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Framatome experience on leak before break

Franco Ch., Gilles Ph., Ensel C.
Framatome, France

ABSTRACT

At the present time, the application of the leak-before-break concept (LBB) is foreseen for the French/German European Pressurized Water Reactor now under development. Within this framework,this paper aims at establishing a progress statement on Framatome's experience concerning the leak before break applications. So far, the major events which have contributed to significantly progress on this field are presented hereafter.

1 INTRODUCTION

As it has been agreed to apply the leak-before-break concept (LBB) at the stage of basic design for the primary circuit of the French / German European Pressurized Water Reactor [1],this paper focuses on major events which have significantly contributed to provide Framatome with a deepened knowledge on Ieak before break methodology and applications . The paper is divided in four main parts indicated as follows.

The first part deals with the technical experience gained by Framatome from its participation to international research programmes such as the Degraded Piping Programme [2] and the International Piping Integrity Research Group programme (IPIRG) [5-6].

The second part focuses on the Framatome work provided within the scope of TACIS project 91/1.2 (e.g. Technical Assistance to the Commonwealth of Independent States sponsored by the European community) concerning the LBB application for the primary piping of the Russian VVER NPP's of the type 440/230 of NPP Kola unit 1 and 2 and Novovoronezh unit 3 and 4 [9]. The work was performed via the consortium Siemens, EdF and Framatome and the Russian subcontractors (headed by VNIIAES).

The third part presents the LBB demonstration implemented by Framatome on the primary circuit of two Belgian PWR Doel 3 and Tihange 2 with the industrial aim to remove existing snubbers on the reactor coolant pumps .

The last part focuses on the LBB application for the primary circuit of 900 MWe French reactors introduced here as a defense-in-depth concept to harden the integrity analyses of primary CF8-M type cast stainless steel elbows.

2 Framatome experience gained from international research programmes

The French research programme on LBB ([3][4]) has been carried out in close connection with the joined EDF-CEA-FRAMATOME participation in the IPIRG I & II programmes. Overall descriptions of these programmes are given in [5] and [6]. In IPIRG1 were evaluated the effects of dynamic and cyclic loadings on cracked pipe section behaviour in straight pipe and pipe system experiments. The same type of experiments have been conducted in IPIRG II, but considering "seismic" load history effects, shorter cracks and local stiffness effects in cracked elbows.

The 11 dynamic pipe system experiments are of primary importance to check the validity of critical crack size assessments based on the linear dynamic computation of the sound pipe system in combination with a non linear quasi static analysis of the pipe section. From IPIRG I, we learned that dynamic effects , except in ferritic pipings susceptible to dynamic strain ageing, may be neglected in LBB demonstrations. On the opposite, cyclic loadings with load ratio of -1 combined with small incremental crack growth can significantly lower the load carrying capacity of cracked pipings. In two pipe system experiments double-ended guillotine breaks were observed. However these events occured only after extensive stable crack extension under cycles of continuously increasing amplitude. Although this loading was extremly severe, and that the IPIRG loop prescribes a load control type of loading at the crack location, the crack grew in a stable manner in the cast stainless teel pipe up to 94% of the circumference.

Detailed non-linear dynamic analyses of five of the IPIRG II pipe system experiments have shown [7] that the Net Section Collapse method may overestimate the maximum load, but that in all cases J based predictions of initiation and maximum moment are conservative. These analyses, which take into account plasticity effects in the whole system as well as the weakening effect of the crack on the dynamic behaviour, give results in good correlation with experimental measurements. This validates the cracked pipe element developed by the CEA and allows us to understand under what conditions classical de coupled critical crack size estimates are acceptable.

In the frame of the IPIRG I & II and related programmes, a large number of technical issues were addressed giving practical guidelines to conduct LBB assessments in pipes and fittings. The results were largely summarised in the LBB95 conference [8] organised by CEA , EdF and FRAMATOME . Furthermore estimation schemes as well as databases on pipe fracture experiments and material characteristics have been developed in these programmes. These collection of high quality results contained in these bases, will be used in France to extend the validation of fracture mechanics methods selected for LBB demonstrations.

