Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division 2

Leak-Before-Break Developments Under ATLAS+ Horizon 2020 Project

John Sharples[1], Peter Gill[1], and Brian Daniels[1]

[1]Jacobs, Walton House, 404 Faraday Street, Birchwood Park, Warrington, WA3 6GA, UK
(john.sharples1@jacobs.com, peter.gill@jacobs.com, brian.daniels1@jacobs.com)

ABSTRACT

The Horizon 2020 ATLAS+ project "A*dvanced Structural Integrity Assessment Tools for Safe Long-Term Operation***"** commenced in 2017 and finished in late 2021. The project was focused on nuclear piping and associated components and addressed leak-before-break (LbB) in some detail.

The LbB aspects are associated with various elements of deterministic and probabilistic methodologies and the development of unified European guidance on leak-before-break assessment of piping and associated components. This paper summarises some of the key studies undertaken on LbB under the project, including a brief overview of the best practice document.

INTRODUCTION

Under the EU ATLAS+ project, leak-before-break (LbB) studies have been undertaken, particularly with regard to the leak rate evaluation aspects of a LbB argument. Several different models that are available for leak rate evaluations have been reviewed and an assessment made of the differences by way of comparative studies. A best practice guidance document has been produced that consists of sections containing information that summarise the key aspects that may need to be considered in LbB assessments. All of these sections are supplemented by appendices containing detailed information and background to the specific guidance presented. In addition, studies have been undertaken on probabilistic modelling of LbB aspects to assess the influence of real safety factors and on the influence of the repair methodology by weld overlay in the verification of the LbB criterion. A brief overview of these studies are presented in the following sections, including a brief description of the best practice LbB document.

AVAILABLE MODELS

Early in the ATLAS+ project, a review of relevant available models for evaluating leakage rates through cracks was undertaken. In this regard, it is recognised that both crack geometry and fluid mechanics are important and that complex loading may require the use of specialist finite element methods to obtain accurate crack opening area (COA) values. Two-phase choked flow phenomena also complicates the fluid flow through the crack and specialist thermal hydraulics codes are ideally required to determine the mass flow rate through the crack.

The study began by summarising the latest leak rate assessment tools in use worldwide. It is noted that a method to calculate leakage rates through complex paths has been developed using an ordinary differential equation (ODE) to determine the Mach number. This leakage rate model has been developed to account for crack opening displacements that vary non-linearly through the wall of a pipe. This situation typically arises when there is a through-wall crack at a weld, where significant residual stresses are present.

An investigation was carried out involving a plate geometry under complex loading. Upper bound (termed level 2) weld residual stresses (WRS), obtained from Section IV.4 of the R6 assessment procedures [R6 (2019], were simulated on the plate using thermal fields, and crack opening areas derived. Due to the non-linear through-wall nature of crack opening areas, the leak rate was calculated using a bespoke tool developed at Jacobs based on the ODE methodology referred to above.

Leak rate calculations were also carried out by Jacobs from postulated cracks in a girth weld connecting a 316L stainless steel pipe to a A508 class 3 ferritic pipe, finite element modelling of which was performed by Framatome (Germany). The test case was based on one of the STYLE project [Nicak et. al. (2014)] mock up experiments, which is a thick walled pipe containing a dissimilar metal weld. The loading was kept relatively simple in the first instance, with global bending and pressure. This was then extended to include WRS to assess how the Crack Opening Displacement (COD) and COA changes under more complex loading.

In addition, work was undertaken on a round robin exercise on leak rates undertaken as part of Work Package 4 (Assessment of Safety Margins Using Probabilistic Approaches) of ATLAS+. The round robin consisted of two test cases. The first test case was simplistic in that the CODs were prescribed meaning that no material properties, geometry or loading were required. The second test case necessitated consideration of actual geometry, loading and material properties and was based on a circumferential crack in a pipe.

The principal conclusions from the above-mentioned studies were:

- As indicated from the plate study, CODs are significantly influenced by the presence of WRS when considered in isolation and under elastic conditions. An elastic plate with an imposed residual stress field showed that there was a benefit of using a non-linear crack opening instead of the standard linear model.

