Recent RSK Amendments of Acceptance Criteria for the Analysis of LOCA

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47th Annual Meeting on Nuclear Technology
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Overview and disclaimer

• This presentation deals with the
  – RSK statement “Requirement for LOCA analyses by statistical methods”, April 2015,

• It represents the view of three RSK members who participated in the elaboration of these documents.

• Presumably the background and the spirit of the statement and recommendation should be adequately captured.

• However it is not an official RSK presentation.
Background

- In 2005 RSK passed a recommendation on requirements for statistical LOCA analyses.
- In the context of a pilot analysis for a German PWR the consideration of these requirements led to several questions.
- These are picked up in the April 2015 RSK statement on statistical LOCA analyses.
- This presentation focuses on the acceptance criterion of 1200°C for peak cladding temperature (PCT), mainly relevant for large break LOCA (LBLOCA) analysis.
• With respect to sufficient cladding ductility and strength after a LBLOCA temperature transient testing results show the detrimental influence of hydrogen in the cladding (due to operational and so-called “secondary” hydriding).

• Like several other institutions around the world, the RSK examined whether a revision of the former LOCA criterion concerning sufficient cladding ductility and strength (i.e. the 17% ECR criterion) is necessary.
RSK statement on “Requirement for LOCA analyses by statistical methods”

• According to the 2005 RSK recommendation a statistical treatment of model and plant parameters is admissible.
• However, maximum values for total core power and local power density, as determined by the reactor power limitation system (RLS), have to be assumed. Only measurement and calibration errors can be treated statistically.
• Especially the maximum local power density (respectively the stored energy) has a strong influence on the PCT.
• While applying the 2005 RSK recommendation the question arose whether total core power and local power density could also be treated statistically based on “realistic” operational values.
Basic methodological questions

• The safety demonstration should provide a high degree of confidence that all fuel rods in the core meet the PCT criterion.

• Here “high degree of confidence” is to be understood in a qualitative sense not in a strictly mathematical-statistical manner.

• Concerning „high degree of confidence“, the recent RSK statement mainly deals with two questions:
  a) Which methodological approach assures that the result of the safety demonstration implies $\text{PCT} \leq 1200^\circ\text{C}$ for all fuel rods?
  In the context of a statistical LOCA analysis: How can the result “$\text{PCT} \leq 1200^\circ\text{C}$ for all fuel rods with a high probability and a high degree of confidence” be achieved?
b) How can it be assured that the boundary conditions of the safety demonstration (especially concerning total core power and maximum local power density) are not violated during operation?
The “classical” bounding approach

a) Validity of demonstration for all fuel rods in the core

- The safety demonstration does not consider all fuel rods but only one single rod, the hot rod (HR). This “single-rod” approach is comparable to DNB analysis for PWRs.
- The HR combines several adverse properties which in combination are expected to result in a PCT value that bounds the respective maximum temperatures of all realistic fuel rods in the core – despite all the variability that is present in the core.
- These adverse properties are expected to have a very low (not further quantified) probability of common occurrence.
- However, a strictly analytical demonstration that this expectation is fulfilled is not available. It is based on engineering judgment and large experience with sensitivities of LOCA analyses.
b) Compliance with boundary conditions

• Important operational parameters influencing PCT are the spatial distribution of power density, maximum local power density and total core power.

• Selection of bounding values for power density and total power, whose compliance is assured by the reactor power limitation system, and the most adverse top peaked power profile ensure that the boundary conditions of the safety demonstration are not violated during operation.
Statistical LOCA analysis

a) Validity of demonstration for all fuel rods in the core

• In case that the penalizing adverse properties of the HR are removed and more realistic operational values for multiple hot rods are chosen, the basic principle of the safety demonstration based on a “single-rod” approach is questioned.

• Even in the case that for every rod in the core the 95% / 95% one-sided tolerance limit is shown to be less than 1200°C, one cannot automatically deduce that $PCT \leq 1200°C$ for all fuel rods with a high probability and a high degree of confidence (most probably it is the case if hot rods have $PCT << 1200°C$).
• As an example, assume that there are 2000 realistic hot rods in the core. For each of these realistic hot rods the probability for $PCT < 1200°C$ should be exactly 99%. Therefore the 95% / 95% one-sided tolerance limit is smaller than 1200°C for each rod, i.e. every rod fulfills this statistical acceptance criterion.

• However in this case the expectation value for the number of fuel rods with $PCT > 1200°C$ is 20. This is due to large number (2000) of relevant rods in the core.
Concerning statistical LOCA analyses with “realistic” input values, RSK therefore decided to set up an acceptance criterion for the whole core:

With a probability of 95% and a 95% degree of confidence at most one fuel rod is allowed to exceed a PCT of 1200°C.

Alternatively the safety demonstration can also be based on the analysis of one fuel rod in the core (like in “classical” HR analysis). In this case the equivalence of the “single-rod” approach with the acceptance criterion for the whole core has to be shown.
b) Compliance with boundary conditions

- Realistic operational values for total core power and maximum local power density are lower than the respective set points of the RLS.
- In the case that the values for these parameters are realistically chosen for the safety demonstration their adherence during operation is no longer ensured by the RLS. Adherence has to be assured by other means.
- The RSK statement asks for evidence that the probability distributions utilized are valid (or bounding) for the core cycle(s) under consideration.
• Probability distributions have to be based on full power operation. They should incorporate operational experience and the results of pre-calculation of the power density distribution for the relevant cycle(s).