3. LBB application within the scope of TACIS 91/ 1.2

The aim was to analyse the feasibility of the LBB behaviour for the primary piping of VVER 440/230 NPP Kola unit 1&2 and Novovoronesh unit 3&4 and to draw recommendations in order to improve the safety of these plants. The work has been performed by the western consortium Siemens, EdF and Framatome and the Russian subcontractors headed by VNIIAES .The scope of the programme,the results and the recommendations have been widely detailed in Ref [9]. The following part of the text emphasises one particular stage of this study : the consistency of computations and analyses conducted by the two partners Siemens and Framatome to verify the fulfilment of the leak before break requirements .

During the programme, Siemens and Framatome have separately conducted the LBB application based ,respectively on the methodology used in Germany [10] and on the US NRC requirements [11].The absence of fatigue as a risk of failure over the entire life of plant has been established. The LBB demonstration was led with two deterministic fracture mechanics approaches , the accustomed methods from Siemens side derived from limit load and flow stress concept and a more sophisticated elasto-plastic fracture mechanic method based on the crack driving force J on Framatome side. Preliminary investigations on material properties collected by our Russian partners led to a satisfactory situation on Charpy impact strength values evaluations. As the J resistance curves were not available for the as built pipings, an additional work has been performed by Framatome to establish a reasonable lower bound of toughness properties for base metal , homogeneous and inhomogeneous welds, taking into account the potential degradation effects such as ageing effects. From chemical composition specifications, welding process and acceptance tests, correlation formulae have been established between J and impact strength at operating temperature. J-R curves have been provided , using current extrapolation techniques drawn from Ref. [14] to consider large crack propagations.

Critical through-wall cracks estimation schemes were compared for the all sensitive areas in VVER 440/230 primary circuit. Figure 1 shows the results derived from Siemens procedure [10] and from EPRI formalism [12] selected by Framatome specialists to predict J values. In each zone, the results correlate satisfactorily.

The leak rate predictions have been computed with the two computer codes FLORA in Germany and ASTEQ the computer code developed by Framatome. A two-phase flow model taking into account the pressure and temperature variations , the roughness of wall and the friction coefficient are implemented in both codes .The break area is supposed constant through the hydraulic channel. In order to satisfy the LBB procedure requirements on the validity of numerical tools, comparisons have been done from the two computer codes on mass flow rate predictions. Results are plotted in figure 2, assuring a very good correlation as the roughness parameter is 30 μm ,characteristic of stainless steel material. In addition to the mass flow rate, the leak rate predictions are influenced by the shape of crack area and by the crack opening displacements. Figure 3 shows the crack lengths resulting from a leakage rate of 10 GPM derived from the two computer codes combining the hydraulic and geometrical assumptions. The results are in a good agreement, small differences arising mainly from the different geometrical assumptions.

Finally, the LBB conclusions given by Framatome and Siemens were the same and more particularly concerning NV 3&4 where the LBB implementation requires necessary improvements (analysis of seismicity and/or implementation of additional optimized seismic supports).

The scope of TACIS project has allowed at first to significantly complete the data bank on material properties of VVER 440, secondly to complete the validation on the applicability of predictive methods and numerical tools introduced in LBB demonstration and finally to point out the consistency on the LBB conclusions given from two different procedures: the current German practice based on limit load and flow stress concept and the J based approach selected by Framatome.

