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Leak-before-break assessments of pressurised components

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ABSTRACT

This paper presents the results of a AEA Technology led CEC Working Group Codes and Standards (WGCS) contract study on comparing leak-before-break (LBB) methodologies in European Union (EU) countries. The study has been associated with comparing the LBB procedures used in France, Germany and the UK, and applying them to a benchmark of a typical LWR primary circuit piping butt weld.

1. INTRODUCTION

Under a CEC Working Group Codes and Standards (WGCS) contract, an AEA Technology led study has been undertaken on comparing Leak-Before-Break (LBB) methodologies in European Union (EU) countries. The study, involving Framatome (France), Siemens (Germany), Mitsui Babcock Energy Limited (UK), National Nuclear Corporation (NNC, UK) and AEA Technology plc (UK), has been associated with comparing the LBB procedures used in France, Germany and the UK, and applying them to a benchmark of a typical LWR primary circuit piping butt weld.

This paper describes the programme outline and summarises the main findings of the study.

2. OUTLINE OF PROGRAMME

The main elements of the work programme was planned and carried out as follows:

1. A description of LBB procedures used in France, Germany and the UK respectively was given.
2. The respective LBB procedures were demonstrated by application to a benchmark problem for a typical LWR primary circuit piping butt weld. This was performed in two stages. Firstly, critical crack length for a circumferential through-thickness crack was evaluated for internal pressure loading only at normal operation (i.e. at a pressure of 15.4 MPa). Also, for the same value of pressure and type of crack, crack opening area values were evaluated for a range of crack lengths. Secondly, the respective LBB procedures were demonstrated by undertaking detailed calculations to establish a LBB case based on the information supplied for the benchmark problem.

Although, the results of these are not covered in this paper, detailed elastic and elastic-plastic finite element calculations were also carried out to evaluate J-Integrals and Crack Opening Areas for a range of crack sizes and loadings appropriate to the benchmark.

3. LBB PROCEDURES

The review of the various LBB procedures indicated that in Germany, LBB is an integral part of the "Independent Redundancies" arm of the Break Preclusion Concept [1] and as such is accepted by the German licensing authorities. Similarly, LBB in the UK has been successfully applied over the past few years and procedures are contained in a revised Appendix 9 [2] of R6 [3]. However, French licensing authorities have not given their approval for LBB to be applied to existing plants although LBB studies have been performed as defence-in-depth arguments [4].

The French LBB procedures are based on the NUREG 1061 [5] approach with prescribed safety factors. The German procedures incorporate a more detailed approach in that they involve calculating the growth of a postulated initial surface flaw up to and beyond penetration of the back-surface. The revised UK R6 procedures contain both of these alternative approaches. No stringent safety factors are prescribed in either the German or UK approaches.

Crack opening area and hence leakage rate is calculated for normal operation in France, Germany and in the UK. Critical crack length in France and Germany is usually evaluated for normal operation + Safe Shutdown Earthquake (SSE). The UK R6 LBB procedures state that the critical crack length should be evaluated for the most onerous load case and thus in theory calculations need to be performed for all upset and emergency loading conditions. However, consistent with the US, French and German approaches, it may be possible for a satisfactory LBB case to be presented to the UK licensing authority (the Nuclear Installations Inspectorate, NII) with critical crack length being based on normal operation + SSE.

In Germany, critical crack length for austenitic and ferritic steel piping is evaluated on the basis of plastic collapse solutions. Elastic-plastic fracture mechanics calculations are performed in France and in the UK. In France, a full instability analysis is performed based on the J-integral formulation. Critical crack length is evaluated by the R6 method in the UK but it is likely that licensing requirements would limit the extent of ductile tearing to 2mm.

