK recommendation entitled
“Nachweis einer Restduktilität/Restfestigkeit mittels einer ECR-Grenzkurve”.
In case of discrepancies between the English translation and the German original, the original shall prevail.

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## 1 Background and request for advice

At the 78th meeting of the PLANT AND SYSTEMS ENGINEERING (AST) committee on 07/03/2012, GRS reported about the current state of experimental demonstration of the coolability criteria regarding loss-of-coolant accidents (LOCA) in pressurized water reactors (PWR) [1] and expressed doubts regarding the validity of the demonstration of the residual ductility of the cladding. The reason for these doubts were insights gained from experiments which suggested that the residual ductility of cladding depends not only on oxidation but also on the hydrogen concentration in the cladding. Hence operational as well as accidental (secondary) hydrogen up-take may lead to a loss of the residual ductility if cladding oxidation values lie below the verification criterion applied so far. Especially in areas of ruptured cladding it would then not be possible to safely exclude that the cladding might break upon thermal shock (quenching). If this involves a dispersal of fuel from the cladding, this might result in problems in connection with core coolability.

At its 93th meeting on 24/10/2013, the committee tasked an ad-hoc working group with discussing these issues. The working group was to clarify first of all whether and, if so, under which conditions the committee could agree to the proposal of GRS ("GRS limit curve"). Should a consensus on the latter not be possible, the working group was to make a new proposal for a different stipulation.

In a total of 7 meetings, the working group prepared this recommendation and the report about the current situation [2]. Both documents were discussed in detail by the PLANT AND SYSTEMS ENGINEERING (AST) committee and finalised at the committee's 107th meeting on 28/05/2015 for presentation to the RSK. The RSK adopted the recommendation at its 476th meeting on 24/06/2015.

## 2 Current situation

The current situation

- regarding the criteria for ensuring core cooling in a loss-of-coolant accident,
- regarding recent experimental findings, especially
  - concerning the influence of the hydrogen content at the start of the accident,
  - concerning the transient hydrogen up-take following the ballooning and burst of the cladding (secondary hydrogen up-take),
  - concerning break-away oxidation,
  - concerning the influence of the hydrogen up-take on embrittlement,
- regarding the proposal by the NRC to adapt the Equivalent Cladding Reacted (ECR) criterion as well as
- regarding a proposal by GRS to modify the ECR criterion

is described in detail in the report of the ad-hoc working group ECR of the AST [2]. Only excerpts of this description are given in the statement in hand.

## 3 Assessment

### 3.1 Need for modification of the ECR criterion applied so far by using an ECR limit curve dependent on hydrogen content (ECR(H) limit curve)

The RSK states that the currently applied 17%-ECR criterion according to the "Safety Requirements for Nuclear Power Plants" [3] does not sufficiently consider the material-specific effects of operational as well as accidental hydrogen up-take and has thus to be updated in the light of the recent findings presented (see report of the ad-hoc ECR working group of the AST [2]). What exactly has to be updated is specified in the following.

### 3.2 Safety demonstration for cladding by means of an ECR(H) limit curve

The 17%-ECR criterion that has been applied so far is based on so-called ring-compression tests of cladding samples that have previously been subjected to high-temperature oxidation [4]. In recent years, a number of ring-compression tests have been performed on partly pre-hydrogenated or irradiated cladding samples made of the materials used for present-day cladding [5].

The very short cladding samples used in the ring-compression tests are measured regarding the sample cross-section and the state of oxidation; they show no relevant axial variation of the ductility- and strength-reducing parameters. This favours the derivation of correlations between the hydrogen content of the cladding and the admissible ECR value. In this respect, the evaluation of ring-compression samples with exactly characterised properties and boundary conditions has fewer uncertainties than the evaluation of semi-integral tests[1]. This also allows the evaluation of the ring-compression tests by finite-element (FE) methods, as done by GRS in [6]. The evaluation allows the derivation of local material correlations, such as the failure stress/yield strength ratio as a function of the oxygen and hydrogen content, c.f. [6].

The hydrogen-dependent ECR limit curves (see figure 1) derived from these tests either directly [7] or by FE methods [6] can be applied without any further considerations to cladding sections outside the deformation and burst range as in this case there will be no relevant transient hydrogen up-take (no secondary hydrogen up-take) during the course of the LOCA (see section 3.3 below on this issue).

