Leak Before Break Considerations for LMFBR Structures

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Abstract

Design and safety aspects of LMFBR's are discussed. The specific conditions of LMFBR's and in particular the pool-type reactor now favoured in Europe for commercial use are outlined. The leak-before-break-criterion is evaluated with respect to the pool design and the safety concept. A procedure is proposed to demonstrate the leak-before-break-behaviour by fracture mechanics analyses. The corresponding boundary conditions are discussed.

1. Introduction

The development of LMFBR's is accompanied by extensive international efforts regarding the qualification and selection of structural materials for the coolant boundary and components. To achieve the requisite level of safety relative to other reactor types different requirements have to be met depending on the characteristic design and operating conditions of LMFBR's such as:

- The coolant sodium is operated well below the boiling temperature.
- The operating pressure is low and depends solely on the discharge head of the pumps, which results in relatively thin-walled vessels and piping structures.
- The main loadings result from thermal transients and thermal expansions.

The first two conditions are regarded as essential by the licensing boards in the USA and Japan to classify sodium systems as Moderate Energy Fluid Systems (MEFS) / 1 - 3 /. The background of this classification is the very small amount of stored mechanical energy in such a system. Thus only small leakages have to be considered. The consequences of postulated coolant leakages on the reactor core and subjected components and structures depend on plant design, leakage location and size. Particularly in case of the pool-type reactor now favoured for commercial LMFBR's in Europe (SPX-1, -2; SNR 2) the definition of the coolant boundary with respect to in-pool structures (pipes and shells) has to be revised.

2. Design and Safety Aspects

Design, material selection and criteria for quality assurance are the basement for integrity demonstrations of the coolant boundary. The following criteria are specified:

- Design and stress analysis in accordance to structural design criteria for all operational conditions.
- Quality assurance in accordance with high standards throughout construction and installation.
- Selection and qualification of tough materials.

By designing in accordance to codes various failure modes are precluded. The effects of small defects are intended to be covered by "safety" factors as defined usually. Design basis is the reference leakage, a well defined upper-bound leakage size in accordance to hypothetically formed stable through-wall cracks.

The objective of achieving the requisite structural integrity level necessarily includes the evaluation of cracked structures / 4 /. The effect of macroscopic defects on the mechanical behaviour of the structure is investigated. A judgement for crack nucleation processes in a perfect structure is not given by fracture mechanics analyses. The objective of investigations is the demonstration of integrity and structural stability:

- No significant propagation of initial defects.
- Formation of stable crack configurations including leakages (leak-before-break-behaviour).

Particularly for the second objective specific plant design features play a dominant role. Using the results of crack growth calculations the change in the safety margin between an initial defect, a postulated initial leakage and sizes of unstable crack configurations can be analyzed. The importance of such an analysis and its relevance to safety aspects depend on information about several parameters, e. g. loading of the structure, geometry of crack and structure and material data.

The limited potential for crack growth under in-service loadings is demonstrated. Significant crack growth which may cause leakages in a systematic manner is possible only due to some loading histograms of a plant life. As can be seen from fig. 1 the leak-before-break criterion is equivalent to the preclusion of rupture. Its general objective is the demonstration of structural stability by analyzing the crack stability. However, this type of fail safe behaviour can be demonstrated also by other diverse measures within the safety analyses.

The prime objective of corresponding fracture mechanics investigations is the demonstration of limited potential for crack length development. From fig. 2 the two possible ways to demonstrate preclusion of rupture by fracture mechanics arguments are obvious as explained in the following. They both rely on the required "safety distance" between a defect and its critical configuration for the particular situation:

- Demonstration of limited potential for crack growth, particularly in length direction (shifting the crack development line to the left).
- Demonstration of a great "critical" crack size or, if possible, the exclusion of rupture by comparing the stored mechanical energy in the system with its crack growth resistance properties (shifting the double crossed area and the critical crack length to the right).