4. LBB implementation for the main coolant lines of Belgian PWR

The LBB demonstration was intended for implementation on the primary coolant lines of two Belgian 900 MWe type PWR unit DOEL 3 and TIHANGE 2 [13]. The objectives of the utility ELECTRABEL were to reduce the number of large hydraulic snubbers on each primary pump and to eliminate in the reactor coolant pump integrity analyses , an overspeed occurring subsequent to a guillotine break at the pump outlet.
The LBB demonstration was led in accordance with the requirements of the US NRC regulation given in Ref. [11].At First, new dynamic analyses were performed by the architect engineer TRACTEBEL, taking into account the new support configuration of the main coolant pump. In addition to current seismic analyses,the Belgian safety authorities required to complete the dynamic analyses with the loadings resulting from a main steam line break and three auxiliary lines breaks since the LBB concept was not applied to the lines.
The next stages of the demonstration were conducted by Framatome at the TRACTEBEL's request. FRAMATOME demonstrated the absence of any indirect risk of failure over the entire life of the plant such as water hammer, erosion-corrosion, stress corrosion cracking and fatigue. The demonstration of a limited fatigue crack growth was performed using the ASME XI reference defect postulated at the inner surface of the most loaded RCS weld in normal operation conditions. The fatigue crack growth analysis was performed considering 21 second category transients. The thermal and mechanical stresses were computed with a 2-D axisymmetric model of the weld. The maximum and minimum stress intensity factors for each transient were determined using the influence function technique. The crack growth was derived from Paris's law in PWR environment.
The predictive method selected to compute the critical through-wall crack size was based on J approach, using the EPRI handbook given in Ref. [12].The tearing resistance curves were derived from CT specimen measurements or from reasonable lower bound correlations between Charpy energy and toughness values. In all cases, in order to provide criteria giving large crack extensions in concordance with the computations, J resistance curves were extrapolated using techniques widely presented in Ref [14]. The peculiarities of this study came from the selection of two homogeneous analyses per weld of concern. In the first analysis,the crack is postulated in the middle of weld and the material properties of weld metal are considered. In the other analysis,the crack is located in the Heat Affected Zone (HAZ) and base metal properties are selected. The second one led to more severe results due to the lower yield strength of the base metal.
The leak rate through the crack area was computed using the computer code ASTEQ, presented here above within the scope of TACIS.
The LBB requirements given by the US NRC regulation were fulfilled ,based on minimum leak detection capabilities of 0.5 GPM .
The demonstration was presented and accepted by the Belgian safety authorities. It led to the removal of two large snubbers on each reactor primary pump and of some

restraints to facilitate the SG replacement at DOEL3 and it allowed to disregard the overspeed loading in the pump integrity analysis.

5. LBB application as a defense-in-depth concept for the integrity of the primary cast stainless steel elbows

The French Utility, EdF and FRAMATOME have performed recently a very intensive work for a better understanding of the thermal ageing effects on CF8-M type cast stainless steel elbows. Within the framework, at the French utility's request, FRAMATOME has investigated the integrity of the primary circuit of 900 MWe French reactors using the LBB as a defense-in-depth concept.

The LBB demonstration was mainly based on the US NRC procedure completed with a deepened work on elbow components [15 -16 -17]. Through-wall defects were postulated at locations in the primary loop which have the least favourable combination of stress level and material properties for base metal and weldments. The most representative zones were the homogeneous and dissimilar welds connected to heavy components and the five cast stainless steel elbows.

Each zone was investigated combining a deterministic fracture mechanics demonstration based on J approach and a leak evaluation based on critical flow assumptions and implemented in ASTEQ code. In agreement with the US NRC requirements, a margin of 10 was introduced on the leakage prediction and the minimum leak detection capability was supposed to satisfy 1 GPM.

Each weld was assimilated to a fictitious homogeneous straight pipe combining the minimum thickness and the least favourable combination of tensile and toughness properties surrounding the weld. The J approach was based, as indicated here above, on the GE-EPRI handbook [12],when the straight pipe is subjected to a bending moment and an axial load and the tensile properties fitted on a Ramberg-Osgood law. The relevance of our assumptions concerning the Ramberg-Osgood fit on strain stress curves or concerning the selection of crack location was argued on the basis of finite element analyses as it is shown in Ref [15]. The US NRC margins were fulfilled for each primary girth welds.