4. BENCHMARK CALCULATIONS

4.1 Critical Crack Length

Comparisons of the French, German and UK calculated values of critical crack length are presented in Table 1. The French calculations are based on crack instability analyses. The crack driving J was calculated using the FAR code which is an implementation of the GE-EPRI method [6]. Four different ways of representing the material J-Resistance curve were used. The UK R6 calculations are based both on initiation fracture toughness and on fracture toughness corresponding to 2mm of tearing. The effect of including residual stresses was considered in the UK calculations but these results, which show a decrease in the critical crack length values, have been excluded in Table 1 for simplicity of presentation. The German calculations are based on limit load using two Siemens in-house developed solutions. It can be seen that the French and German values are significantly higher than the UK values. The difference between the French and UK values is mainly a consequence of the amount of tearing allowed for in the respective fracture mechanics calculations (2mm for the latter and as much as 37mm for the former).

4.2 Crack Opening Areas

Comparisons of the French, German and UK calculated values of crack opening area are presented in Figures 1 and 2. The French values were obtained by the GE-EPRI method [6], the UK values were obtained from results of elastic finite element calculations [7] and the German results were also obtained from elastic solutions. The three sets of calculated crack opening area values give similar results to one another for Normal Operating Pressure (Figure 1), the French values being the highest and the German values, the lowest. For Normal Operating Loads (Figure 2), the German and UK results are very similar to one another with the later again having the slightly higher values. The French results are a little higher than the other two sets of results and the curve diverts away from the other two curves at the higher values of crack length. This is presumably due to plasticity effects which are taken into account in the Framatome FAR code which is based on the GE/EPRI method. (It should be noted that the UK LBB methodology outlined in Appendix 9 of R6 contains the option of elastic-plastic solutions of crack opening area [3]. Such solutions were not considered within the scope of the present study though.)

4.3 Leakage Rates

The French calculations of leakage rate were carried out using the ASTEQ computer programme and these showed that a crack length of 120mm corresponded to the leak rate target value of 38 litres/min (specified detectable leakage rate of 3.8 litres/min x 10). Initial UK calculations using the SQUIRT computer programme showed that a crack length of 110mm corresponded to a leak rate of only 3.8 litres/min. Therefore, SQUIRT resulted in a leakage rate which was a factor of 10 lower than that obtained from ASTEQ for approximately the same length of crack. Since there is no significant difference between the French and UK evaluated crack opening areas for crack lengths in the range of 110 to 120mm (Fig. 2), the factor of 10 difference is evidently due in the main to differences in the respective leakage rate computations. This aspect was examined in some detail by way of undertaking further leak rate calculations using SQUIRT. The details of these are as follows:

In the initial SQUIRT calculations, the computer programme default values of thermal hydraulic parameters were specified. Two further SQUIRT calculations were performed by taking account of experimental observations made by Chivers [8] in relation to fluid friction factor parameters. Firstly, in order to "model" the case of the crack surfaces being relatively smooth, a low roughness (R_a) value of 10^{-7}mm was considered. Crack length versus leak rate for this R_a value is presented in Figure 3. Three "ASTEQ computer code calculated points" are included in Figure 3. It can be seen that these points lie extremely close to the SQUIRT results. Although this implies that the ASTEQ computations may have been based on a very low value of surface roughness, a roughness value of 30μm was actually specified as this is reported by Framatome to be a "characteristic value for stainless steel material". Secondly, a roughness (R_a) vale of 20μm was considered since, in his studies, Chivers [8] observed that this was a reasonable value in order to "model" a fatigue crack. Crack length versus leak rate for this R_a value is also presented in Figure 3. It can be seen that for crack lengths greater than approximately 75mm, the calculated leak rate values are increasingly higher than those obtained from the SQUIRT computer code default calculations.

Based on this revised set of crack length versus leak rate results, the UK detectable leakage crack length (corresponding to 3.8 litres/min) would only be reduced from 110mm to 100mm. However, the Framatome detectable leakage crack length (corresponding to 10 x the 3.8 litres/min detectable leakage rate) would be increased from 120mm to approximately 200mm.