- There is a variety of leak rate codes and models in use around the world, and a round robin revealed differences between the following three codes:

    - SQUIRT [Paul et. al. (1990)] (recommended by R6 and implemented by Jacobs (formerly Wood) in the UK),

    - LOCI[1] (based on the USA NRC's LEAPOR code as a module in the xLPR probabilistic application), and

    - XPIPE (recommended by KTA 3206 [KTA 3206 (2015)] in Germany)

- Differences between the three codes were observed, and the reasons for these differences were investigated. Upon close scrutiny, it was found that there is an inherently higher friction factor employed in the XPIPE implementation of the KTA 3206 leakage rate models. Also, the Jacobs SQUIRT implementation required revisions to the thermal hydraulics algorithms in order to be consistent with the description of these models in the primary documentation for the extended Henry-Fauske model. All differences are now either eradicated or if not, the reasons for the differences are well understood.

[1] LOCI evolved from the LEAPOR leakage rate code which was developed for the xLPR Program in the USA by Dr. Paul T. Williams (currently at OCI) while he was at the USA Department of Energy's Oak Ridge National Laboratory (ORNL).

- It is also interesting to note that the XPIPE software gives very similar results for the modified Bernoulli model and the two-phase model. This may suggest that the modified Bernoulli equation is suitable for some applications, and given its simplicity, makes it a desirable option. More work is required to establish under what conditions the modified Bernoulli model is appropriate.

- A girth weld in a pipe, which has the same geometry considered in the STYLE project formed the basis of a LbB assessment. It was shown that the WRS reduced both the leak rate and the J-Integral in the case considered. This means that the detrimental impact of WRS on leak rate is somewhat compensated by the benefit (i.e. reduction) on the J-Integral for this WRS profile. Despite this being a specific case, it highlights a more general point that in order to undertake a realistic LbB assessment, one should consider WRS in both the limiting defect size as well as the COA calculation.

The conclusions led to the following recommendations being made for estimating COA and leak rates in LbB assessments:

- WRS should be considered in the calculation of COA, especially for small cracks where elastic conditions (small scale yielding) prevail.

- Best estimate leak rate tools such as LOCI or SQUIRT should be used in LbB assessments.

- Other software, such as XPIPE can be used but any possible conservatism in the code should usefully be considered when assessing the final results

BEST PRACTICE GUIDANCE DOCUMENT ON LEAK-BEFORE-BREAK

Best practice guidance on LbB assessment was produced, based on the knowledge of the authors and the work coming out of ATLAS+. The best practice guidance document takes into account and highlights LbB methodologies from various codes and assessment procedures developed and utilised in different countries. This enables the user to be well informed when performing a LbB assessment and effectively provides a template for carrying out LbB assessments.

The guidance contains two types of LbB methodologies. One approach is based on a through-wall crack being considered from the outset and being able to demonstrate that there is a sufficient margin between the limiting crack length and the detectable leakage crack length (termed simple approach as Type S). The other approach is whereby the starting point is a surface crack and calculations are undertaken to assess how the crack will propagate through the wall (by fatigue crack growth for example), break through to the other surface and be re-characterised as a through-wall defect. Leak rates are then evaluated as the through-wall crack continues to propagate, until the detectable leakage size is reached. The size of this defect is then again compared with the critical crack length size. This is termed here as the full approach or Type F. Type S would likely be used to assess LbB in specific locations of a component or it may be useful for undertaking scoping type of calculations in order to rank regions of a piping system where LbB is likely or not to be possible. Type F would likely be employed for cases where a crack-like defect is known to exist in a component (as evaluated by Non Destructive Examination techniques) and it may be required to establish as to whether such a defect will result in LbB.

The guidance points towards the usefulness of undertaking sensitivity studies in order to provide additional confidence in LbB arguments, by varying the inputs based on an assumed level of uncertainty. It is explained that this could lead to probabilistic assessments being performed to provide the likelihood of the LbB in the region of interest. This will provide the most insight into the LbB behaviour and requires Monte-

Carlo analysis over many thousands of iterations. If this facility is not available, then it is noted that safety factors can be applied to the limiting defect size and the leakage crack size for example in order to ensure the assessment is conservative.

The two types of methodologies and the strong emphasis on undertaking sensitivity studies are considered to be an enhancement on some of the current LbB methodologies and practices.

The best practice guidance report contains various sections with each section being supplemented with an appendix containing more comprehensive information on the particular aspect being addressed. Such information includes results of relevant comparative studies that have been undertaken during the project.

