Chapter 10

Leak-Before-Break Technology for Piping in Nuclear Industry

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Leak-Before-Break Technology for Piping in Nuclear Industry

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Abstract

Leak-Before-Break (LBB) concept is applied in the nuclear industry to eliminate from the piping design the postulated guillotine breaks. The adoption of this technology allows to design mechanical component and supports without the high dynamic loads which results from the pipe rupture. This chapter shows how thermo-hydraulics, material science, and elastic-plastic fracture mechanics are employed to apply the LBB technology to eliminate rupture from a large primary loop piping.

Keywords: LBB; guillotine break; fracture mechanics; leak rate

1 Problem Description

The concept of leak-before-break (LBB) in piping has been used in the nuclear industry since the mid-1980s. The basic idea of the LBB is to perform an analysis to demonstrate that leakage through a circumferential crack (or flaw) is detected by the leakage monitoring system and the plant is shutdown before the unstable crack growth. The LBB demonstration involves some engineering disciplines, highlighting thermo-hydraulics, materials science, and fracture mechanics.

Historically, the LBB concept was developed to eliminate double-ended guillotine break loss-of-coolant accident (LOCA) from the structural design. LOCA is postulated to occurs in primary loop piping and other high energy lines, those with operating temperature or pressure greater than 200^{o}F or 275 psig, respectively. Once the LBB is demonstrated these ruptures are excluded from the design basis and the dynamic stresses resulting from LOCA are not considered in the structural analysis of the mechanical components. As a result, it is no longer necessary to design the reactor vessel internals and nozzles, primary loop equipment and supports, and piping against these dynamic loads.

Another advantage of applying LBB is that pipe-whip restraints and jet-impingement shields, both required to protect critical equipment from the dynamic effects of the postulated rupture, could be removed. As the costs of these protection elements are high, and in some cases their existence makes it difficult or even impossible to inspect components in service, the removal or non-installation of these restraints and shields is highly desirable not only for economic reasons, but also, to reduce the radiation dose received by maintenance personnel.

The most common approaches to apply LBB are those based on the J/T methodology or on the limit load theory. The two mandatory technical references for LBB analysis in Brazil and U.S. are NUREG-1061 [1984] and SRP 3.6.3 [1987]. In 2007, SRP 3.6.3 was issued with no significant change in calculation procedures compared to the original edition. LBB is demonstrated when all requirements in these documents are met.

In this chapter, the LBB concept is used to eliminate from the design of the primary loop the postulated guillotine break. In Figure 1, the segment of one reactor coolant loop piping (the hot leg) is schematically represented with a circumferential crack in the region adjacent to the weld, subject to axial loads *P* and moment *M* resulting from normal operating (pressure, deadweight, and thermal expansion) and accident conditions (basic design earthquake, DBE). The geometric characteristics of the pipe are the outside diameter, D_o, equal to 33.9 inches and the thickness, *t*, of 2.45 inches, which is manufactured from SA-351 CF8A cast stainless steel. The weld is constructed with stainless steel SFA-5.4 (SMAW for filler) and SFA-5.9 (GTAW for root pass).