Crack lengths corresponding to the detectable leak rate of 3.8 litres/min, 5 x the detectable leak rate and 10 x the detectable leak rate are presented in Table 2 for each of the cases considered in Figure 3.

4.4 *Demonstration of LBB*

4.4.1 General considerations

LBB could be satisfactorily demonstrated by both the French and German methodologies for the case under consideration. However, a LBB case would be difficult to make following the assumed UK approach. The main differences are due to the fact that the UK calculated critical crack lengths are significantly lower than those of the French and German (see Table 1). This is coupled with the fact that the original UK leakage rate calculations using SQUIRT resulted in values which were a factor of 10 lower than those calculated by the French ASTEQ code. It has already been noted that whilst the French calculations were performed for a full instability J analysis resulting in crack extensions up to 37mm, the UK R6 calculations were limited to 2mm of crack extension so as to comply with the licensing requirements invoked for Sizewell B. It is not known whether a full instability analysis, as that performed by Framatome, would be acceptable to the French licensing authorities in a real LBB safety case.

The UK analysis strictly adhered to the guidance given in the revised Appendix 9 of R6 in that the most onerous loading case was considered for evaluating critical crack length (although only the values for Operating Loads + SSE is shown in Table 1). As opposed to both the French and German approaches, residual stresses were also required to be considered for the UK methodology (again, the results of these calculations have not been included in Table 1). Consistent with the US, French and German approaches, it may be possible for a satisfactory LBB case to be presented to the UK licensing authority (the NII) with critical crack length being based on normal operating load + SSE. This scenario would increase the likelihood of LBB being possible for this case with the critical crack length being twice the detectable leakage crack length, ignoring residual stresses and 25% higher when the most severe residual stress field is taken into account. This would only be true though for the simplified R6 Appendix 9 procedure based on NUREG 1061. It was shown that a LBB case cannot be made for the more rigorous R6 Appendix 9 procedure based on crack growth considerations (taking the most severe residual stress field into account) since for normal operating load + SSE, the crack length at breakthrough was calculated to be greater than the critical crack length .

In considering residual stress fields when evaluating critical crack length, the German approach is to ignore them completely. The French calculations ignored them on the basis of their finite element calculations which showed that through the thickness averaged J values were practically the same as in the absence of residual stresses. In contrast, the UK approach requires residual stresses to be taken into account so as to ensure conservatism. For the self-balancing through-thickness residual stress fields considered here, the maximum value of stress intensity factor, K_I, which occurs at the surface, is taken.

4.4.2 Leak rate considerations

It can be inferred from the information discussed in Section 4.3 and presented in Figure 3 that the leak rate values may have been overestimated in the French calculations and underestimated in the initial UK calculations. The underestimation of the UK calculations is considered to be due to inappropriate assumptions of friction factor. However, the difference in computed leakage rate between the ASTEQ and SQUIRT codes, assuming similar values of friction factor (30μm for the former code and 20μm for the latter code), is not understood and requires further investigation.

Whilst it is not known at this stage, whether the ASTEQ or the revised SQUIRT (R_a = 20μm) leakage rate computations provides the most accurate results, the likely inpact of the latter on the French and UK LBB calculations has been examined.

Table 3 summarises the French and UK calculated values of critical crack length together with the revised SQUIRT calculated leakage crack lengths corresponding to the detectable leak rate of 3.8 litres/min, 5 x the detectable leak rate and 10 x the detectable leak rate.

The French critical crack lengths are still considerably greater than the 38 litres/min target leakage crack length by a factor of 1.69 - 1.86. However, these factors are less than the value of 2 stipulated in the French procedure. A satisfactory LBB case could not be made from the data presented in Table 3 on the basis of this requirement therefore.