The sections and appendices pertaining to the best practice are as follows:

Section 3 (Appendix A)	Definition and Introduction of Leak-before-Break
Section 4 (Appendix B)	Component geometry
Section 5 (Appendix C)	Crack geometry
Section 6 (Appendix D)	Loads and Stress
Section 7 (Appendix E)	Material properties
Section 8 (Appendix F)	Stress classification
Section 9 (Appendix G)	Crack growth mechanisms
Section 10 (Appendix H)	Limit state of surface crack
Section 11 (Appendix I)	Defect re-characterisation
Section 12 (Appendix J)	Crack opening area
Section 13 (Appendix K)	Leakage rate
Section 14 (Appendix L)	Limiting crack length
Section 15 (Appendix M)	Evaluation and presentation of results

MODELLING OF LBB ASPECTS TO ASSESS INFLUENCE OF REAL SAFETY FACTORS

This study was primarily focussed on probabilistic aspects based on a simplified detectable leakage LbB procedure, implemented in MATLAB [Reference 6], in order to be coupled with the probabilistic software RAP++ [METLAB 2007b]. It is noted that a LbB sensitivity analysis can determine how the model is sensitive to changes in the parameters. It is possible to identify the most influential variables of the system on the failure criteria, the potential problems present and the general robustness of the model. The sensitivity analysis generally precedes a reliability analysis that has the purpose of determining the reliability (or the probability of failure) of a system. It is based on distribution function of the stochastic parameters from experimental data, engineering judgement or "goodness-of-fit" tests. The probabilistic problem is then set with the integration of a failure or several failures functions.

The RAP++ [Groouteman (2016)] tool used for the probabilistic analysis is a C++ based program with a graphical user interface that generates the input file for the program to be run. Various methods are contained in RAP++. These include: Adaptive Directional Importance Sampling (ADIS), Adaptive Radial based Importance Sampling (ARBIS), Directional Sampling (DS), Monte-Carlo (Importance Sampling) simulation (MCS, MCS-IS), Latin-Hypercube Sampling (LHS), First-Order Reliability Method (FORM), and, Second-Order Reliability Method (SORM).

In the choice of a probabilistic scheme suitable for the LbB application, it was evident that the most important parameter must be the accuracy. Because the Monte-Carlo method is computationally too expansive, the choice falls on the second most accurate scheme, that guarantees a reasonable calculation time, the Adaptive Based Radial Importance Sampling (ARBIS)

A sensitivity analysis was performed of which the definition of a base case was required. The variables distributions were dummy distribution, random normal variables chosen with engineering judgement. The base case was determined from a deterministic assessment using input data that resulted in a good margin from a LbB perspective. The sensitivity analysis was performed with RAP++ and with distributions prescribed for yield stress, fracture toughness, Young's modulus, global roughness and local roughness. Geometry dimensions, loadings and limit loads were considered as fixed parameters. The results showed higher correlation coefficients for the material parameter fracture toughness and yield stress. The two parameters together contributed to around the 80% of the uncertainties. In order to optimize the analyses of this study, these two parameters were chosen as stochastic parameters. The correlation between the failure function G and the variables fracture toughness and yield stress could be measured with the so-called Spearman and Pearson correlation coefficients.

Concerning safety factors. It is noted that for deterministic LbB assessments, the US NRC prescribe safety factors on Critical Crack Length and Detectable Leakage Rate (factor of 2 on CCL or 1.4 on the loads and factor of 10 on detectable leakage rate, DLR). From a probabilistic point of view, there is not an equivalent acceptance criteria and so a probabilistic limit was determined considering only the safety factor on DLR. In order to evaluate the probability of failure, different realistic pipe sizes were considered and a benchmark created. The probabilistic method applied for this was again ARBIS.

The study was carried out on two materials, 1020 MnMoNi55 ferritic steel and austenitic stainless steel AISI 316L. The benchmark was divided into 12 groups, and in each group the ratio between the internal radius and the thickness spanned from 15 to 36.5. Examples of the probabilistic results are shown graphically in Figure 1 for Groups 10, 11 and 12. Pf is defined as the probability that the leak rate associated to the critical crack size is smaller than the minimum detectable leak rate (DLR). The dependence on the probability of failure and the leak rate is emphasised. The Spearman coefficient for the two series is ~ -0.8. This result suggests that, as the leak rate is related to the probability of failure, a safety factor on the detectable leak rate is strictly connected to the probabilistic limit.

These results for both materials suggest an equivalent probabilistic limit for the safety factor on the detectable leak rate of $\sim 10^{-3}$ for all cases except the 10th group ($10^{-4}\sim 10^{-5}$). These values are the implicit accepted probability of failure when the safety factor is applied in the cases studied. As can be seen from Figure 1, for Group 10 this probability changes and this is due to the fact that the parameters that influence the leak rate from the crack have different worth in different regions of interest.