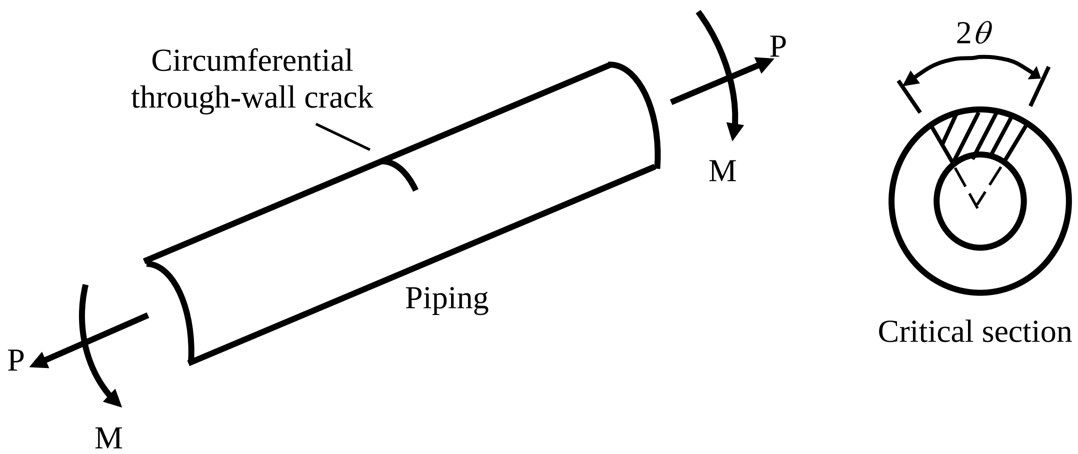

Figure 1: Segment of the pipe and section where the break is postulated

2 Step-by-Step or the Application of LBB

As established in NUREG 1061 and SRP 3.6.3, to demonstrate the LBB requirements are met, the following seven steps are considered:

1 - Show that the piping is not susceptible to degradation in service such as high or low cycle fatigue, stress corrosion cracking, erosion, damage caused by water hammer, etc. An assessment must be prepared to demonstrate that the integrity of the piping during plant lifetime will not be affected by any type of degradation.

2 - Obtain the tensile and fracture properties of the base and weld metals, given by the stress and strain curve and the *J*-integral *versus* crack extension (J-R) curve), both estimated using the actual information of the piping materials or, in the absence of these, in similar data found in the literature. The properties are established assuming that the material is thermally aged, that is, its original characteristics are modified (reduced toughness) by the effect of the operating temperature.

3 - Determine the loads (axial force and moment) for leak rate analysis and crack stability. In the first case algebraic combination is used for normal operating loads. The crack stability check is performed with the sum of the absolute values of the normal operating and accident (DBE) operating loads.

4 - Postulate the through-wall circumferential flaw in the section of the piping with the highest stress in conjunction with the most unfavorable tensile and fracture material properties. Several sections of piping must be analyzed because the critical location is not always the point of the highest stress.

5 - Multiply by 10 the leakage monitoring system capability. Typically, plants have monitoring systems that detect leaks of less than 1.0 gpm (gallon per minute) in no more than one hour.

6 - Perform leak rate analysis for cracks subject to normal operating loads. In this step, the flaw under this condition will open and produce the leakage detected by the monitoring system. The leakage crack size is multiplied by 2.0.

7 - Use elastic-plastic fracture mechanics based on the J/T method to verify if the previously obtained crack is stable under normal operating combined with accident loads. If this requirement is met the guillotine break will not occur. Alternatively, depending on the toughness of the material, the analysis may be conducted by limit load theory.

The safety coefficients for leakage (10, step 5) and crack size (2, step 6) aim to cover the uncertainties inherent in the formulations used in the calculation of the leakage crack size (step 6) and critical crack size (step 7).

The main aspects of LBB that is covered in this chapter are crack stability analysis (step 7), material characterization (step 2) and leakage analysis (step 6).

3 Crack Stability Analysis

In LBB applications the circumferential through-wall flaw is subject to extreme stresses in which the normal operating and accident loads are superimposed. In this condition, as the plastification level is expressive, the analysis is carried out in an elastic-plastic regime. Depending on the toughness of the material, the J/T approach, developed in NUREG/CR-3464 [1983], is the most used technique for checking the crack stability. The analysis using the limit load theory is described in Section 6.

J-integral and tearing modulus T are quantities that represent the potential for crack extension. When applied J is smaller than J_{Ic}, defined as J at flaw initiation, crack growth does not occur. On the other hand, when J is equal to or greater than J_{Ic}, stable tearing is initiated. In this situation, the J/T method is adopted to determine when the defect becomes unstable, that is, the instant associated with the pipe rupture. The correlation between the J and T is

$$T = \frac{dJ}{da}\frac{E}{\sigma_f^2} \tag{1}$$

with dJ the increase in J to an amount of crack extension da, σ_f the flow stress, assumed as the average between the yield and ultimate strength of the material, S_y, and S_u, respectively, and E is the modulus of elasticity. The crack instability occurs when the applied tearing modulus is greater than the material tearing modulus T_{mat},

$$T > T_{mat} \tag{2}$$

with T_{mat} obtained experimentally.