The UK critical crack length is greater than the 38 litres/min (10 x detectable value) leakage crack length only for Normal Operation + SSE when residual stresses are ignored. The factor for this case is 1.11. When residual stresses are included for this load case, the critical crack length is greater than the 3.8 litres/min (actual detectable value) leakage crack length by a factor of 1.38. Although still likely to be difficult to achieve in practice, the revised SQUIRT leakage calculations thus show some improvement to the UK LBB case. Although such calculations have not been included in this study, it is worth pointing out that the UK LBB case would be further improved if the ASTEQ leakage tate values were considered.

5. CONCLUSIONS

1. Several differences between the French, German and UK LBB methodologies have been highlighted and these are summarised in Section 3.
2. As would have been anticipated, the French values of critical crack length, based on a full instability analysis, and the German values, based on plastic collapse, are significantly larger than the UK R6 values whereby the fracture toughness value was limited to 2mm of tearing.
3. The French, German and UK calculated values of crack opening area give similar results to one another for Normal Operating Pressure, the French values being the highest and the German values, the lowest. For the Normal Operating Loads, the German and UK results are very similar to one another with the latter again having the slightly higher values. The French results are a little higher than the other two sets of results and the curve diverts away from the other two curves at the higher values of crack length. This is presumably due to plasticity effects which are taken into account in the French FAR code which is based on the GE/EPRI method.
4. The SQUIRT computer programme, used in the initial UK calculations, resulted in a leakage rate which was a factor of 10 lower than that obtained from the ASTEQ computer programme used in the Framatome calculations. For a given value of leak rate, the French calculated "leakage" crack length is therefore lower than that calculated by the UK. Further computations using SQUIRT have established that these differences are due in part to inappropriate assumptions being made in the original SQUIRT calculations with regard to friction factors. However, assuming similar values of friction factor, there are significant differences in the computed leakage rate values between ASTEQ and SQUIRT which requires further investigation.
5. The calculations indicated that LBB could be satisfactorily demonstrated by both the French and German methodologies for the case under consideration. It is not known though whether a full instability analysis for evaluating critical crack length, as that performed by Framatome, would be acceptable to the French licensing authorities in a real LBB safety case. The calculations suggested that a LBB case would be difficult to make following the UK approach whereby the R6 revised Appendix 9 is methodology is employed but with the amount of ductile tearing limited to 2mm (in order to satisfy anticipated licensing requirements). Although still likely to be difficult to achieve in practice, the revised SQUIRT leakage calculations showed some improvement to the UK LBB case. Although such calculations have not benn considered in this

study, the UK LBB case would be further improved if the ASTEQ leakage rate values were considered.

Table 1: Comparison of Critical Crack Lengths (in mm)

Normal Operating Pressure (15.4 MPa)		
France	Germany	UK
1198 (14mm) (for JR1) 1212 (9mm) (for JR2) 1216 (14mm) (for JR3) 1212 (10mm) (for JR4)	1260 (for FSC) 1222 (For PLL)	664 (for K_{ini}) 948 (for K_{2mm})
Normal Operating Loads		
France	Germany	UK
	596 (for FSC) 488 (for PLL)	114 (for K_{ini}) 310 (for K_{2mm})
Normal Operating Loads + SSE		
France	Germany	UK
338 (37mm) (for JR1) 344 (9mm) (for JR2) 372 (28mm) (for JR3) 354 (28mm) (for JR4)	494 (for FSC) 358 (for PLL)	90 (for K_{ini}) 222 (for K_{2mm})

JR1 - J-R curve defined by Framatome three slope method
JR2 - J-R curve defined by zero slope after Δa limit of exponential curve fit is exceeded
JR3 - J-R curve extended such that Δa limit of exponential curve fit is ignored
JR4 - J-R curve defined by Framatome method after Δa limit of exponential curve fit is exceeded
xmm - amount of crack growth prior to instability
FSC - flow stress concept
PLL - plastic limit load
K_{ini} - fracture toughness for initiation of tearing
$_{2mm}$ - fracture toughness for 2mm of tearing

