EXPERIENCES WITH FRACTURE MECHANICS LEAK-BEFORE-BREAK EVALUATIONS WITHIN THE GERMAN INTEGRITY CONCEPT FOR NPPS

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ABSTRACT

The Integrity Concept for mechanical components and systems practiced in German nuclear power plants (NPPs) is a concept to ensure break preclusion including the application of the Basic Safety Concept. In the German Basic Safety Concept the fundamental requirements of materials, design and manufacturing of the safety relevant components and pipe systems are defined, completed by independent redundancies keeping in mind unit specific conditions.

Only if break preclusion has been verified for safety relevant pipe systems, reduced leak postulates can be used: In general a leak of 0.1 x pipe section or smaller leaks based on a fracture mechanics foundation.

Therefore the evidence of break preclusion contains the ensurance of a design and manufacturing following the Basic Safety Concept as well as of knowing and controlling the causes of possible in-operation degradation mechanisms combined with a numerical leak-before-break fracture mechanics analysis.

The paper presents the outlines of a fracture mechanics evaluations procedure within a break preclusion evidence methodology. The procedure is agreed by the several German TÜV inspection organisations for NPP and takes into consideration recent national and international developments. The attention is in particular turned to the well-founded determining of safety margins as integral parts of the fracture mechanics analysis

KEYWORDS

Leak-before-break, basic safety, break preclusion, leak postulate, safety margin

1 INTRODUCTION

In German nuclear power plants (NPPs) usually the so-called Integrity Concept [1] for mechanical components and piping systems is applied. This includes the Basic Safety Concept as well as the Principle of Break Preclusion.

During the last years there was an ongoing discussion about content and coverage of pipe break preclusion analyses against the background that there are no distinct determinations for fracture mechanics verification in the German nuclear technology regulations. Hence no state-of-the-art evaluation standards are established comparable e.g. to the U.S. NRC Standard Review Plan, Chapter 3.6.3 [3] and the French RCC-MR, Appendix A16 [4]. Further standards and regulations, e.g. ASME Code, Section XI [5], R6 [6] and FITNET [7] procedures, API 579 [8] and FKM-guideline [9], were advanced during the last years.

Therefore several German TÜV inspection organisations have developed VdTÜV report 62 “Fracture mechanics verification to validate reduced leak assumptions in pipes (break preclusion)” [2].

2 PRINCIPLE OF BREAK PRECLUSION AND LEAK-BEFORE-BREAK VERIFICATION

Leak-before-break verification is regarded as one but not the only part of the Principle of Break Preclusion: If a crack grows/breaks locally through the wall of a pressurized component it has to result in a stable, detectable leak rather than in a sudden, disruptive break. One side of the analysis is the verification of material engineering and fracture mechanics Leak-Before-Break Behaviour (*grown* < *critical* crack size, e.g. $2c_{Leck} < 2c_{krit}$). The other side is represented by the Leak-Before-Break Criterion (leakage detectability and deduction of measurements, i.d. $2c_{LÜS} < 2c_{krit}$). Both sides result in a complete leak-before-break verification. Figure 1 exemplarily shows this in a Leak-Before-Break diagram.