The J-integral, the parameter that indicates the driving force that extends the crack, is calculated using the General Electric and Electric Power Research Institute (GE/EPRI) scheme. The total value of J is the sum of the elastic J_e and plastic J_p components. For pipe with circumferential through-wall flaw subject to combined axial load P and moment M, Zahoor [1989] defines the following equations

$$J_e = f_t \frac{P^2}{4Rt^2E} + f_b \frac{M^2}{R^3t^2E} \tag{3a}$$

$$J_p = \alpha\sigma_o\varepsilon_o R(\pi-\theta)\left(\frac{\theta}{\pi}\right)h_1\left(\frac{P}{P_o}\right)^{n+1} \tag{3b}$$

with R the mean radius of the pipe and t the thickness, θ half-angle of flaw (in radians) illustrated in Figure 1, P_o the reference load, assumed the value in which the pipe section is fully plastic, and α and n the constants of the Ramberg-Osgood stress and strain curve, written as

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n \tag{4}$$

with σ and ε true stress and strain, σ_o the reference stress, usually assumed the yield stress, and ε_o the reference strain, equal to σ_o/E.

The correction factors f_t and f_b are functions of crack size and type of load; the dimensionless function h depends on the component and crack geometry, type of load, and constant n from the Ramberg-Osgood equation. Values of f_t, f_b, and h, shown in Figure 2, are found in Zahoor [1989].

To determine the applied tearing modulus, T, two solutions are calculated for J. One, with flaw length a, and other with $a+\Delta a$, where $\Delta a=R\Delta\theta$ and $\Delta\theta$ commonly assumed to be 0.01θ. Thus, from Equation (1)

$$T = \frac{J_{a+da} - J_a}{\Delta a}\frac{E}{\sigma_f^2} \tag{5}$$

4 Material Properties

Fracture properties are given in terms of the J-R curve, which indicates the materials resistance to stable crack growth. The correlation between the J-integral of the material, J_{mat}, and the crack extension, Δa, is expressed as

