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Discussion of the rules to be applied for the leak before break analysis of the primary loop piping

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ABSTRACT

Several technical and regulatory issues pertaining to the application of the Leak Before Break (LBB) methodology to the primary loop piping of pressurized water reactors are discussed and illustrated by examples from the LBB applications to the Belgian units.

INTRODUCTION

The Leak Before Break (LBB) concept allows to eliminate the double-ended guillotine break of the primary loop piping from the design basis, whenever it can be demonstrated that the presence of an hypothetical flaw will produce a detectable leakage well before reaching a size sufficient to induce a break. This situation can be demonstrated by a fracture mechanics analysis of the flawed component, under normal operating and accident conditions (including the Safe Shutdown Earthquake (SSE)). This concept was successfully applied to the primary loop piping of five Belgian pressurized water reactor (PWR) units, operated by the utility Electrabel.

The licensing of these studies gave rise to extensive discussions with the Belgian Safety Authorities, of the details of the rules to be applied for such analyses. Although U.S. rules are generally applied in Belgium, in this particular case the Safety Authorities imposed several additional requirements leading to an increased conservatism.
At the light of this experience, this paper presents a discussion of the rules to be applied for a Leak Before Break analysis of the primary loop piping, and of some related technical issues. Although no definite answers are proposed to all of these questions, the consequences of the selected rules are illustrated by practical examples of their application to the Belgian units.

REGULATORY CONTEXT

The use of the LBB concept was first accepted by the NRC in 1984 in the Generic Letter 84-04 [1], and the Code of Federal Regulations [4] was amended in 1987 to permit the use of LBB in all qualified high energy piping.

The detailed discussions of the limitations and acceptance criteria for LBB applications is provided in Nureg 1061 volume 3 [2]. A Standard Review Plan Section (3.6.3) entitled "Leak before break evaluation procedures" [3] was published for comments in August 1987 and is still not published in a final form at the present date. Many LBB analyses worldwide are based on these documents, and this is also the case for the analyses performed for the Belgian units.

MAIN BENEFITS OF THE LBB APPLICATION

A detailed discussion of the benefits of the LBB analyses of the Belgian units is beyond the scope of the present paper and can be found in [6]. Since some of the regulatory requirements discussed later are related to those benefits, they are summarized hereafter:

- In some units where three large bore hydraulic snubbers were installed on each primary pump, the LBB made it possible to reduce the overall number of snubbers on the primary loops from 9 to 3 in each plant, which represented a significant saving in terms of investment cost (these snubbers had to be replaced for maintenance reasons), but also of the integrated maintenance cost of this equipment for the remaining life of the plant and of the radiation dose to the workers.
- The LBB facilitated the steam generator replacement operations that were carried out in Tihange 1, Doel 3 and Doel 4 plants, by allowing not to reinstall some pipe whip restraints that had to be dismantled for the replacement operation.
- The LBB made it possible to justify some supports of the primary loop in stretch-out conditions, which would have been very difficult otherwise since these supports already had a small margin with respect to the acceptable value for the design conditions.
- In the same context of stretch-out conditions, the LBB, by eliminating the large LOCA, also made it possible to justifiy the integrity of the reactor pressure vessel (RPV) and internals despite the increased loading resulting from the lower primary coolant temperature. Specific analyses remained nevertheless necessary, due to special requests from the Safety Authorities, that will be discussed later.
- The LBB approach was also used to justify the primary coolant pump overspeed. In case of large LOCA at the pump outlet, with simultaneous loss of the connection to the grid, the overspeed of the pumps could reach values unacceptable for the flywheel. Eliminating the large LOCA solved the problem, although limited analyses still had to be performed, but with longer opening times (3 sec.). In this case the overspeed was limited to a few percents of the nominal speed.
- The LBB approach was also used to avoid significant modifications of pipe whip restraints and accident supports of primary loop piping in some units, where these structures were not designed in accordance with the present requirements.

METHODOLOGY

The LBB demonstration was performed in accordance with the requirement of the U.S. regulation, which are also applicable to the Belgian units ([1] to [3]). These requirements form the basis of most LBB analyses performed to date, and have been described extensively in numerous publications. They do not need to be explained in details any more, and only the main steps of the analysis are summarized hereafter:

- demonstrate the absence of degradation mechanisms which could challenge the integrity of the piping (water hammer, stress-corrosion cracking, erosion/corrosion, fatigue, etc.);
- demonstrate by a fatigue analysis that an existing flaw would not grow significantly under service transients;
- establish pipe material properties, taking into account service degradation (thermal ageing);
- calculate the service and accident loads at the different locations in the primary circuit ;
- calculate at different locations the size of the through-wall flaw yielding a leakage equal to ten times the detectable leakage under service loading which is called the "leakage crack size" a_q;
- demonstrate for each location that the critical crack size a_c under accident loading (for a combination of loads in absolute sum) is at least two times larger than the "leakage crack size" a_q.