Additional work has been performed for primary cast stainless steel elbows. The typical problem was to identify the worst location and orientation of the defect in the elbow component. Elastic finite element computations (F.E.) were carried out to each primary uncracked elbow .The evaluation of elastic stress levels led to conclude that the more severe through wall cracks were oriented axially at the intrados or 45° oriented on the crown. The most severe configuration depends on the geometry elbow and loading conditions. The elbow classification is described in Ref. [15], and for each of the 3 classes elastic-plastic finite element computations were performed with two different crack sizes. The aim was at first to bracket the critical flaw size and then to support the development on J estimation scheme in order to be able to predict the critical flaw size and the break area.

The J and break area estimation schemes were established by Framatome using the reference stress the existence of which has been evidenced from F.E results indicated here above. The formulae presented in Ref. [16-17] were proposed for elementary loads as well as for combined pressure and bending moment .They provided a convenient way to derive J values and break areas in the considered elbows under complex loading conditions. In all cases , the primary cast stainless steel elbows of 900 MWe NPP have fulfilled the LBB conditions according the NRC margins.

6. Conclusions

The paper is a progress statement on the LBB applications and developments conducted by Framatome. So far, the major events which have significantly contributed to progress on this field are :

- An active participation in international research programmes (Degraded piping Programme,IPIRG 1&2)
- Within the scope of TACIS 91 dealing with the VVER 440/230 safety enhancement programme, an extensive work via the western consortium Siemens EdF Framatome on the necessary improvements for the LBB implementation on primary circuit of NPP Kola unit 1&2 and Novovoronezh unit 3 & 4.
- At TRACTEBEL's request, the LBB demonstration implemented on the primary circuit of the two Belgian PWR DOEL3 and TIHANGE2 to reduce large hydraulic snubbers on primary pump, presented and accepted by the Belgian safety authorities.
- At EdF's request, the LBB demonstration applied on the primary circuit of the French PWR type 900 MWe as a defense-in-depth concept to substantiate the proof of the integrity of cast stainless steel elbows.

In all cases , the feedback experience strengthens the validation file of our predictive methods (including new J estimation scheme and break area method for elbows) regarding the critical crack size and leak rate predictions , extents the qualification of our numerical tools and completes our material data bank .

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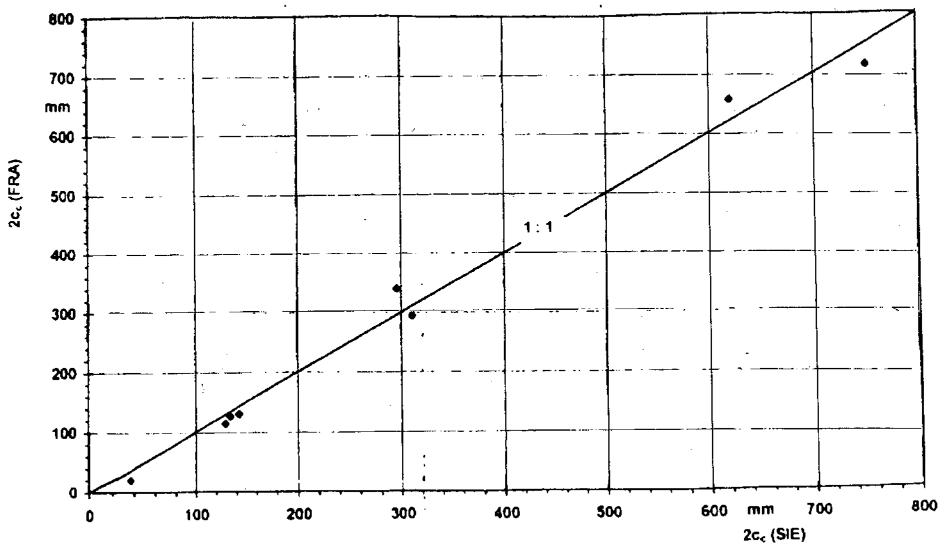