[1] Test set-ups simulating the thermal-hydraulic boundary conditions of a LOCA for one individual rod or a fuel rod bundle. Here, cladding sections are used that are filled either with real fuel or with a surrogate material.

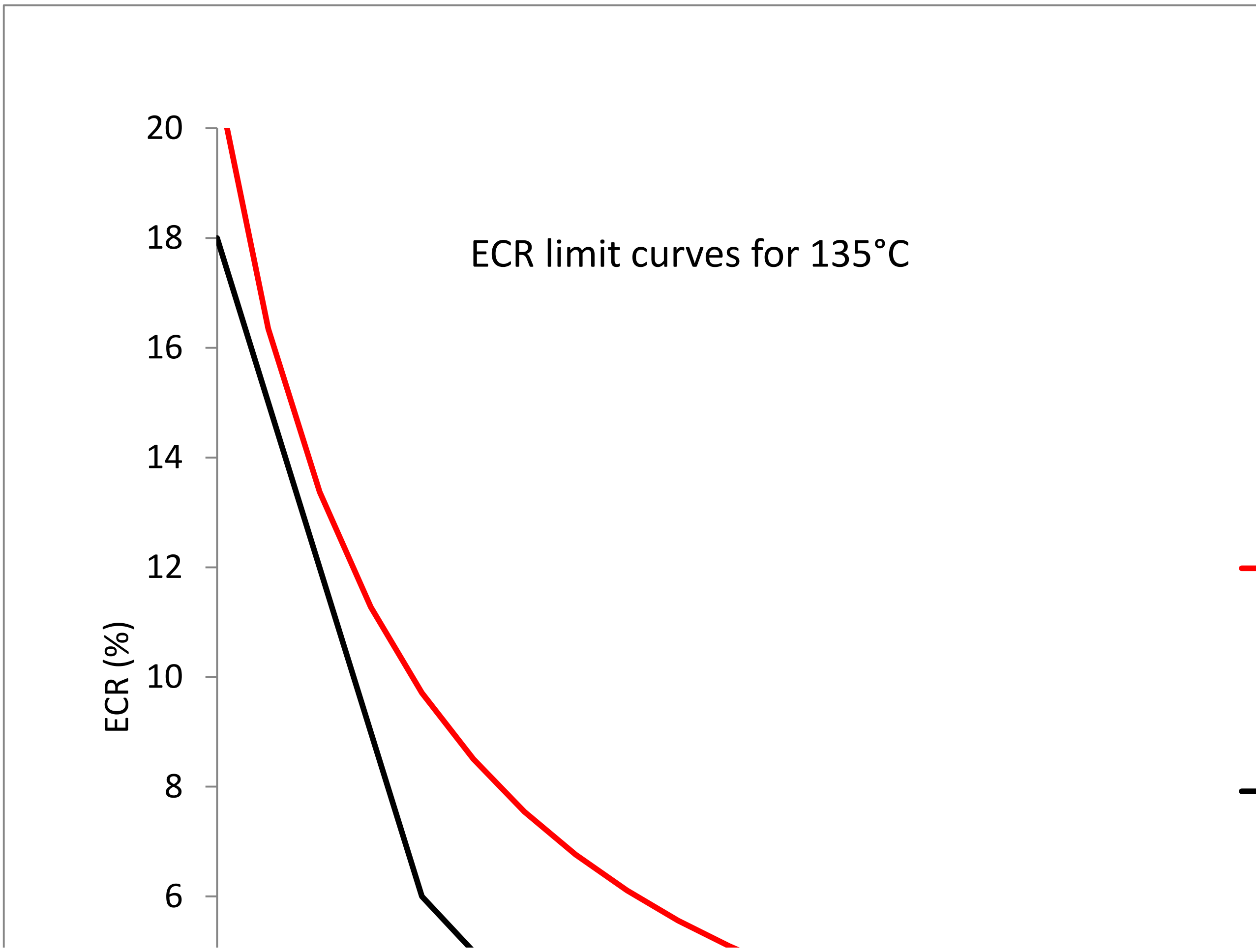


Figure 1: Comparison of the GRS limit curve according to [6] and the NRC limit curve according to [7].