DISCUSSION OF A FEW TECHNICAL AND REGULATORY ISSUES

Selection of locations to analyze

U.S. rules require to analyze the location(s) where the highest stresses coincide with the worse material properties. Experience shows that such a selection is far from being trivial, the LBB margins being influenced by the service stresses, the accident loadings, and the material properties. Selecting "a priori" some locations requires to be able to justify that they are indeed the most limiting, which may lead to long licensing discussions. In order to avoid the potential problem, the option was taken in Belgium to analyze systematically most of the primary loop piping welds, eliminating only those for which it could easily be demonstrated that they could be enveloped by the selected locations. This led to analyze 21 locations, for circumferential welds only, (figure 1) without increasing significantly the cost of the study thanks to the development of specific softwares allowing a large automatization of the analysis.

Accident loadings:

The only accident loading under which the through-wall flaw stability must be demonstrated according to the U.S. regulatory documents ([2], [3]) is the Safe Shutdown Earthquake (SSE). For low seismicity regions, the loads resulting from this accident are far from being the most severe, and the steam line break for example may produce much higher loads in some specific locations of the primary coolant piping. The Belgian Safety Authorities required to take this loading into account, which is more conservative than the usual U.S. procedure, and the Steam Line Break (SLB) case was analyzed assuming a double-ended guillotine break of the steam line at the location which results in the highest forces on the steam generator. Since the steam generator snubbers, located roughly at mid-height of the steam generator, practically constitute a fixed point, the loading due to a SLB results in a very high tensile force in the hot leg (additional with the tensile force due to the internal pressure) and a very high bending moment at the steam generator inlet elbow (see table 1 hereafter).

The rupture of the main auxiliary lines connected to the primary piping (pressurizer surge line, ECCS line from the accumulators and shutdown cooling line) was considered as well.

Table1: Forces and moments at the steam generator inlet nozzle

	Fx (axial) kN	Mx (bending) kNm	My (bending) kNm	Mz (torsion) kNm
Dead weight	30	8	2	3
Pressure	7650	0	0	0
Thermal expansion	589	2045	-58	-79
SSE	645	486	243	102
Steam Line Break	2306	1650	37	33

Weld material properties

Another point where the regulatory texts are imprecise is the selection of the material properties for the analysis of welds, generally characterized by a lower tearing resistance than the base materials, but a higher yield stress. The most conservative approach would be to consider the base material tensile properties combined with the tearing resistance of the weld. This approach was judged to be exceedingly conservative, and two analyses were performed, one with base material properties, and the other with weld properties.
The results show that the influence is negligible for the leakage size crack, since under operating load the structure remains largely elastic. For the critical crack size, it appeared most of the time that the base material was the limiting location, since the higher yield stress of the welds more than compensates their lower tearing resistance. This conclusion obviously depends on the relative properties of the weld and the base material, and is not considered to be of general validity.

Pipe thickness to use in the analysis

The regulatory documents do not specify explicitly the pipe thickness to be used in the analysis: nominal design value, as-built value or minimum specified value? A related question is how to take into account a localized underthickness of the pipe? The policy followed in Belgium was to use the nominal thickness, for consistency with the piping analysis generating the loads to be applied. This is also consistent with the position expressed in [2], which states that the LBB approach should be implemented conservatively, but that large margins are not required at each stage of the process provided that the overall objective is met. A localized underthickness would only be of concern if its extension was larger than the critical crack size.

Loads to be considered for the justification of RPV and steam generator internals

When the LBB behaviour is successfully demonstrated for the primary loop piping, this eliminates the need to consider a large break LOCA. In this case, the question remains of the loading to be considered to justify the integrity of the reactor pressure vessel and steam generator internals if the operating conditions are modified (e.g. due to power uprating or operation in stretch-out conditions).
Considering that some design basis events were not analyzed in details because they were enveloped by the postulated double-ended guillotine breaks of the primary loop piping, the Belgian Safety Authorities argued that the LBB application might reduce the protection against these other unspecified events. Therefore, they required to consider in the design basis of the reactor core and internals, and for the steam generator tube bundle, the instantaneous rupture (1 ms) of the steam generator manhole covers (hot leg and cold leg), as well as a slow break (3 s) of one times the flow area, anywhere in the primary coolant piping.
More information on the regulatory aspects and the specific requirements of the Belgian Safety Authorities may be found in [5].