Finally, it is noted that the analyses on the two materials referred to above show that the probability of failure essentially depends on the leak rate, the latter then changing accordingly to the different problem parameters. This phenomenon is due to the fact that the domain of the integration of the joint probability distribution is defined by the leak rate and the detectable leak rate. Nevertheless, this is not sufficient to prove the dependence that has been found. The probability distributions are not the same for the two materials in that the nominal value for both the fracture toughness and the yield stress is different and the standard deviations are also not the same.

The relation between the two joint probability densities lies in the ratio between the standard deviations and the nominal values. For both the materials, the standard deviation for the fracture toughness is 15% of the nominal value, while for the yield stress, it is 3%. This determines that the shape of the surface that must be integrated is the same, that changing the nominal values of fracture toughness and yield stress changes the Lr parameter (proximity to plastic collapse in the R6 type methodology) associated with the particular case, and that the probability of failure will be correlated to this Lr.

A small study was undertaken involving a change in the probability distributions for the two materials and the relative change in the correlation between the leak rate and the probability of failure. The yield stress distribution was kept constant and the fracture toughness probability distribution standard deviation was varied from 15% to 27.5% of the mean of the distribution. A first benchmark was chosen as that of Group 1 for the ferritic steel. A second benchmark was chosen as the first 3 groups but in this case the standard variation was 20% of the nominal value.

This study showed that the deterministic limit is still correlated to a probabilistic threshold ~ 10^{-2}. Furthermore it showed that the probabilistic analysis depended strongly on the distribution of the chosen random variables. In order to improve the accuracy of such analyses it is necessary to improve the accuracy in which experimental data are provided.

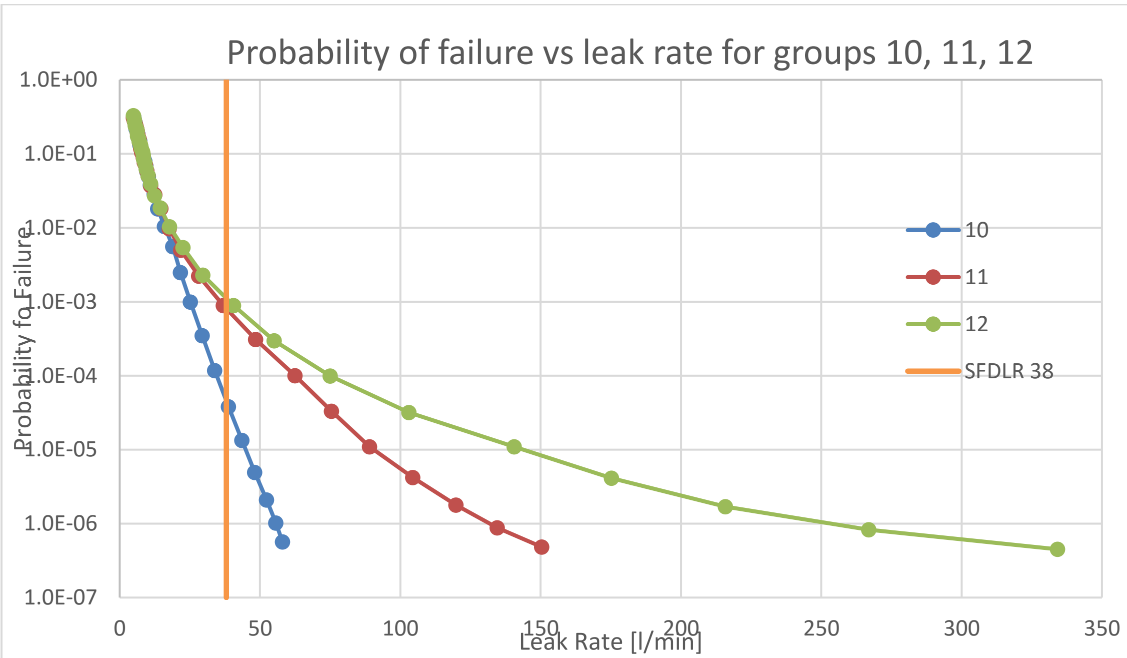

Figure 1. Pf versus leak rate for groups 10, 11 and 12

The two different materials had the same shape of the normal distribution that fits the experimental data on the fracture toughness and the yield stress. It was found that a relatively small change of the ratio between the nominal value and the standard deviation (5%) can give a variation of the probability of failure of one order of magnitude for the region of interest (DLR = 38 l/min). In other regions, the increase of probability of failure for such standard deviation change is of almost two orders of magnitude (in the asintotic region) as shown in Figure 2. The precision of the distribution of fracture toughness and yield stress is therefore fundamental for a best estimate of the safety factors worth in terms of the probability of failure of the LbB assessment.