On the other hand, the material changes brought about by the deformation and bursting are not fully covered by the samples subjected to ring-compression tests. Due to the geometrical conditions, ring-compression tests for material samples from the deformation and burst range cannot be used for determining limit curves. The damage symptoms in the semi-integral test in the area of the burst opening result from the combination of a reduction in the load-bearing wall thickness (the so-called prior-beta layer) trough deformation and oxidation, with an uptake of oxygen and hydrogen in this load-bearing layer [8]. Since semi-integral tests have shown [5, 9, 10] that the deformation and burst range is susceptible to embrittlement and cladding failure, there is a need for using different approaches to its assessment.

The hydrogen content of the cladding that stems from operational oxidation remains largely unchanged during high-temperature oxidation. This is added by the up-take of hydrogen into the cladding during a LOCA, which takes place exclusively following a bursting of the cladding and only on the inside of the burst opening (so-called secondary hydrogen up-take). In order to achieve a consistent result, the admissible ECR value would have to be compared with an axially distributed ECR(H) and H value that has originated under LOCA conditions when applying ECR(H) limit curves that take hydrogen content and secondary hydrogen up-take into account (as is the case with the ECR(H) limit curve derived by GRS).

For applying the ECR(H) limit curve to the deformation and burst range within the framework of the safety demonstration, at least the following prerequisites would have to be fulfilled:

a) The ECR(H) limit curve has to cover the necessary spectrum of relevant ECR values and hydrogen concentrations (fulfilled for the ECR(H) limit curve of GRS [6]).

b) The geometries of the ballooned area (incl. wall thicknesses) and the burst opening must be analytically predictable. It may be assumed that there is a dependence on the fuel rod condition at the start of the LOCA transient and on the cladding temperature/time distribution during the course of the transient.

c) The local distributions of the ECR values and the hydrogen concentration due to secondary hydrogen up-take must be analytically predictable. It may be assumed that there is a strong dependence on b) and on the cladding temperature/time distribution during the course of the transient.

d) Taking the respective local distributions of the ECR and H values from c), adherence to the ECR(H) limit curve would have to be verified locally.

e) Influences on the load transfer caused by the reduction of the wall-thickness of the cladding due to deformation as well as the fracture-mechanical effect of the crack geometry would have to be additionally considered.

In the opinion of the RSK, such a safety demonstration is currently not possible for the following reasons:

- There is no database available for a sufficiently exact modelling of b), c) and e).

- Regarding a numerical calculation of b), c) and e), there are presently merely approaches to modelling individual aspects available.

Against this background, a safety demonstration for the deformation and burst range is suggested that is composed of different elements (see subsection 3.4 on this issue).

The NRC limit curve is generally also applicable to BWR cladding materials (Zry-2). The cladding temperature/time distributions in connection with a LOCA in a German BWR differ clearly from those of a PWR (generally lower temperature level), so that a similar high-temperature oxidation (high ECR values) or a deformation and bursting of the cladding is not to be expected.

### 3.3 Safety demonstration for cladding sections outside the deformation and burst range

In the following, cladding sections outside the deformation and burst range are those sections that during a LOCA have neither suffered any noteworthy transient deformation nor have burst as a result of a deformation.

The problems described in subsection 3.2 in connection with the application of a ECR(H) limit curve to cladding sections with a deformation and burst range are not relevant for cladding sections outside the deformation and burst range. Since there is no transient hydrogen up-take, a safety demonstration using an ECR(H) limit curve for the operationally absorbed hydrogen is possible.

Regarding cladding sections outside the deformation and burst range, the RSK arrives at the following conclusions:

- The criterion for the Peak Cladding Temperature (PCT) of 1200° C is still suitable for preventing any impermissible embrittlement of the cladding as a result of increased oxygen solubility in the load-bearing prior-beta layer.[2]

- Having to maintain a residual strength instead of a residual ductility is a sufficient verification requirement since a fragmentation[3] of the cladding upon quenching is also prevented with a high degree of safety if a sufficiently high residual strength is ensured (for details, see subsection 3.4).