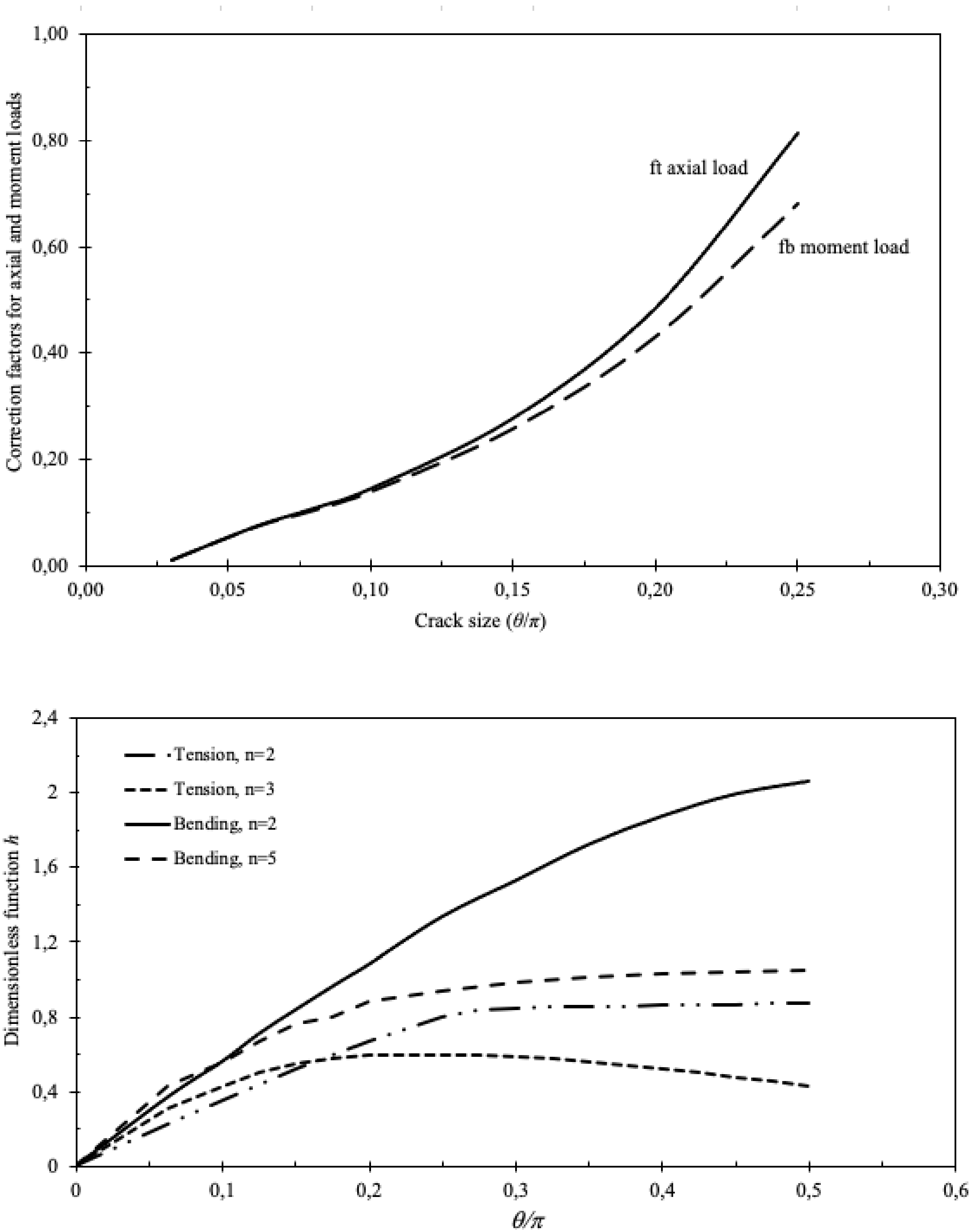

Figure 2: Values of f_t, f_b, and h as a function of through-wall circumferential crack

$$J_{mat} = c\Delta a^m \tag{6}$$

with c and m constants obtained by experiments. Instability is achieved when the J increase exceeds the corresponding increase in toughness. This establishes the ductile failure criterion (ductile tearing failure mode) as $T > T_{mat}$, where the materials tearing modulus is, as in Equation (1),

$$T_{mat} = \frac{dJ_{mat}}{da}\frac{E}{\sigma_f^2} \tag{7}$$

The properties of base metals and welds of the pipe analyzed in this chapter consider the fracture toughness modeled by Equation (6), with the data from the J-R curves shown in Table 1 and represented in Figure 3. All information are for thermally aged materials available in NUREG/CR-4513 [1994] for base metal and NUREG/CR-6428 [1996] for weld.

Table 1 – Fracture properties for aged material (minimum values)

	J_{Ic} in-lb/in^2	c in-lb/in^2	m
Base metal (SA 351-CF8A)[1]	1500	5660	0.34
Weld metal (stainless steel)[2]	228	3813	0.64