The study concluded that the probability of failure is only slightly changed when geometric parameters (wall thickness and pipe diameter) are changed. Consequently, the safety factors are appropriate for the set of geometrical parameters analysed. The direction suggested for improving the research results is to include also the variation of the leak detection system. The probability of failure is influenced by the detectable leak rate. Another possibility of further improvement is to change the material's properties distributions. For both materials studied, the probability distribution functions have the exact same shape (the standard deviations are the same percentage of the nominal value). The material properties of interest are the only probabilistic variables taken into account and it has been shown that a small change of those distributions would lead to different results.

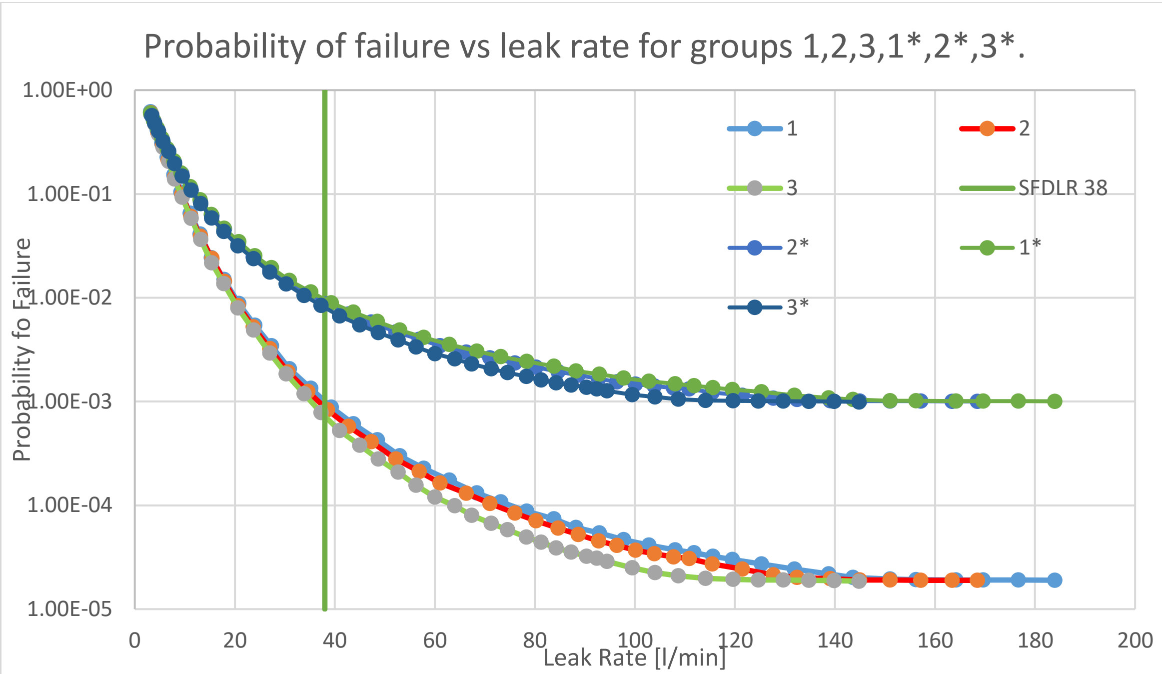

Figure 2. Revised Pf versus leak rate for groups 1, 2 and 3

When probability of failure, Pf (defined as the probability that the leak rate (LR) associated to the critical crack size is smaller than the minimum detectable leak rate (DLR)) is plotted against leak rate, the Pf associated with the DLR containing a safety factor (say of 10.0) can be determined. This points to the fact that a safety factor on the DLR is strictly connected to the probabilistic limit. Consequently, the influence on the probability of failure of the different parameters of the system has been shown in that safety factors, with the limit of the cases studied, are probabilistically evaluated and shown to be equivalent.

INFLUENCE OF THE REPAIR METHODOLOGY BY WOL IN THE VERIFICATION OF LBB CRITERION

This study arose from the fact that one of the limitations in NUREG-1061, Vol. 3 [NUREG-1061 (1984)], and SRP 3.6.3 [NUREG-0800 (2007)] is that locations on piping systems that are susceptible to stress corrosion cracking (SCC) do not qualify for LbB. Following primary water SCC (PWSCC) events in some nuclear power plants in Spain, the application of LbB at Alloy 82/182 locations has been questioned.