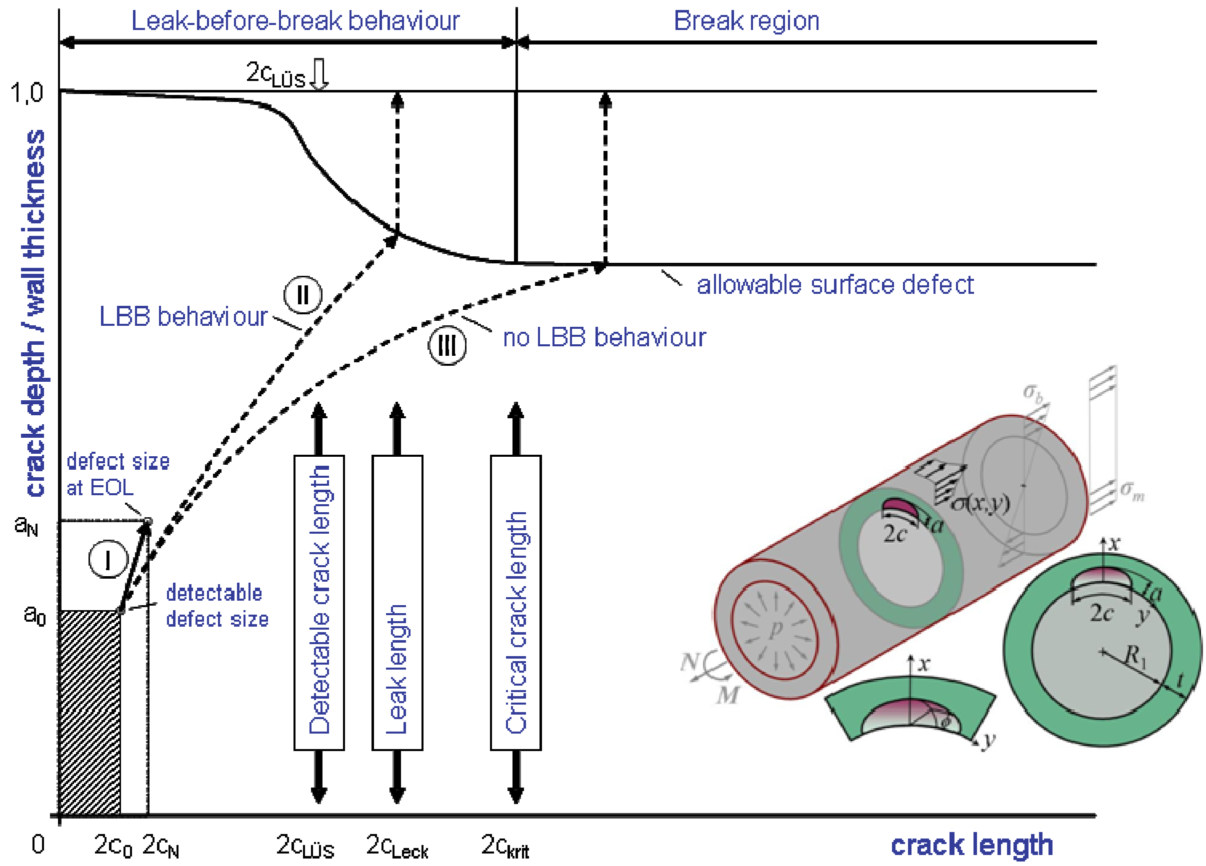

Figure 1: Leak-Before-Break diagram, schematically

The Principle of Break Preclusion is the aim behind the German Integrity Concept for mechanical NPP components and piping systems. The basic precondition for the application of reduced leakage assumptions in German NPPs is the compliance with the demands of the Guidelines of the Reactor Safety Commission (RSK) [10] and the KTA rules, e.g. [11]. The Integrity Concept contains the following main principles, which are also enclosed in the Basic Safety Concept, as described in [10], see Figure 2:

- Compliance of Basic Safety principles
  (fabrication quality by design, materials and manufacture)
- In-service monitoring to detect and restrain the causes of possible degradation mechanisms on time.
- Evaluation of ISI data to validate that no degradation mechanisms are active, i.e. that no inacceptable crack growth occurs.
- Fracture mechanics validation of no large break.
- Validation of negligible crack growth by means of a crack growth analysis.
- Leakage detection system as an additional device of in-service monitoring.