[1] Properties at 550°F [2] Properties at 617°F

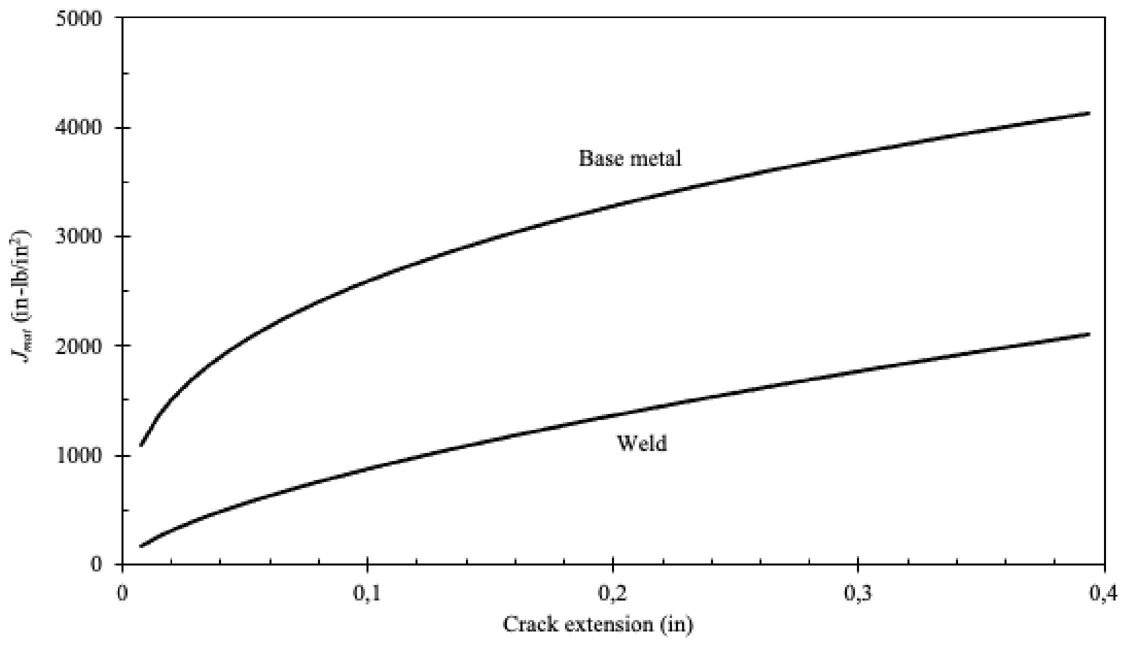

Figure 3: J-R curve for aged material (minimum values at 550°F)

The GE/EPRI scheme requires, in addition to fracture properties, that the stress and strain curve of the material be represented by the sum of the elastic and plastic deformation portions given by the Ramberg-Osgood as presented in Equation (4). Values from this curve are shown in Table 2 and in Figure 4. As in the previous case, the properties are for thermally aged materials and were taken from the NUREG/CR-6142 [1994] and NUREG/CR-4513 [1994].

Table 2 – Tensile properties for aged material

	E **ksi**	**σ_o ksi**	**S_u ksi**	**α**	***n***
Base metal (min.)(1)	24940	21.78	64.82	1.28	5.9
Base metal (avg.)(1)	24940	25.80	79.86	0.45	5.9
Weld metal (min.)(2)	25215	47	60	-	-

(1) Properties at 550°F (SA 351-CF8A) (2) Properties at 617°F (stainless steel)

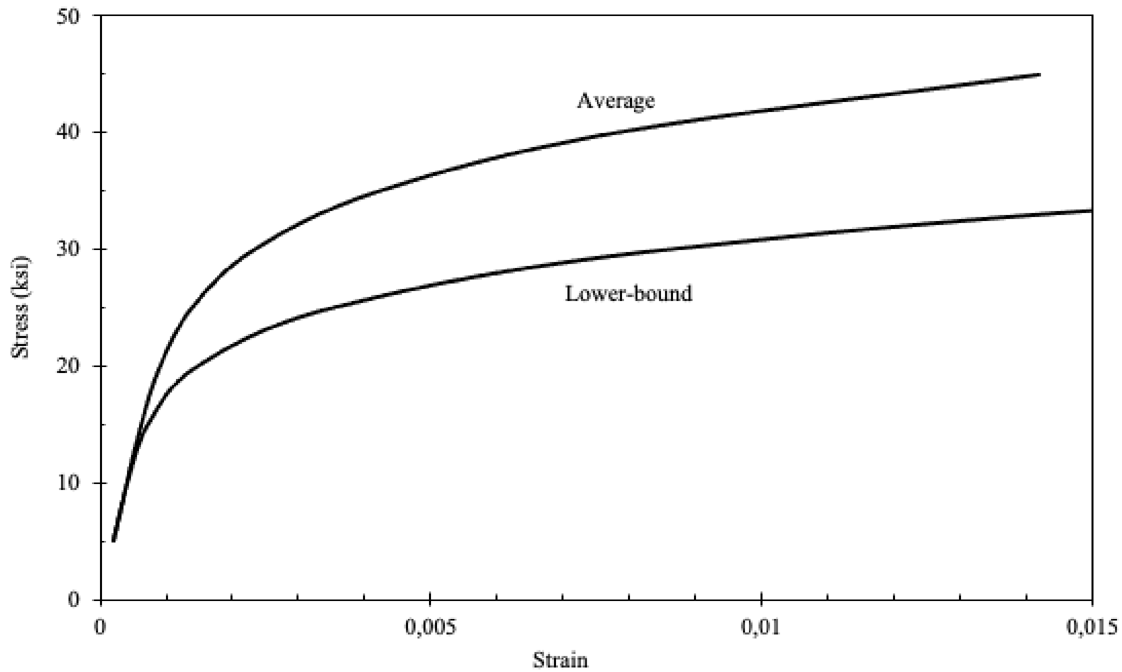

Figure 4: Stress and strain curve for aged material (SA 351-CF8A at 550°F)