One of the strategies adopted by the nuclear plants against the PWSCC in the Alloy 82/182 dissimilar metal welds (DMWs) is the mitigation of these welds through the installation of weld overlay (WOL), in particular in pressurizer (PZR) nozzle DMWs. This is because these welds tend to be partially un-inspectable due to tapers, contours, and materials issues. In addition, they are more susceptible to PWSCC because their operating temperature is higher than that of other components of the reactor coolant system.

The SRP 3.6.3 methodology [NUREG-0800 (2007)] for LbB criterion verification is not specifically intended for WOL mitigated welds. The study was thus associated with limit load evaluations by net section collapse equations for two-layered materials that have been developed and leakage crack size whereby it has been necessary to consider the PWSCC morphology.

There are two types of weld overlays—full structural weld overlays (FSWOLs), which have a minimum thickness of one-third the pipe wall thickness, and optimized weld overlays (OWOLs), which have different design requirements and result in less applied weld overlay metal.

Weld overlays create a new outer diameter (OD) surface geometry more favourable for ultrasonic inspection and result in a new examination volume that is fully inspectable (Figures 3 and 4). Because of the short safe end length on the overlaid PZR nozzles, it is necessary to extend the overlay length over both the nozzle-to-safe end DMW and the safe end-to-pipe weld to allow for examination of both welds (Figure 4).

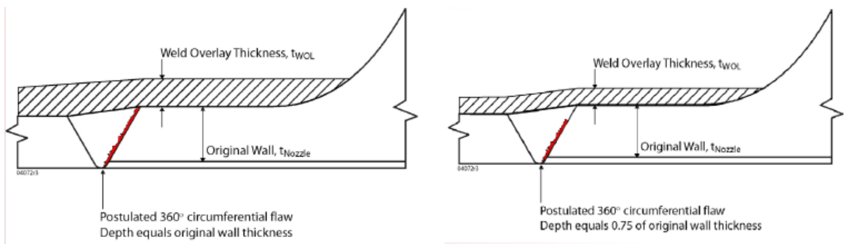

Figure 3. Typical WOL configurations

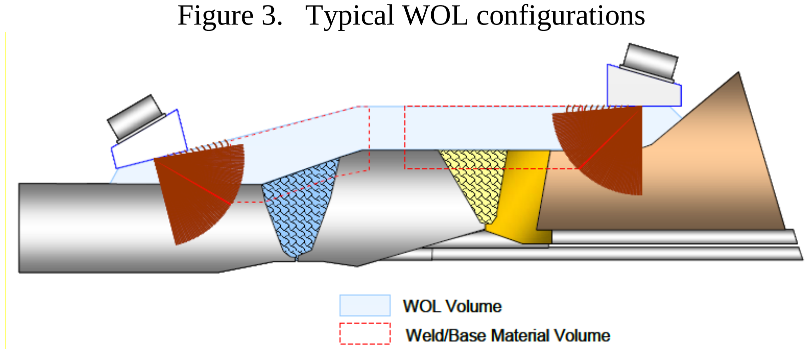

Figure 4. Inspectability of an extended WOL encompassing DMW and adjacent stainless steel weld

Depending upon the weld geometry, fabrication practices, and the presence of a nearby safe end-to-pipe weld, Alloy 82/182 piping butt welds may have tensile residual axial and hoop stresses within a zone near the inside surface of the weld. This tensile zone contributes to the susceptibility of Alloy 82/182 to PWSCC. Weld overlays convert tensile residual stresses in the inner diameter regions of these welds, to zones of compressive residual stresses, or substantially reduced tensile residual stresses.

In Spain, FSWOL have been applied to the DMWs between the pressurizer nozzles and the adjacent austenitic stainless steel piping. Among these DMWs, the pressurizer surge nozzle DMW has been qualified for LbB in most of the Spanish PWRs.

The FSWOL thickness is designed based on the ASME Code, Section XI, IWB-3640 and Appendix C, "Evaluation of Flaws in Piping" [ASME XI (2021)]. The design-basis flaw is a circumferential flaw around the weld that is postulated to be present in the DMW. In addition, potential concerns about the integrity of the original butt weld material are not applicable, since no credit is taken in the design process for the load carrying capability of the original weld. The OWOL design relies on a portion of the underlying

DMW to remain intact and carry a portion of the piping loads because the design-basis crack is 75% through the original pipe wall.

The weld overlay length must consider three requirements: (1) length required for structural reinforcement (to allow for adequate transfer of axial loads between the pipe and the weld overlay), (2) length required for access for pre-service and in-service examinations of the overlaid weld (and the safe end-to-pipe weld), and (3) limitation on the area of the nozzle that can be overlaid.