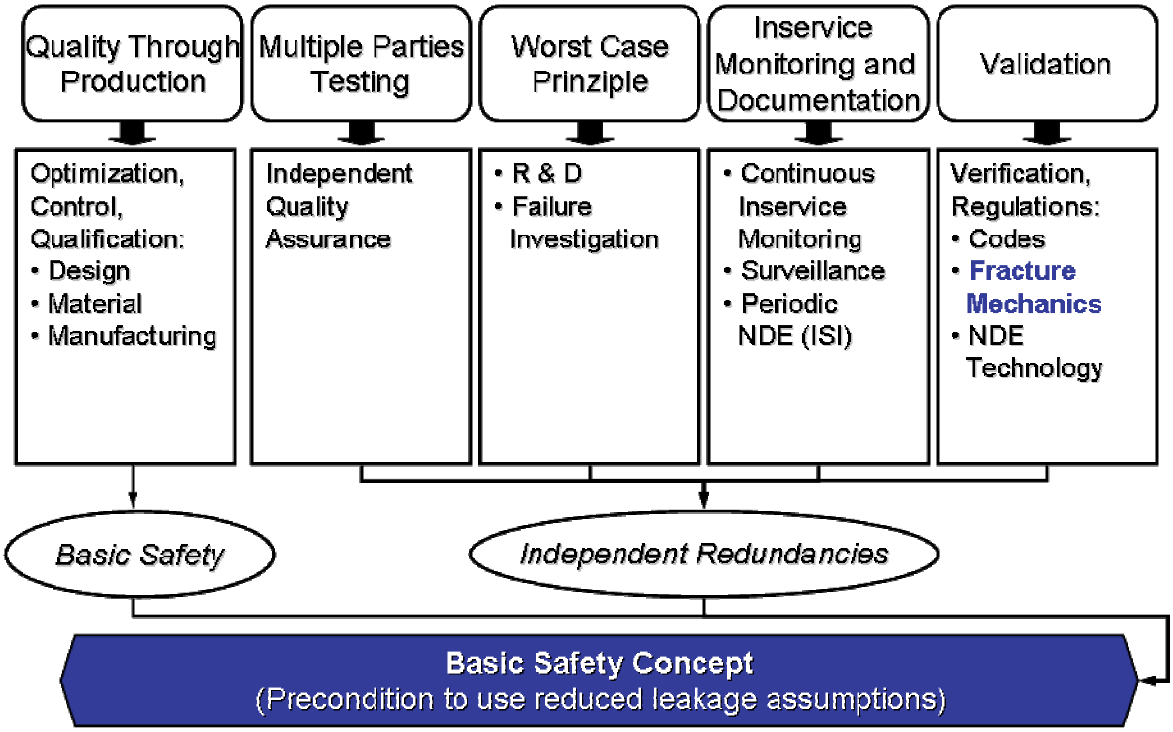

Figure 2: Basic Safety Concept

If break exclusion has been verified for safety relevant pipe systems then reduced leak postulates can be used: In general a leak of 0.1 x pipe section or smaller leaks based on a fracture mechanics foundation.

This paper will focus on the fracture mechanics specifications for the leak-before-break verification as a part of break preclusion evaluations, as presented in VdTÜV report 62 [2].

3 VERIFICATION CONCEPT

VdTÜV report 62 [2] presents the fracture mechanics evaluation procedure within a break preclusion evidence methodology agreed for NPP applications by several German TÜV inspection organisations cooperating within VdTÜV. The verification concept of [2] to validate leak-before-break includes the following evaluation steps as its basic principles:

1. Postulation of initial defects (surface cracks).
2. Calculation of surface crack growth.

3. Validation of acceptance of grown surface defects.
4. Evaluation of defect size detectable with the means of the leakage detection system (at normal operation conditions).
5. Through-wall crack validation:
   The critical crack length must be larger than the detectable crack length.

These evaluation steps are based on several requirements and qualifications which in general were mentioned in chapter 2 above and are exemplified in the following explanation.

3.1 Postulate of Initial Surface Defects

The postulated initial cracks must be larger than cracks detectable by the used non-destructive evaluation (NDE) technique and/or present defects in the pipe. According to [2] generally postulated defect geometries are:

- A short semi-elliptical surface crack
  with a crack depth $a = 0.3 \cdot t$ during a wall thickness $t < 25\ mm$
  and $a = 0.2 \cdot t$ during $t \geq 50\ mm$ respectively.
  Linear interpolation between $25\ mm \leq t < 50\ mm$ is allowed.
  The crack length should be $2c \geq 6 \cdot a$.
- A long surface crack with a constant crack depth of $0.1 \cdot t$.