3. Demonstration of Leak-Before-Break

To demonstrate the leak-before-break-behaviour of the coolant boundary a procedure has been developed. The procedure is based on the following conclusions:

The equivalence of the leak-before-break-criterion with the preclusion of rupture (see fig. 2) clearly shows that in case of a leakage its detection is a sufficient information for the fail safe behaviour of a structure. However, with no signal on hand the failure behaviour of the presently stable structure is not clear, i. e. a global plastic instability is not excluded. One example of such a situation is a long, slender and stable part-through crack (see right bottom area of fig. 1). All cracks longer than the critical cracks are stable as long as they are positioned below the ligament instability line. Their type of failure following a phase of stable growth e. g. due to in-service loadings is an instability (and not a stable leakage). For such cracks the leak-before-break-philosophy cannot be used. Therefore it is concluded that preclusion of rupture implies the use of other criteria than leak detection only.

A detectable leakage will not cause rupture in case of

- sufficiently low primary stresses,
- a ductile material,
- low deformation velocities,
- a rapid decrease of loading.

The procedure for the demonstration of fail safe behaviour (preclusion of rupture) is shown schematically in fig. 3. The procedure is proposed for the following boundary conditions:

- Initial cracks may grow in service by fatigue, creep and/or combined loading. A conservative assessment has to be chosen.
- The choice of a surface crack is conservative with respect to other locations / 5 /. Theoretical and experimental data are a solid basement for the evaluation of cracked LMFBR structures.

- The fracture mechanics requirements to the non-destructive examinations depend significantly on the type of investigations (integrity or type of failure).
- Usually the investigations are carried out for the piping structures which are regarded as representative for the plant.
- Leakages although excluded by design measures would occur most probably in highly stressed areas, weldments and locations without possibility to classify the state by in-service inspection or leak detection. In a LMFBR piping structure this location is found for example in the crown of an elbow.
- A leakage is defined as a through-crack. A stable leakage will not cause significant geometry changes of the structure.
- Leakage sizes depend on local conditions. Fracture mechanics calculations indicate that the leakage rate changes with the 3rd power of local stresses whereas the crack growth rate - i. e. the change of the leak length - is a function of the exponent of the crack growth law, i. e. approximately 4 for fatigue and 14 for creep. It can be concluded that relative to higher stressed areas the crack growth rate decreases more rapidly than the leakage rate. Therefore at lower stressed areas the leak detection is favoured in relative terms.
- Creep induced failure being initiated e. g. by coalescence of creep defects has to be excluded by design and in-service measures.
- Rupture is defined for cracks reaching the critical configuration leading to failure of a structure. The critical crack size of the proposed procedure is defined as shown in figs. 1 and 2. This size is not tolerable due to a number of different aspects including fracture mechanics arguments and is not necessarily identical with failure. Further open questions as for example the character of deformation have to be considered conservatively.

The procedure proposed is as follows:

After defining the initial crack at the start of the plant the propagation is calculated by using the loading histogram of the plant for the particular location investigated and the material properties. The structural stability (no significant geometry changes) is checked by investigating the stability of the crack. For cracks longer than the critical crack no fail safe behaviour is possible, i. e. rupture is not precluded. Vice versa by starting with the critical crack configuration those initial cracks can be calculated which will lead to fail safe behaviour. For cracks shorter than the critical crack it has to be checked in the next step, whether the crack will penetrate the wall forming a small, stable leakage. In case of a part-through crack without a leakage the calculation of crack growth will proceed. Usually a high number of loading histograms of a plant life are necessary within the calculations to cause wall penetration. For this situation the detectability of the leakage has to be checked together with an evaluation of necessary steps to keep the plant in a safe state. The failure of this type is classified as "fail safe" (leak-before-break or preclusion of rupture). If the leak is not detectable there is no necessity to classify the type of failure as "not fail safe". It is proposed to use the loading histogram of at least one plant life for calculation of the specific crack and check again the stability. If this crack remains stable the situation is also regarded as "fail safe".