• Administrative provisions have to be taken into account as well as the influence of the relevant control and limitation systems.

• The deviation of core parameters from pre-calculated values to be expected during the cycle has to be taken into account as well as the uncertainty of the calculation compared to measurement.
• Additionally, possible power density effects of fuel element bow have to be considered.
• Set points of the RLS have to be incorporated into the probability distributions.
RSK recommendation on “Demonstration of residual ductility/residual strength by means of an ECR limit curve”

Background of the RSK recommendation

- High temperature oxidation of fuel cladding leads to an embrittlement of cladding material due to phase transitions and increased oxygen solubility.
- Hydrogen taken up during normal operation and “secondary” hydrogen picked up during the LOCA transient due to stagnant steam conditions (inside the fuel rod after cladding burst) leads to further embrittlement.
"Safety Requirements for Nuclear Power Plants" specify the well-known 17%-ECR criterion as one of the acceptance criteria for LOCA analysis.

According to the Safety Requirements this criterion should assure the preservation of sufficient residual ductility of the cladding to avoid fragmentation of cladding (and subsequently of the fuel) during quenching.

A working-group of RSK’s committee on “Plant and Systems Engineering” intensively discussed the actual state-of-the-art concerning avoidance of cladding/fuel fragmentation during LOCA.
The conclusion was that the 17%-ECR criterion does not sufficiently consider the material-specific effects of operational as well as transient hydrogen up-take and has thus to be updated in the light of the recent findings.
Technical Background

• The 17%-ECR criterion is mainly based on so-called ring-compression tests of cladding samples that have previously been subjected to high-temperature oxidation.

• Supplementary semi-integral and mechanical tests have been conducted to evaluate cladding behavior during and after LOCA transients.

• Ring-compression tests are usually performed with non-deformed samples cut from fresh or irradiated cladding.

• For fresh cladding the effect of hydrogen is evaluated by hydrogen loading prior to the tests.
• It is well known since the 1970s that hydrogen has a detrimental effect on the ductility of the cladding.

• In recent years, a number of ring-compression tests have been performed on fresh and irradiated samples made of the actual cladding materials (e.g. ZIRLO and M5).
The influence of cladding burst

• Cladding behavior during quench is markedly influenced by cladding ballooning and eventual burst.

• In the ballooned and burst region mechanical behavior of the cladding is influenced by significant material thinning, presence of a crack and massive hydrogen uptake in the cladding around the burst opening due to stagnant steam inside the fuel rod (secondary hydriding).

• The material changes caused by ballooning and bursting are not fully covered by the samples subjected to ring-compression tests.

• It was already recognized in the 1970s that the requirement of retaining sufficient residual ductility cannot be fulfilled for the ballooned and burst region.
• Massive hydrogen uptake due to secondary hydriding and the presence of the burst crack lead to significant embrittlement. Concurrently wall thinning due to ballooning reduces the load bearing cross section of the cladding.

• However, by limiting the ECR value, sufficient residual strength can be retained to accommodate the quenching loads and to avoid cladding fragmentation.
• Semi-integral tests with fuel rod simulators subjected to temperature transients and quenching are used to evaluate the behavior of ballooned and burst cladding. Also subsequent mechanical tests (4-point-bending tests) have been performed recently.

• The results of a large number of semi-integral tests allow the determination of ECR values as a function of the hydrogen content such that sufficient cladding strength is retained after the LOCA transient.
Limit curves for ECR values in dependence of hydrogen content

- Based on an evaluation of ring-compression tests limit curves for admissible ECR values in dependence of the hydrogen content of the cladding were derived by US NRC and GRS.

**US NRC Curve**

- The curve of US NRC refers to operational hydrogen pickup and is limited to maximum hydrogen contents of 800 ppm.
- It is based on the retention of some residual ductility of intact cladding sections loaded in ring-compression tests. The tests were performed after high temperature oxidation.
• Effects of ballooning and burst as well as secondary hydriding are not explicitly incorporated in the US NRC curve.

• However, it was shown by additional experiments that sufficient residual strength in the ballooning / burst region (including the effect of secondary hydriding) is preserved if the US NRC curve is adhered to.

• The “margin” contained in the US NRC curve due to its reference to residual ductility provides this sufficient residual strength.
**GRS curve**

- The GRS limit curve is also valid for very high hydrogen contents.

- It is derived from the recalculation of a significant number of ring-compression tests (essentially the same as the tests used for US NRC curve) and is based on the retention of residual strength of the cladding (at the level of the yield strength).

- The hydrogen uptake due to secondary hydriding after cladding burst is covered by the limit curve. Other effects that occur in connection with ballooning and burst are not part of the data basis of the curve.
RSK’s main conclusions

Cladding sections outside the ballooning / burst region

• The criterion for the peak cladding temperature (PCT) of 1200°C is still suitable for preventing an inadmissible embrittlement due to high temperature (limitation of oxygen solubility).

• To prevent fragmentation of the cladding in a LOCA due to high temperature oxidation, the ECR value has to be limited in dependence of the operational hydrogen up-take (limitation of transient oxidation).

• The limit curves derived by US NRC and GRS are both suitable for preventing a fragmentation of the cladding sections on quenching.
Cladding sections within the ballooning / burst region

- 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.
- 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 limit curve of the US NRC, a sufficient residual strength is ensured.
• The hydrogen up-take from secondary hydriding 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 limit curve of GRS to the hydrogen up-take and oxidation profile along the deformation and burst range.

• Here, contrary to the limit curve of the US 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 listed in an appendix of RSK’s recommendation.