- To prevent fragmentation of the cladding in a LOCA, the ECR value has to be limited considering the operational hydrogen up-take. To this end, the NRC on the one hand presented an ECR(H) limit curve [7] that is based on the maintenance of a residual ductility in ring-compression tests. GRS, on the other hand, presented an ECR(H) limit curve [6] based on the maintenance of a residual strength at the level of the yield strength, cf. Figure 1. From the committee's point of view, based on the recent experimental results, both limit curves are thus suitable for preventing a fragmentation of the cladding.

In connection with the safety demonstration using the ECR(H) limit curve of GRS or the NRC, the following boundary conditions for the calculation of the ECR value have to be observed:

- For the calculation of the ECR value, the high-temperature oxidation on the outside of the cladding has to be taken into account.

- Operational pre-oxidation has to be taken into account in the form of a reduction of the cladding wall thickness.

- When calculating the ECR value, the reduction of the cladding wall thickness due to expansion has to be considered as an average over the cross-section.

- Since regarding oxidation, the ECR(H) limit curves of GRS and the NRC have been determined on the basis of the Cathcart-Pawel and Leistikow correlations, respectively, these correlations – or other correlations that are conservative in comparison - also have to be applied when demonstrating compliance with the admissible ECR value.

[2] When providing verification by means of the NRC limit curve, an experimentally conditioned limitation of the admissible PCT has to be considered for operational hydrogen concentrations larger than 400 ppm, cf. the corresponding remarks on the derivation of the NRC curve in [2].

[3] In this statement, fragmentation of the cladding is also understood as the bursting of the cladding in the deformation and burst range.

- A possible contribution of an additional inner oxygen up-take (e.g. from an inner oxidised cladding surface or the bonding layer between pellet and cladding) can be neglected because cladding without bursting shows a temperature-time distribution that is favourable in this respect.

- When determining the admissible ECR value, the operational hydrogen up-take has to be derived by means of experimentally validated correlations.

### 3.4 Safety demonstration for the deformation and burst range

In the deformation and burst range, it is not possible to ensure a residual ductility due to the possible high secondary hydrogen up-take and to the wall thickness reduction in combination with the crack geometry [4, 11].

Experiments have shown, however, that a residual strength of the cladding is sufficient to bear the loads occurring in a LOCA, exclude a fragmentation of the cladding, and thus ensure a coolable geometry [11]. To ensure a sufficient residual strength, a corresponding limitation of the transient oxidation is necessary and sufficient. This follows i.a. from

a) the KIT-QUENCH-LOCA experiments: these are bundle experiments involving cladding temperature-time distributions that are prototypical for German PWRs;

b) the JAERI/JAEA experiments: these show the capacity to bear additional axial loads compared with the KIT experiments;

c) considerations by the NRC regarding the applicability of its ECR limit curve to the deformation and burst range.

on a)
Although fuel rods have burst in the KIT-QUENCH-LOCA experiments that have been carried out so far and which are prototypical for German PWRs (involving Zry-4, but also the currently used cladding materials M5 and Optimized Zirlo), no fuel rod was fragmented upon quenching; cooling channel blockages of a maximum of 30% occurred. Post-examinations are still going on (cf. also the representations in [12, 13, 14]).

Below low ECR values of < 5%, which are prototypical for German PWR plants, the KIT-QUENCH-LOCA experiments that have been carried out so far have confirmed that there is no cladding fragmentation upon quenching.

on b)
The JAERI/JAEA semi-integral experiments were carried out with consideration of different external axial loads up to a full restraint of the cladding, see Figure 2. Zry-4 cladding segments with and without initial hydrogen content were subjected to a temperature transient with a target temperature of 1200 °C, during the course of which ballooning and bursting of the cladding as well as secondary hydrogen up-take occurred.