Table 2: Crack Lengths Corresponding to Various Leak Rates

	Crack Length (in mm) Corresponding to Leak Rate of:		
	3.8 l/min	19 l/min (factor of 5)	38 l/min (factor of 10)
SQUIRT (Default Values)	110	230	320
SQUIRT ($R_a = 10^{-7}$mm)	40	85	105
SQUIRT ($R_a = 20\mu$m)	100	170	200
ASTEQ	-	-	120

Table 3: French and UK Calculated Critical Crack Lengths and Revised SQUIRT Calculated Leak Rates

		French	UK
		Critical Crack Length (mm)	
Normal Operation + SSE	Without RS	338 - 372	222
	With RS	-	138
Most Onerous Load Case	Without RS	-	140
	With RS	-	58
		Leakage Crack Length (mm)	
Leak Rate:	3.8 litres/min	100	
	19 litres/min	170	
	38 litres/min	200	

RS - Residual Stress

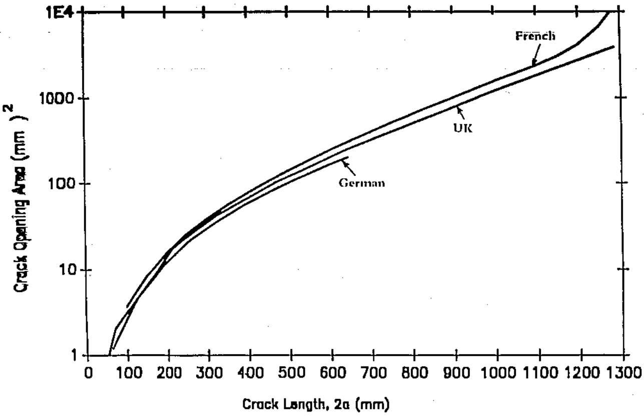

Figure 1 Comparison of Crack Opening Area Values for Normal Operating Pressure (15.4 MPa)

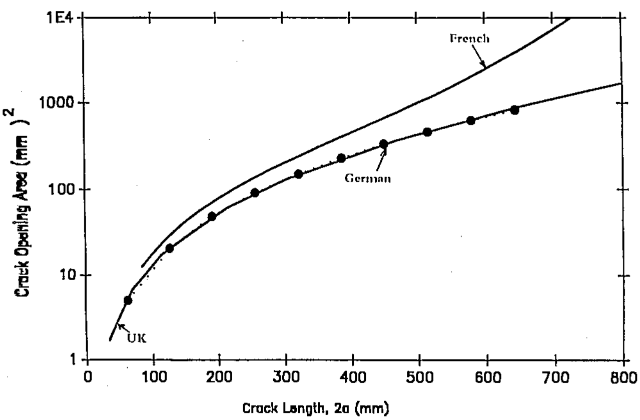

Figure 2 Comparison of Crack Opening Area Values for Normal Operating Loads

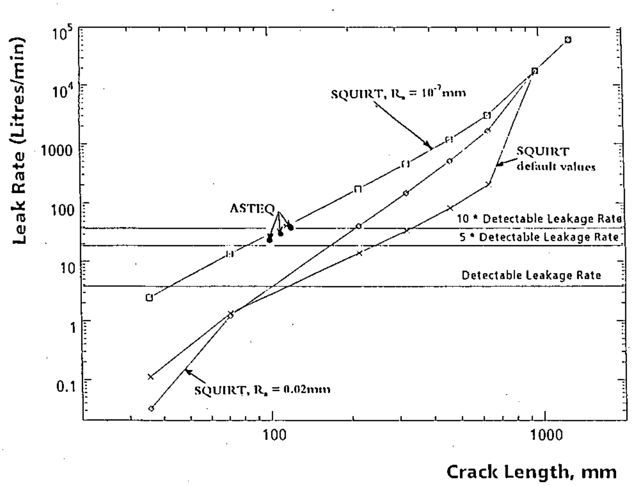

Figure 3 Comparison of Leak Rate Results

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