If smaller defect sizes are used this has to be justified. The postulate of initial defect sizes strictly implies the qualification of the defect detection capabilities of the used NDE technique as well and the knowledge of the defect status of the considered piping.

3.2 Calculation of Surface Crack Growth

Crack propagation of the postulated initial surface defects for the regarded operation time has to be considered, taking into account the load cycles of normal and upset operation conditions as well as pressure tests (level A, B and P service loads). Erosion, corrosion or high cycle vibrations may not question the verification concept.

The influencing parameters of potential operational damaging mechanisms have to be recorded and evaluated within the in-service monitoring acc. to the rule KTA 3201.4 [11]. Fatigue crack propagation may be described by using the Paris law or derivatives, taking into consideration also environmental influences. For NPP piping components made of ferritic steel the fatigue crack propagation rates acc. to ASME Code, Section XI [5], Appendix A can be used, for austenitic nuclear piping components ASME Code, Section XI [5], Appendix C in combination with NUREG CR-6176 [12] may be applied.

3.3 Acceptance Validation of the Grown Surface Defect

The acceptance validation of the grown surface defect postulate is an important inherent cornerstone of the evaluations procedure presented in [2]. It implies the verification of the surface crack stability against global failure (pipe break), including distinct safety factors. This verification is neither an allowance evaluation of detected flaws nor a leak preclusion criterion. It is one way to verify Leak-Before-Break Behaviour (*grown* < *critical* crack size) that is in general slightly more restrictive than the way presented in Figure 1 above.

All specified loads in all service load levels A – D have to be contained in the verification as well as secondary stresses including residual stresses. Therefore the surface crack verification against global failure is not self-evidently covered by the verification of a through-wall crack of the same crack length because possible higher weld residual stresses may be taken into account in the surface crack analysis.

The critical surface crack size calculated by means of fracture mechanics evaluations and divided by a safety factor results in an acceptable crack size. Break preclusion is validated if the *grown surface* defect size ≤ *acceptable* defect size.

From our point of view, safety factors are necessary as inherent parts of the analyses because they help to cover the following and more hardly-quantifiable uncertainties in:
- geometry (e.g. actual radius, wall thickness, pipe ovality, misalignments)
- fracture mechanics material property values
- NDE: flaw detectability, defect position, geometry and size
- local load evaluation (weld type and form)
- calculation model (supports, non-linear pipe system characteristics).

Keep in mind that in the new revisions of ASME Code, Section XI [5] the term “safety factors” has been replaced by “structural factors”.

Safety factors for the acceptance validation of the surface defect acc. to [2] are different for different service load levels, see table 1. The safety factors on primary loads are in the style of ASME Code, Section XI [5]. For all secondary stresses the safety factor 1.0 is proposed.

service load level (plant operating conditions)		A (normal)	B (upset)	C (emergency)	D (faulted)
safety factor	primary stress	2,7	2,4	1,8	1,4
	secondary stress	1,0	1,0	1,0	1,0

Table 1: Safety factors for stability verification of surface defects, acc. to [2]

The overall safety factors listed in table 1 can be replaced by partial safety factors if detailed investigations were done about scattering of the analysis input parameters, see e.g. [6] - [9].

3.4 Through-Wall Crack Assumptions

The first step of the through-wall crack evaluations according to VdTÜV report 62 [2] is to evaluate the detectable defect length $2c_{LÜS}$ (see Figure 1) regarding the installed leakage detection system. Only normal plant conditions have to be taken into consideration. The detectable leakage mass flow rate must be known and validated. A safety factor of 10 on the detectable mass flow rate is usual and well accepted e.g. according to U.S. NRC Standard Review Plan [3] to estimate the corresponding leakage area and crack length of a through-wall crack. But the safety factor can be modified if the local flow resistance of the leak is taken into consideration in a validated manner.