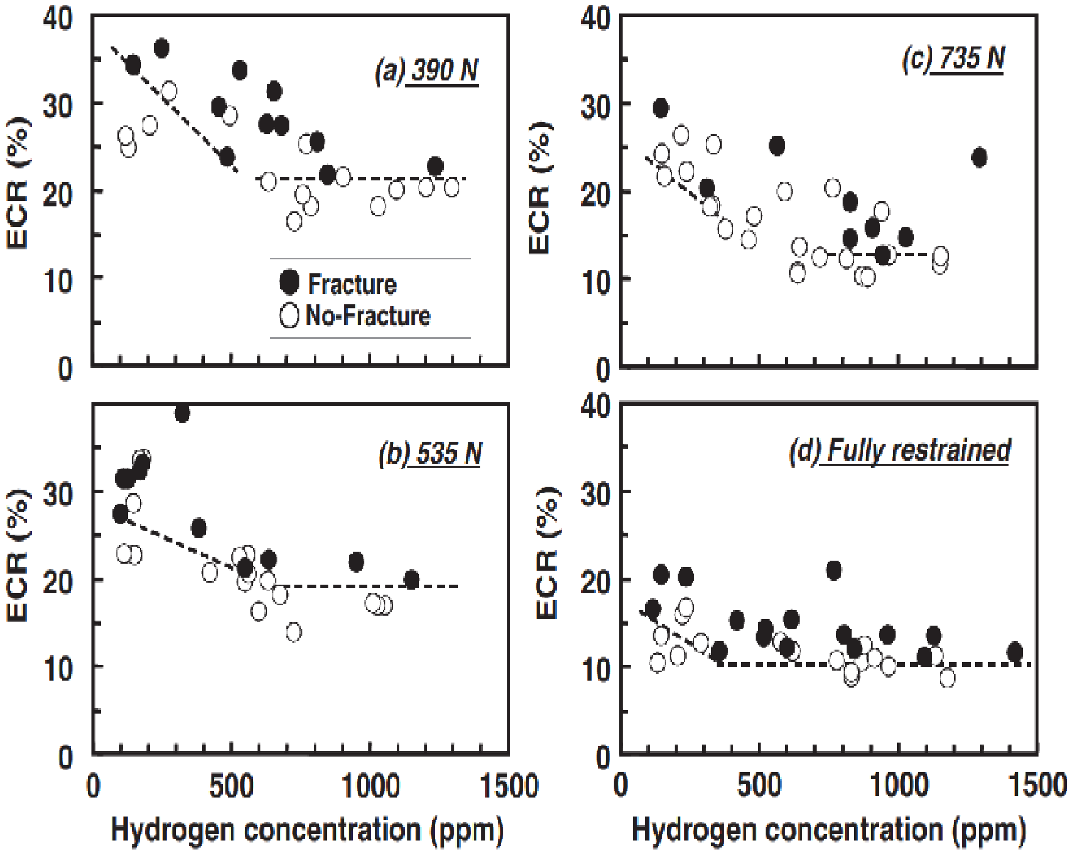


Figure 2: Admissible Baker-Just ECR value as a function of the forced loads and the operational hydrogen content (Figure 12 from [15])

The implementation of external axial loads shows that there are considerable margins compared with the thermal-shock loads that occur during quenching if the ECR values that are admissible for the respective load are satisfied.

The wall thickness of the cladding for fuel assemblies of a 17 x 17 geometry used in these experiments was at 0.510 mm and therefore less than that of the German PWRs (0.725 mm for 16 x 16 fuel rods and 0.640 mm for 18 x 18 fuel rods). Given an equal ECR value, the prior-beta layer bearing the load during quenching is therefore thinner in the experiments involving fuel rods in a 17 x 17 geometry than that of fuel rods in the German PWRs, so that this results in further margins.

Hence the ECR values determined in this connection by means of the Baker-Just correlation can be used as a reference for an estimation of the admissible high-temperature oxidation for the deformation and burst range. It has to be considered that when determining the ECR values in the deformation and burst range, the mean wall thickness of the cladding deformed in the ballooned area was used as a basis.

The JAERI/JAEA experiments back up the KIT experiments that are prototypical for the German PWRs. They show that considerable additional mechanical loads beyond the thermal-shock loads can be borne if the ECR value is limited correspondingly.

on c)
The NRC has reflected in [16] about the applicability of its ECR(H) limit curve derived from ring-compression tests also to the deformation and burst range and included in the process the relevant influences of the fracture geometry, the wall-thickness reduction, the inner oxidation through steam admission, and the resulting increased up-take of hydrogen. The background of these reflections was that these effects are not covered by the ring-compression tests. Additional to the ring-compression tests, semi-integral LOCA tests have been carried out and evaluated [9]. From these, the NRC concludes that if the admissible ECR values derived from the ring-compression tests are satisfied, an acceptable material behaviour (sufficient residual strength) is also ensured in the deformation and burst range, depending on the operational hydrogen content.