Another design requirement for the WOL is that any actual observed or postulated flaws in the DMW must be demonstrated, by a crack growth calculation, not to grow beyond the allowable size (i.e. not to grow into the overlay for FSWOL) before the next scheduled in-service inspection (ISI). If a pre-FSWOL inspection is not performed, an initial flaw 75% through the original weld thickness is postulated for crack growth analyses. If a qualified ultrasonic (UT) examination is performed prior to application of a FSWOL, and no inside surface connected planar flaws are detected, initial flaws originated from the inside surface of the weldment equal to 10% of the original wall thickness may be assumed for the crack growth calculation.

The initial WOL acceptance examination includes a liquid penetrant examination of overlay material surface plus 13 mm of base metal on either side of the overlay, plus a UT examination of overlay material plus underlying HAZ for fabrication welding defects. FSWOL pre-service and in-service UT examination volume includes the weld overlay thickness and the outer 25% of the original pipe wall to confirm that flaws have not propagated into the outer 25% of the original weld volume. For OWOL, the portion of original pipe to inspect is the outer 50%.

A weld overlay may change the weld geometry of the original weld upon which an LbB analysis was based, which may invalidate the original LbB analysis. Re-calculation of the piping and nozzle stresses may be needed if the addition of weld overlays substantially change the deadweight loading or the flexibility of the piping system. Updating the LbB analysis entails calculation of the leakage and fracture mechanics margins for the piping system to ensure that the modified piping system satisfies the licensee's design basis. The LbB method of evaluating the leakage at weld overlay locations may involve a departure from the original LbB analysis methodology. It is noted that WOLs are made of two layers of different materials, each layer having different mechanical properties and geometry. Both layers endeavour to share the load.

In using the current SRP 3.6.3 equations for evaluation of weld overlaid structures, two limitations have been identified. Firstly, the allowable stress for the weld overlay and the base material weld may be different. Secondly, the weld overlay is applied at a relatively larger radius than the base material, such that it has a significantly higher section modulus and area per unit circumference than the base piping. In addition, pressure on crack faces may be important. To circumvent these difficulties, a limit load model by a two-layer cylinder [Deardoff and Cofie (2008)] was sited. The approach is based on the limit load equations of ASME Code, Section XI, IWB-3640 and Appendix C for flaw acceptance evaluations.

In terms of the leakage rate evaluations, in the original LbB evaluations for most plants, the leakage was calculated based on fatigue crack morphology, where the crack surface was expected to be quite smooth and straight, whereas for SCC, the flow path is relatively rough and consists of many turns. Based on the occurrence of PWSCC in PWR piping systems, the potential existence of PWSCC cracking must be considered where the cracking could occur in susceptible materials.

It has been determined that the crack morphology, characterized by the local roughness, number of flow path turns, and total leakage path length, is significantly different between fatigue cracking and SCC. A procedure has been proposed in NUREG/CR-6300 [NUREG-6300 (1995)] for SCC crack morphology that defines the surface roughness, effective flow path length and number of flow path turns as a function of the ratio of the crack opening displacement (COD) to the global roughness of the flow path. For very tight cracks, there is a relatively longer flow path with many local turns, but the local roughness is relatively lower.

For cracks with a much larger opening, the roughness is better represented by the global roughness but the number of turns and effective flow path length decreases.

For defining the crack morphology, the model proposed in NUREG/CR-6300 was considered. It takes into account both global roughness and the local roughness. These are then combined with the COD, by a set of equations to develop an effective roughness. A similar set of equations was developed to determine the effective number of turns, with the assumption that the number of turns decreases to about 10% of the local number of turns when the COD is equal to 10 times or more the global roughness. Similarly, the total flow path length is increased due to the crack being skewed relative to the pipe wall and due to the turns within the material. Then, the ratio between the total flow path length and the pipe wall thickness is determined by a set of equations. Crack morphology parameters in NUREG/CR-6300 pertain to IGSCC cracks. For this reason, crack morphology parameters for PWSCC cracks can be taken from [Rudland et. al. (2003)].

It is noted that computer programs such as PICEP [Norris and Chexal (1987)] address single material for evaluations. In addition, it is not configured to directly include the methods for computing morphology using the method proposed in NUREG/CR-6300. For the leakage evaluation, the PICEP computer program has been used in several LbB analyses of Alloy 82/182 DMWs mitigated with WOL. To determine the effects of crack morphology on leakage flaw sizes, additional calculations needed to be conducted using PICEP with input revised to simulate SCC morphology.