As explained in clause 3.3 above, acc. to VdTÜV report 62 [2] Leak-Before-Break Behaviour has to be verified not as grown < critical *through-wall* crack length but by the acceptance validation of the grown *surface* defect. This way prevents the need of re-characterising a wall-penetrating surface crack as through-wall crack of a leakage length $2c_{Leck}$. But in the actual fracture mechanics evaluation procedures [6] and [7] as well as in the French rule [4] one can find recommendations for that re-characterisation. Our own experiences and FEA calculations have confirmed the assumption that the outside crack length $2c_{Leck}$ of a wall-penetrating surface defect is in general smaller than the grown inner-surface crack length .

3.5 Through-Wall Crack Validation

The detectable crack length $2c_{LÜS}$ of a through-wall crack calculated according to clause 3.4 above including a safety factor on the mass flow rate has to be found as smaller than the critical through-wall crack length $2c_{krit}{}^*$. The critical through-wall crack length shall be evaluated as the minimum crack length expected to fail under all service load levels except double-ended guillotine break (DEGB) load cases in the same pipe line.

According to VdTÜV report 62 [2] the same fracture mechanics evaluation procedures [6] and [7] should be used for the estimation of the critical through-wall crack length $2c_{krit}{}^*$ as well as for the stability verification of the surface crack according to clause 3.3 above.

A safety factor of 1.4 shall be put on primary loads. This overall safety factor can be replaced by well established partial safety factors.

3.6 Illustrative Example

Figure 3 shows the results of a carried out leak-before-break analysis in a Leak-Before-Break diagram. It illustrates all 5 evaluation steps of the verification concept according to VdTÜV report 62 [2] as listed in clauses 3.1 - 3.5 above.

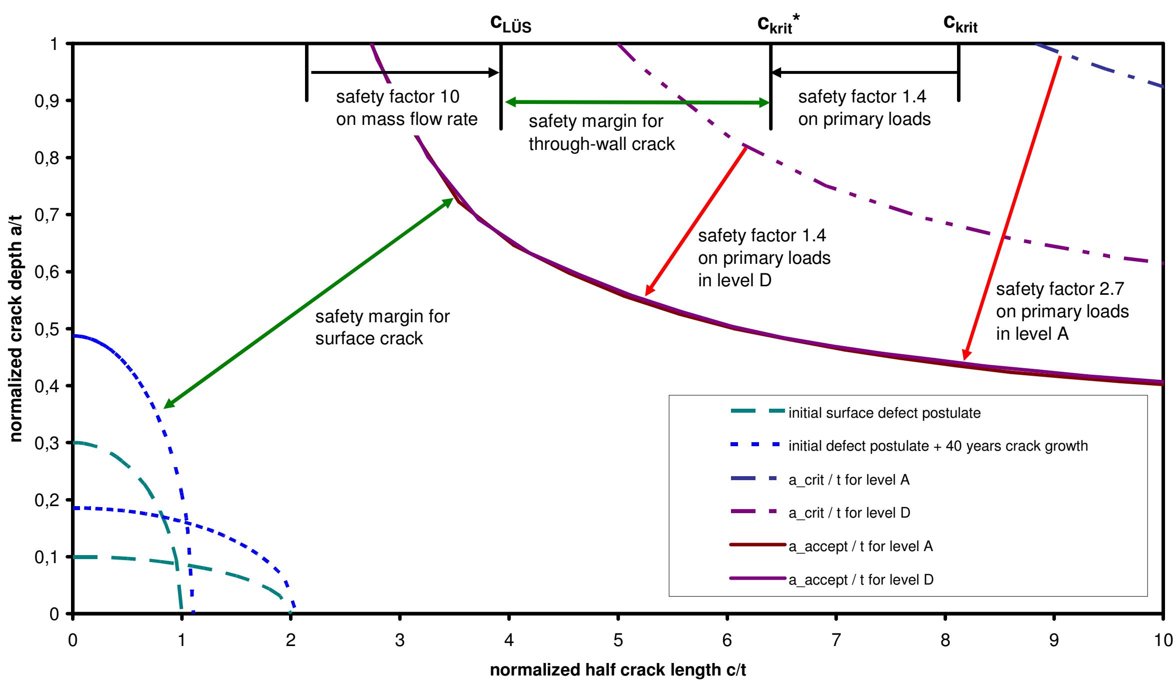

Figure 3: Leak-Before-Break diagram, calculation example

As can be seen in Figure 3 the Leak-Before-Break Criterion is fulfilled and Leak-Before-Break Behaviour is verified. Safety factors are applied acc. to [2] and safety margins are calculated both for surface as well as for through-wall defect assumptions.