As the evaluation in [9] shows, the results of the semi-integral tests (high-temperature oxidation without external axial loads) and the subsequent 4-point bending tests carried out at ANL and Studsvik are consistent with the results of the JAERI/JAEA experiments.

Against the background of the findings presented under a) to c), the RSK comes to the conclusion that the ECR(H) limit curve of the NRC [7] can be used for the demonstration of a sufficient limitation of the ECR value in the deformation and burst range since – according to current knowledge – it sufficiently limits the degree of oxidation for the deformation and burst range in dependence of the operational hydrogen up-take. This covers implicitly the embrittling effect of the hydrogen up-take from secondary hydrogen up-take. The present experiment results show that if the ECR value is limited in accordance with the limit curve of the NRC, a sufficient residual strength in the deformation and burst area is ensured so that a fragmentation of the cladding upon quenching can be excluded. Hence, no additional data beyond the operational hydrogen content and the maximum ECR value resulting from the high-temperature oxidation are necessary for the demonstration.

In connection with the safety demonstration, a two-sided oxidation in the deformation and burst range following the bursting of the cladding has to be considered for the calculation of the ECR value. Apart from that, the boundary conditions given in subsection 3.3 apply for the safety demonstration.

The ECR values in the deformation and burst area cover the ECR values of the cladding sections that have not burst.

A sufficient residual strength of the cladding can also be demonstrated by applying the ECR(H) limit curve of GRS to the hydrogen up-take and oxidation profile along the deformation and burst range. Contrary to the ECR(H) limit curve of the NRC, additional data regarding the locally varying degree of oxidation and hydrogen up-take from the KIT-QUENCH-LOCA are necessary for the demonstration. The boundary conditions for this safety demonstration path are shown in Annex 1.

## 4 Conclusions

In summary, the RSK concludes the following from the discussions regarding the demonstration of a residual ductility/residual strength by means of an ECR(H) limit curve:

Cladding sections outside the deformation and burst range[4]

- The criterion for the peak cladding temperature (PCT) of 1200°C continues to be suitable for preventing an inadmissible embrittlement of the cladding due to increased oxygen solubility in the load-bearing prior-beta layer.[5]

- To prevent fragmentation of the cladding in a LOCA, the ECR value has to be limited in dependence of the operational hydrogen up-take. For this purpose, the NRC on the one hand has presented an ECR(H) limit curve [7] that is based on the maintenance of a residual ductility in ring-compression tests. GRS, on the other hand, has presented an ECR(H) limit curve [6] that is based on the maintenance of a residual strength at the level of the yield strength.

- From the committee's point of view, both limit curves are suitable for preventing a fragmentation of the cladding sections.

Cladding sections in the deformation and burst range

- In the deformation and burst range, a residual ductility cannot be ensured due to the possible high level of secondary hydrogen up-take as well as the wall-thickness reduction in combination with the crack geometry. Experiments have shown, however, that a residual strength of the cladding is sufficient for being able to bear the load occurring in a LOCA, for excluding a fragmentation of the cladding, and hence for maintaining a coolable geometry. In order to ensure a sufficient residual strength, a corresponding limitation of the transient oxidation is necessary and sufficient.

- If the ECR value is limited in dependence of the operational hydrogen up-take according to the ECR(H) limit curve of the NRC, a sufficient residual strength is ensured to be able to exclude a bursting of the cladding upon quenching. Here, the embrittling effect of the hydrogen up-take from secondary hydrogen up-take is implicitly covered. Therefore no additional data beyond the operational hydrogen content and the maximum ECR value resulting from the high-temperature oxidation are necessary for the demonstration.

- A sufficient residual strength of the cladding can also be verified by applying the ECR(H) limit curve of GRS to the hydrogen up-take and oxidation profile along the deformation and burst range. Here,

[4] Cladding sections which during a LOCA have either not suffered any noteworthy transient deformation or where the deformation that has occurred is not followed by a bursting of the cladding.