This discussion clearly shows the two steps of fracture mechanics analyses within the licensing procedure. Prime objective is the demonstration of integrity with no significant changes of cracks under in-service conditions. The second step is the demonstration of a fail safe behaviour under boundary conditions.

In case of the pool-type reactor the fail safe behaviour is demonstrated for the in-pool pipes and sheets without referring to leak detection. An equivalent level of safety is reached by replacing the not usable leak detection through other measures as for example higher fabrication and quality standards and an improved design. The in-pool structures are guiding the sodium flow; they are not coolant boundaries in the sense of loop systems. In case of the pool reactor this definition is valid only for the secondary piping structure and the auxiliary systems.

According to this the design of SNR 2 pool reactor is based on the leak-before-break philosophy, with demonstrations of fail safe behaviour by fracture mechanics analyses. They are carried out for locations regarded as representative for the plant. These investigations are showing the fail safe character of the plant; they are additional to other investigations demonstrating integrity.

4. Consequences

The procedure proposed can be used to show the fail safe behaviour of a plant. One of the technical consequences is that the requirements for pre-service inspections can be specified in the way that long, slender cracks must be detected. By using adequate conservative boundary conditions those cracks can be quantified. All stable, detectable through-cracks are tolerable in terms of the leak-before-break-criterion by showing a fail safe behaviour. If such cracks are not detectable they are also regarded as tolerable by showing a fail safe behaviour. In this case their stability has to be demonstrated after calculating the leak propagation by using the loading histogram of at least one plant life.

There are various possibilities for either a global or a local different strategy for the plant. This choice depends on the evaluation of non-destructive examinations. They are regarded as one of the redundant measures in the safety strategy of nuclear power plants. Relevant questions to be answered are intensity, quality and type of non-destructive examinations with respect to results of fracture mechanics analyses. Further on certain requirements have to be met by design and function of the plant of which the most important are:

- The possibility for building up thermal strains has to be minimized.
- The elbow radius shall be adapted in accordance to diameter and wall thickness.
- The function of piping hangers and snubbers and/or bellows has to be verified.
- The in-service history of highly loaded locations shall be documented, in-particular by measuring temperature, pressure and geometry changes.

To verify the proposed procedure and the corresponding calculational methods component tests are necessary. Results of a related test are given in / 6 /. The greatest potential for improving the calculational methods is seen for investigations on surface crack behaviour under elastic-plastic conditions and by further development of the tearing modulus approach.

5. References

- / 1 / NUREG - 0800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, USNRC, Rev. I, July 1981
- / 2 / NUREG - 0986, Safety Evaluation Report Related to the Construction of the Clinch River Breeder Reactor Plant, Doc. No. 50.537, March 1983
- / 3 / Y. Nakai, T. Mochizuki, K. Kawashima, Safety Aspects in the Design of "MONJU", Proc. LMFBR Safety Topical Meeting, July 19 - 23/1982, Lyon-Ecully, France, vol. I, 105 - 114
- / 4 / H. Zeibig, L. Grüter, M. Fortmann, Investigations on the Integrity of Fast Breeder Reactor Piping and Components, Proc. 10th MPA-Seminar, October 10 - 13/1984, vol. 2, paper 34; to be published also in Nucl. Engng. & Design
- / 5 / L. Grüter, Evaluation of Part-Through Flaw Behaviour for Leak-Before-Break in LMFBR-Structures, ASME-Paper 84-PVP-18, 1984
- / 6 / P. Meyer, M. Fortmann, S. Bhandari, J. Hélot, Crack Propagation Testing of a LMFBR Elbow at Operating Temperature, Proc. SMIRT - 8, Brussels, Aug. 19 - 23, 1985, Paper F2G1/1*

Figure 1: Crack and failure behaviour in a structure

- ① Surface crack at start of plant
- ② Surface crack after plant life
- ③ max. surface crack leading to a stable leak after plant life
- ④ Surface crack at ligament-instability
- ⑤ Stable leak

Figure 2: Scheme of crack development

LEAK - BEFORE - BREAK-CONCEPT

Figure 3: Leak-Before-Break-Concept