Figure 4 gives a more detailed explanation of the through-wall crack lengths shown in Figure 3. The critical through-wall crack length $2c_{krit}$* was calculated by comparing the crack driving force represented by the elastic-plastic J-integral acc. to [7] with the material crack resistance J_{mat}. Furthermore the figure shows the strongly non-linear relation between leakage mass flow rate $\dot{m}$ and the associated leakage crack length.

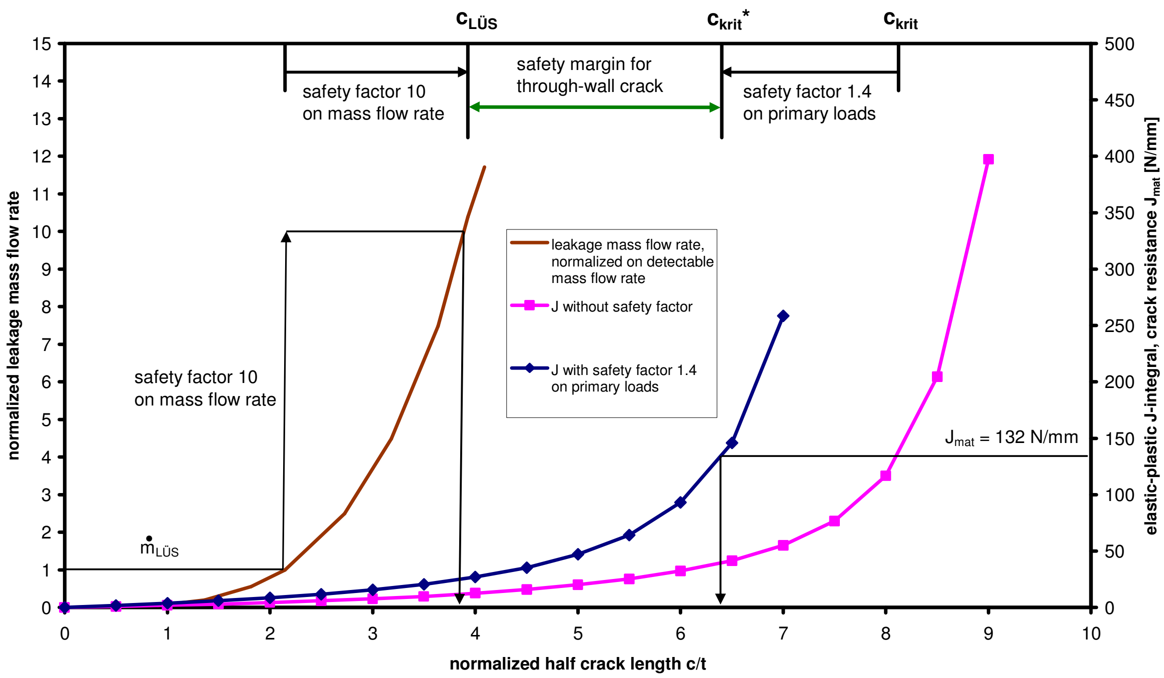

Figure 4: Through-wall crack length justification

4 SUMMARY

The paper presents task, objectives of verification, conditions and verification concept of the German VdTÜV report 62 [2].

The verification concept of VdTÜV report 62 [2] to validate Leak-Before-Break Behaviour as well as the Leak-Before-Break Criterion includes the following evaluation steps:

1. Postulation of initial defects (surface cracks).
2. Calculation of surface crack growth.
3. Validation of acceptance of grown surface defects.
4. Evaluation of defect size detectable with the means of the leakage detection system (at normal operation conditions),
5. Through-wall crack validation:
   The critical crack length must be larger than the detectable crack length.

Explicit safety factors are recommended in VdTÜV report 62 [2] for steps 3, 4 and 5 as inherent and essential parts of the analysis.

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