LBB in the steam generator replacement context

The steam generator replacement may have an impact on the LBB analysis, depending on the technique used for the replacement operation and particularly for the welding in place of the new steam generators. In the case of a steam generator replacement in "two cuts", displacements may have to be imposed to the cold leg and hot leg, in order to close the loop. This clearly introduces residual moments that influence both the leakage crack size and the critical crack size, and must be taken into account in the LBB analysis, although this is not required by the U.S. rules.
The moments induced in the loops by a displacement of a few millimeters necessary to close the gap become rapidly very large, and their effect on the LBB margins is far from negligible. The problem is in fact posed in slightly different terms, namely: what are the limits that must be imposed on the displacements applied to the primary loop piping by the steam generator replacement operations (permanent displacements after rewelding) in order to ensure that the resulting residual moments will not reduce the LBB margins below their required value?
Since this type of loads is not considered in the SRP 3.6.3, no rules are given for their combination with the other loads. It is clear that the combination must be algebraic for the definition of the resulting service moment to be used for the evaluation of the leakage crack size a_q.
The criterion generally used in Belgium on the crack sizes is that there must exist a margin of 2.0 between the critical crack size a_c and the leakage crack size a_q, the load combination being made in absolute sum for a_c. The absolute sum combination, if applied blindly to all types of loads including the residual moments, does not make any sense since the residual moment has a direction and a magnitude that are constant during the whole remaining life of the unit. The consequence of such a combination method would be that a residual moment reducing the service moment, which in itself is a beneficial effect reducing the probability to develop a crack, would appear as detrimental in the LBB analysis. In order to overcome this difficulty, a slightly modified combination technique was used. First, the thermal and residual moments were combined algebraically, and, being both of secondary nature, were considered as an "equivalent secondary moment" (treated conservatively as primary for the analysis). The rules

of the SRP 3.6.3. were then followed rigorously, the only difference being that the thermal moments are replaced by this "equivalent secondary moment".

The methodology developed to determine the limits to be imposed on the displacements resulting from a steam generator replacement, are beyond the scope of the present paper, and their description may be found in [6]. Some typical results on the effect of residual moments on a_c, a_q and the LBB margins are given on figure 2, in a simple case assuming that the service, accident and residual moments have the same orientation, and on figure 3 in the more general case of two residual bending moments. This figure gives the curves of isovalues of a_c/a_q. The resulting limits imposed on the pipe end displacements are typically of the order of 10 to 20 mm in each direction, which is larger than the displacements measured in most steam generator replacements (these limits correspond to a LBB margin $a_c/a_q = 2$).

It is worth mentioning that these studies may also be used to optimize as much as possible the position of the new steam generators in order to maximize the LBB margins by imposing displacements in the favourable direction. This possibility can be used for example to alleviate the effect of the high thermal expansion moments in the hot leg piping.

Fatigue crack growth

Numerous analyses of the fatigue crack growth of a reference flaw in the primary piping have been performed to date, and to the knowledge of the authors the LBB analyses performed for PWR primary loop piping worldwide never led to difficulties to justify the acceptability of the fatigue crack growth during the foreseen operating lifetime of the plant. The question can therefore be asked if such analyses must still be performed on a plant-specific basis for each LBB application, or if one can rely on generic studies. An intermediate position was taken in Belgium, were analyses performed for two units were judged to be sufficiently general to cover the other units. The order of magnitude of the fatigue crack growth, calculated in a very conservative manner, is given on figure 4.

Another question regarding the fatigue crack growth analyses concerns the need to grow the crack, by applying service transients corresponding to several "lifes" of the unit, until the crack grows through-wall, in order to check its stability at breakthrough. This corresponds to the German practice, while in the U.S. the regulation only require to demonstrate that the fatigue crack growth during the operating life is acceptable, and that no mechanism is present that would be susceptible to grow a circumferential flaw on a significant fraction of the circumference (which could be the case for IGSCC for example).

Thermal stratification

The LBB was not applied up to now to a pressurizer surge line in the Belgian units, due to known thermal stratification problems, leading to significant fatigue. It is felt, however, that such an application could be beneficial, by allowing to remove some pipe whip restraints which in the present configuration contact the piping during some thermal stratification transients, increasing the stresses and the fatigue in the line. Increasing the clearances in these restraints would not be possible because in this case the pipe whip loads would become too large for the design of the restraints.