[5] When providing verification by means of the NRC limit curve, an experiment-conditioned limitation of the admissible PCT needs to be observed for operational hydrogen concentrations larger than 400 ppm, cf. the corresponding remarks on the derivation of the NRC curve in [2].

contrary to the ECR(H) limit curve of the NRC, it is necessary to provide additional data on the location-dependent degree of oxidation and hydrogen up-take from the KIT-QUENCH-LOCA experiments to underpin the demonstration. The boundary conditions for this safety demonstration path are given in Annex 1.

The NRC limit curve generally also applies to BWR cladding materials (Zry-2). The cladding temperature/time distributions of German BWRs during a LOCA differ from those of PWRs (generally lower temperature level), so that a comparable high-temperature oxidation (high ECR values) or deformation and bursting is not expected.

## 5 Recommendations

For the safety demonstration regarding the prevention of a fragmentation of the fuel rod cladding in a LOCA, the RSK recommends

- to use the ECR(H) limit curve of GRS [6] or the NRC [7] for cladding sections outside the deformation and burst range to limit the ECR value in dependence of the operational hydrogen up-take

- to use the ECR(H) limit curve of the NRC [7] for cladding sections within the deformation and burst range to limit the ECR value in dependence of the operational hydrogen up-take. Here, the embrittling effect of the hydrogen up-take from secondary hydrogen up-take is implicitly covered.

  Alternatively, the ECR(H) limit curve of GRS may be applied. The boundary conditions for this safety demonstration path are given in Annex 1.

When applying the ECR(H) limit curves, the following boundary conditions have to be kept:

- For the calculation of the ECR value for cladding sections outside the deformation and burst range, the high-temperature oxidation on the outside of the cladding has to be considered.

- For the calculation of the ECR value for cladding sections within the deformation and burst range, a double-sided high-temperature oxidation after bursting has to be considered.

- Operational pre-oxidation has to be considered in the form of a reduction of the cladding wall thickness.

- When calculating the ECR value, the cladding wall thickness reduction due to deformation has to be considered as a mean value across the cross-section.

- Since the ECR(H) limit curves of NRC and GRS have been determined for the oxidation on the basis of the Cathcart-Pawel and the Leistikow correlation, respectively, these correlations – or correlations which, as compared with them, are conservative – also have to be used for the demonstration of the adherence to the admissible ECR value.

- The respective operational hydrogen up-take to be assumed has to be determined by means of a correlation that has been validated on experimental data.

## Annex 1: Safety demonstration using the GRS limit curve with recourse to experimental results of the KIT experiments

The safety demonstration using the GRS limit curve for the deformed and burst area demands that the ECR value averaged over the circumference as well as the hydrogen content following secondary hydrogen up-take averaged over the circumference must be known for all axial positions of the deformation and burst range. Prototypical KIT-QUENCH-LOCA experiments provide the link of ECR values and the accompanying hydrogen content levels both averaged over the circumference. For the safety demonstration using the GRS limit curve, it is additionally necessary to establish a representative link between the fuel rods of a core load and the cladding tested at KIT.

An assessment of core loads in connection with the ECR curve of GRS should be made according to the following pattern:

1 Based on the thermal-hydraulic LOCA analysis for the fuel rod classes included in the core load, graded by burn-up and fuel rod power, the respective cladding temperatures and burst-induced deformations as well as the cladding oxidation levels of the burst location (maximum ECR value according to Leistikow) and the intact cladding section (ECR value in the proximity of the burst opening according to Leistikow) are determined analytically.

2 As the secondary hydrogen up-take that occurs in connection with the burst cladding cannot be calculated as matters stand today, recourse is made to fuel rod experiments of KIT that provide prototypical modelling of the fuel rod behaviour under LOCA conditions. This recourse provides that - in keeping with the calculated maximum ECR value and in keeping with the ECR value of the intact cladding section – the fuel rod from the KIT fuel rod bundles that covers both ECR values conservatively is used. The axial distribution of the secondary hydrogen up-take measured on this fuel rod is used and combined with the analytically determined ECR values.

3 A residual strength has been proven if all combinations of ECR values and hydrogen concentration values in the area of the burst opening lie below the GRS limit curve.

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