In summary, for the evaluation of the leakage crack sizes considering PWSCC for weld overlays in LbB analyses with PICEP, multiple computer runs were necessary because of not directly addressing the crack morphology model in NUREG/CR-6300.

It is noted that ORNL has developed the computer program LEAPOR (Leak Analysis of Piping - Oak Ridge) which is integrated into the computer program xLPR (Extremely Low Probability of Rupture) [xLPR (2011)]. LEAPOR allows the calculation of leakage through fatigue and SCC cracks. For the calculation of leakage through overlaid welds, LEAPOR conservatively uses the SCC crack morphology parameters for both the original weld and the overlay material. It is pointed out though that, to date, no LbB licensed applications have been based on the xLPR computer program.

FINAL REMARKS

Useful work has been undertaken within the ATLAS+ project aimed at obtaining a better understanding of LbB and its application for both deterministic and probabilistic assessments. The information contained in the best practice guidance document will be useful for developing/improving LbB methodology contained in codes/standards and structural integrity assessment procedures such as R6 in the UK. The studies undertaken on probabilistic LbB, will form a good basis for extending the various deterministic LbB methods which are based on conservative assumptions and prescribed margins in some cases, to methods which enable the probability of LbB to be evaluated on a case-by-case basis. The study undertaken on WOL will usefully form the basis for LbB to be applied to such geometries and under conditions of PWSCC.

ACKMOWLEDGEMENTS

Francesco Brigante of NRG, Netherlands and Carlos Cueto-Feigueroso of Tecnatom, Spain are greatly acknowledged for their respective work on the modelling of LbB aspects to assess the influence of real safety factors and on the influence of the repair methodology by WOL in the verification of the LbB criterion.

REFERENCES

ASME XI (2021), ASME Boiler and Pressure Vessel Code. Section XI, “Rules of Inservice Inspection of Nuclear Power Plant Components”.

Deardoff A and Cofie N (2008), “Evaluation of overlaid welds for critical flaw size and leak Rate in LbB sssessment”, presentation at the “International Workshop on LbB in RCS Components with Active Degradation Modes”, January 9-11, 2008.

Groouteman F P (2016), Reliability Analysis Program RAP++ User Manual V3.3, 2016.

KTA 3206 (2015),Safety Standards of the Nuclear Safety Standards Commission (KTA), Nachweise zum Bruchausschluss fur druckfuhrende Komponenten in Kernkraftweken, KTA 3206, Sicherheitstechnische Regel des KTA, November 2015.

METLAB 2007b, The MathWorks Inc., Nafic, Massachussetts, USA.

Nicak T, Keim E, Moinereau D, Schendzielorz H, Meier G, Le Delliou P (2014), “Project Style: Post-Test Analysis of Mock-Up 3”, PVP2014-28296, PVP Anaheim, 2014.

Norris D M and Chexal B (1987), “PICEP: Pipe Crack Evaluation Program (Revision 1): Special report”. United States: N. p., 1987. Web.

NUREG-0800 (2007), U.S. Nuclear Regulatory Commission, Standard Review Plan (SRP) 3.6.3, "Leak-Before-Break Evaluation Procedures", Revision 1, March 2007.

NUREG-1061 (1984), Volume 3, "Report of the U.S. Nuclear Regulatory Commission Piping Review Committee, Evaluation of Potential for Pipe Breaks", November 1984.

NUREG-6300 (1995), U.S. Nuclear Regulation Commission, NUREG/CR-6300, "Refinement and Evaluation of Crack-Opening Analyses for Short Circumferential Through-Wall Cracks in Pipes", April 1995.

Paul D D, Ghadiali N, Ahmad J, Wilkowski G (1990), SQUIRT – User’s Manual, Version 2.1, International Piping Integrity Research Group, 1990.

R6 (2019): Assessment of the Integrity of Structures Containing Defects. Revision 4. EDF Energy Nuclear Generation Ltd. February 2010, Amendment 12, 2019.

Rudland D, Wolterman R, Wilkowski G and Tregoning R (2003), “Impact of PWSCC and Current Leak Detection on Leak-Before-Break,” Proceedings of Conference on Vessel Head Penetration, Inspection, Cracking, and Repairs, Sponsored by USNRC, Marriot Washingtonian Center, Gaithersburg, MD, September 29 to October 2, 2003.

xLPR Version 1.0 Report (2011), “Technical Basis and Pilot Study Problem Results”, Xlrp Computational Group, USNRC and EPRI, February 2011.