Nothing fundamental prevents the application of the LBB to these lines, but of course the stress analysis must be done in a way allowing a precise evaluation of the thermal stratification stresses , which in turn implies a knowledge of the stratification transients. This can only be obtained by an instrumentation of the line coupled with sophisticated analyses. Fatigue crack growth in the surge lines affected by thermal stratification could be significant, and in this case it might be necessary to continue the analysis until the flaw grows through-wall. The criterion to evaluate the need for such an analysis might be the exceedance of a certain crack depth at the end of the operating life of the unit, the precise limit being a subject for discussion. A limit between one half and two thirds of the thickness would seem reasonable.

CONCLUSIONS

Several technical and regulatory issued pertaining to the application of the LBB methodology to the primary loop piping were discussed and illustrated by examples from the LBB applications to the Belgian units.
No definite conclusions as to the necessity or pertinence of additional regulatory requirements in these fields are drawn, but rather these examples are proposed to fuel the reflexion and discussions in view of an harmonization of the LBB rules at an European level.

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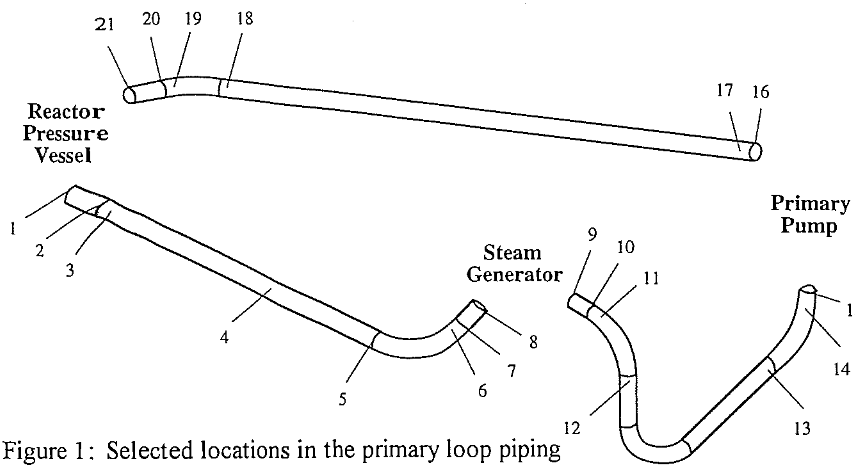

Figure 1: Selected locations in the primary loop piping

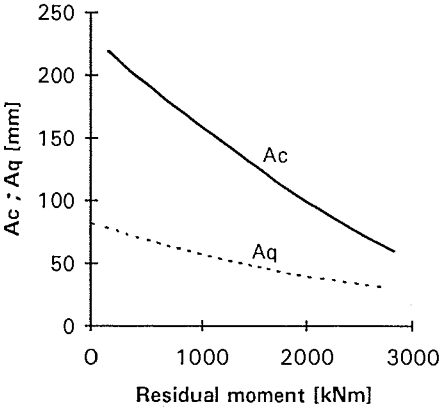

Figure 2: Effect of a residual moment on a_c and a_q

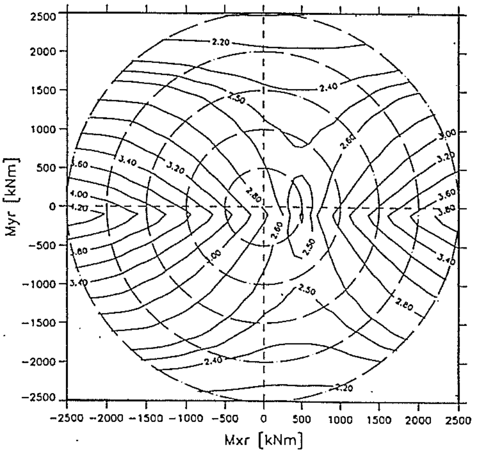

Figure 3: Effect of residual bending moments on the LBB margins

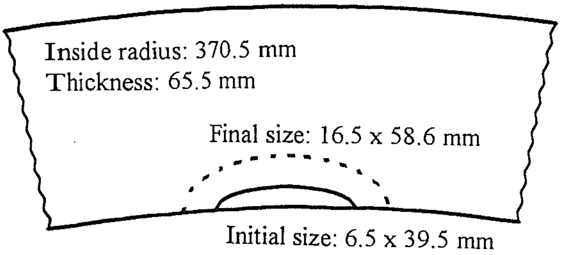

Figure 4: Fatigue crack growth