5 Leak Rate Analysis

In accordance with step 6 of Section 2 of this chapter, the LBB application requires that a correlation be established between the flow rate, *Q*, and the through-wall crack size, θ / π, for the piping under normal operating loads. Based on this result it is determined the crack that will open to produce a leakage capable of being detected by the plant monitoring system.

Leak rate is obtained by two analyses, the first using elastic-plastic fracture mechanics to calculate the crack opening area, COA. Once COA is found, thermo-hydraulic analysis is performed to determine leak rate through the crack.

Several computer programs are available for leak rate analysis. Among them, SQUIRT, from the U.S. Nuclear Regulatory Commission (NRC), PICEP owned by EPRI, and proprietary softwares developed by reactor vendors such as Westinghouse, Framatome, and Mitsubishi. The PICEP [1992] is widely used for LBB applications in the nuclear industry and is adopted in the present analysis.

In PICEP, the conditions for the fluid are subcooled water, saturated or superheated steam, with leak rate dependent on pressure, temperature, and on the morphology of the crack (e.g., surface roughness, straight or sinuous flow path, friction factor). The PICEP leak rate model is based on the Henry-Fauske equations [1970; 1971] for the two-phase fluid through long channels. The program calculates the crack tip opening displacement, COD, using the GE/EPRI scheme. The implemented formulas for COD are compilations of the solutions obtained by the finite element method for axial loads, pure bending, and for the combination between them [Zahoor 1989]. The crack area through which leakage occurs is estimated by assuming elliptical, diamond, or circular shaped openings when viewed from the pipe surface. Analytical and experimental results suggest that the ellipse shape is the most suitable for LBB applications.

The PICEP was validated by comparing its results with those of numerous experiments carried out by the NRC (NRC Degraded Piping Program) and EPRI in the U.S., and by others in Canada, Italy, and Japan. In addition, PICEP results were compared with those provided by software such as the mentioned SQUIRT.

For the leak rate analysis, thermo-hydraulic conditions related to the normal operation of the plant are used. The behavior of the material is represented by the Ramberg-Osgood equation, Equation (4), with its properties given in terms of the average values. This is a conservative option because it leads to leaks that produce larger crack opening angles.

Following step 5 of Section 2, the normalized crack length, θ/π, is obtained with the minimum detectable leakage from the monitoring system (e.g. 1.0 gpm) multiplied by 10. The use of this safety factor minimizes any errors that may be introduced into the model adopted to characterize the crack.

6 Example

In this study, the LBB is verified for a pipe subjected to the loading shown in Table 3. The postulated through-wall circumferential flaw is in the base metal, in one of the critical sections, which were selected from the material properties and stresses acting on the pipe. The values of *P* and *M* in Table 3 are given by the structural analysis of the piping, with *P* being the axial reaction forces, including the pressure load, and *M* is the applied moment, calculated as the square root of the sum of squares of each of the bending and torsion moments. Leakage analysis combines pressure, weight, and thermal loads by the algebraic sum. Stability analysis combine these loads plus DBE by the absolute sum.

Table 3 – Loads at piping critical section

Leakage analysis		**Stability analysis**	
P (kips)	*M* (in-kips)	*P* (kips)	*M* (in-kips)
1500	18713	1838	21327

For the leak rate analysis, it is assumed that the through-wall circumferential flaw is caused by fatigue and has an elliptical shape. In this type of degradation, the crack is straight along the entire pipe thickness. PICEP recommends that leakage and flaw morphology be characterized by surface roughness equal to 0.00157 inches, pressure loss coefficient of 0.61, and the ratio of crack inlet area to exit area be 1.0. Initial fluid conditions are subcooled water, internal pressure of 2250 psia, and temperature of 620^{o}F. Average material properties are given in Table 2 and normal operating loads (pressure, weight, and thermal) in Table 3.