FIGURE 1 Critical through wall crack length -Comparisons FRA - SIE

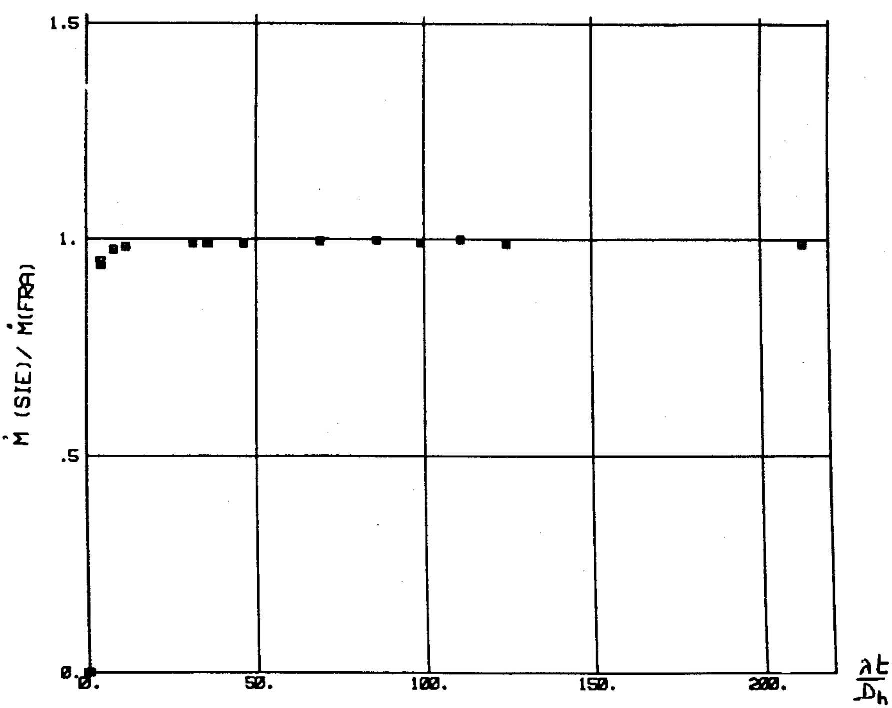

FIG 2 Comparison of flow rates : Code FLORA (Siemens)-code ASTEQ (Framatome)
(Based on Siemens /EdF analysis of Kozloduy)
(λ= Friction coefficient , t = thickness ,Dh = hydraulic diameter)

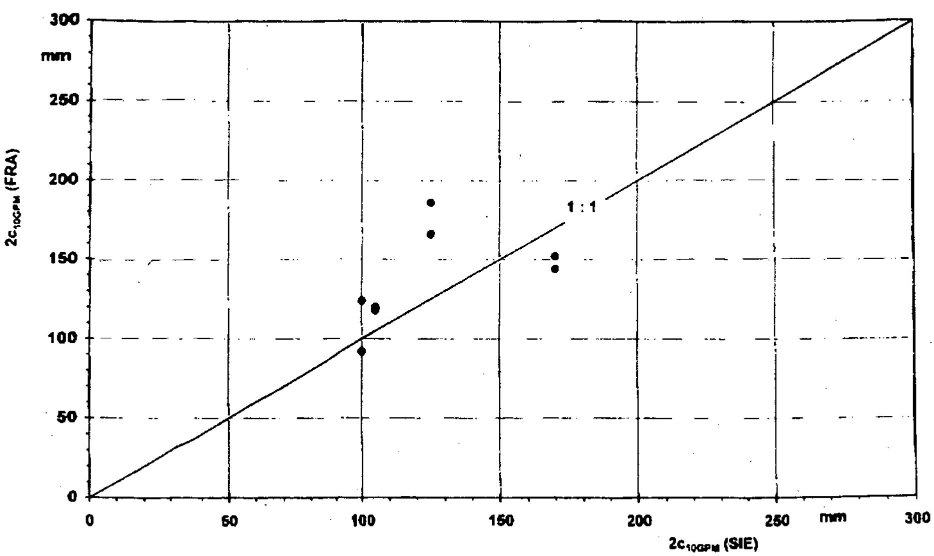

FIG 3 Leakage crack length for 10 GPM for max. loaded welds-Comparison FRA-SIE