The result for the leak rate analysis in terms of the flow rate, Q, and the half-normalized flaw angle, θ/π, is represented in Figure 5 for the base metal at one critical location.

Leakage monitoring systems installed in the plants have the sensitivity to measure flow rates above 0.01 gpm, with 1.0 gpm being the typical number for LBB applications. From step 5 of Section 2, the leakage crack size is found using a safety factor of 10. Thus, with 10 gpm on the curve in Figure 5, θ/π is equal to 0.0695 (12.5 degrees).

In LBB applications, several sections of piping must be analyzed, as the largest θ/π does not necessarily occur where the stresses for the normal operating condition are the highest. This is because the lower the stress, the higher the crack size to maintain constant flow. Consequently, loads lower than those for P and M in Table 3 produce a curve more to the right than shown in Figure 5 which, for a fixed value of Q (e.g., 10 gpm), allows to obtain θ/π greater than 0.0695. Furthermore, other factors, such as the toughness of the material, influence the result and only a complete analysis determines the most critical section.

For the stability analysis, and according to step 6 of Section 2, the leakage crack size associated with the detectable leak rate ($\theta/\pi = 0.0695$) is multiplied by 2.0. Therefore, the stability is verified for θ/π equal to 0.139. In this example, by hypothesis, applied J is greater than J_{Ic}, and thus the crack extension occurs. The J/T method is implemented with the minimum material properties from Tables 1 and 2 and with the combination of normal operating and accident loads (pressure, weight, thermal, and DBE) from Table 3.

With Equations (3) and information from Zahoor [1989], the total value of J is equal to 607.9 in-lb/in2. From Equation (1) the applied T is 3.02. Combining Equations (6) and (7), the material tearing modulus, T_{mat}, is equal to 26. As T is smaller than T_{mat}, the flaw postulated in the SA 351-CF8A base metal is stable, that is, the failure by ductile tearing does not occur. The graphical representation of the method is in Figure 6.

Considering now the flaw is in the stainless steel weld and is subjected to the loads from Table 3 and conditions identical to those in the previous example. Although the flaw is in the weld, the tensile properties of the base metal control fracture. This, θ/π, applied J, and T remain the same (the values of J and T in the weld are smaller than in the base metal). The only changes are in the fracture properties of the materials, Table 1 and Figure 3, now those from the weld. Using the same calculation procedure, the T_{mat}, is equal to 28. As T is smaller than T_{mat}, the flaw postulated in the stainless steel weld is stable, with a safety coefficient slightly higher than that of the case of crack in the base metal. The results for both cases are shown in Table 4.

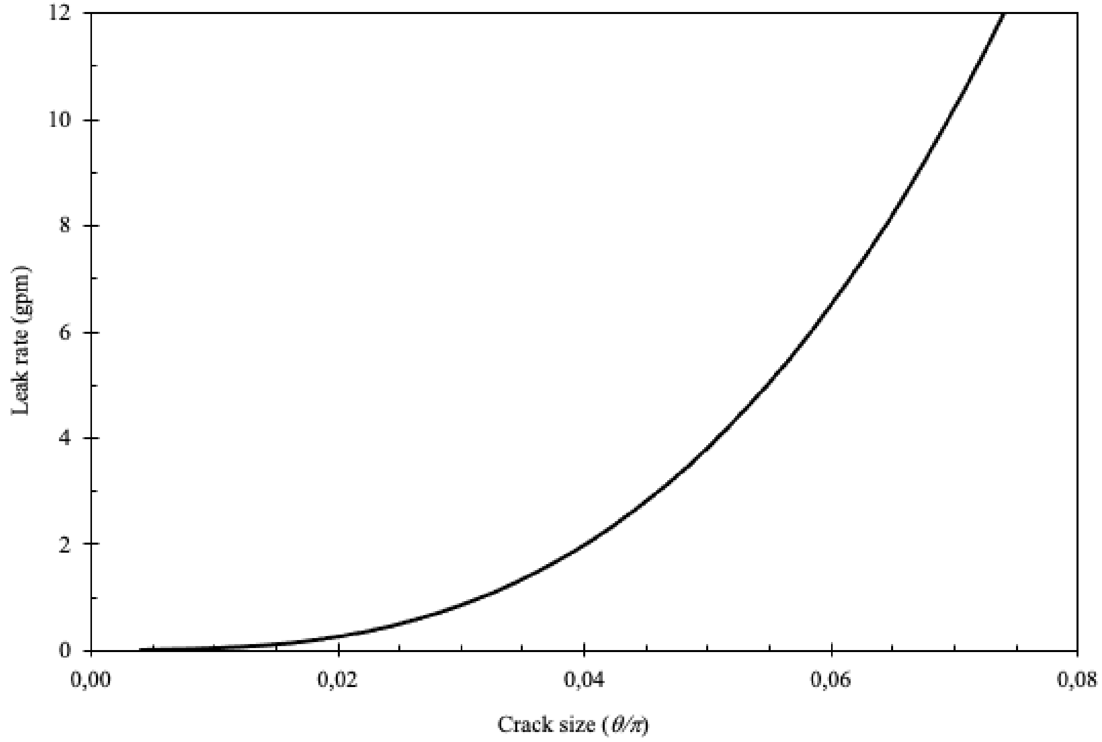

Figure 5: Leakage and through-wall crack size in the base metal

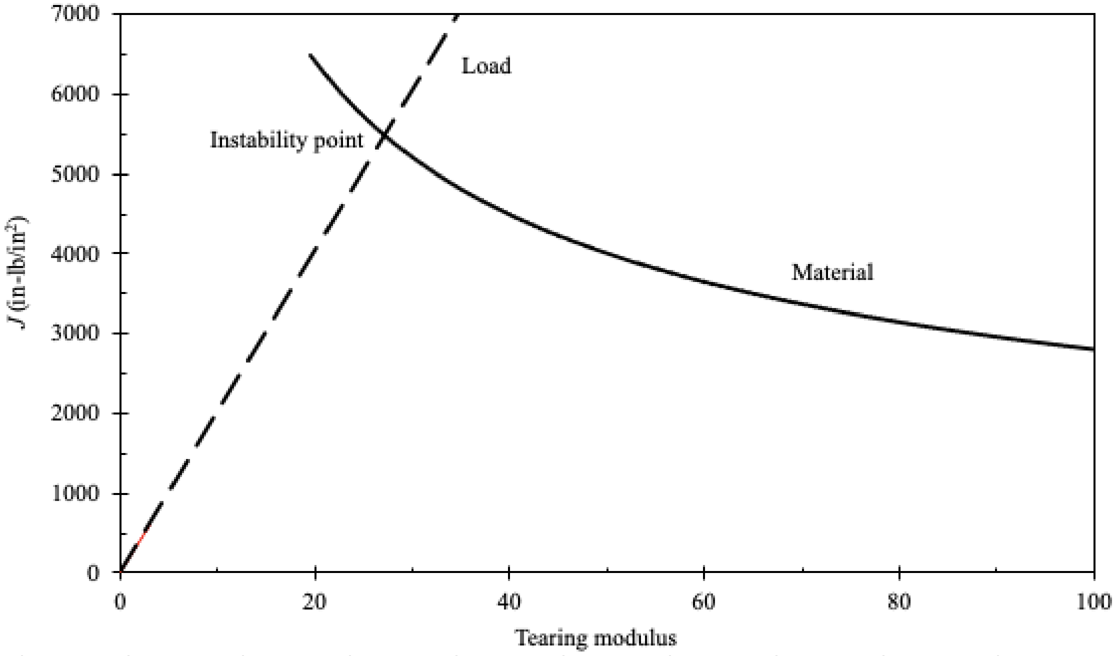

Figure 6: Analysis of crack stability in the base metal (θ /π =0.139)

Table 4 – Crack stability analysis (J/T method)

Through-wall crack location	T	T_{mat}	$\frac{T_{mat}}{T}$
Base metal	3.02	26	8.6
Weld metal	3.02	28	9.3

Another aspect of LBB that should be discussed is that when the toughness of base and weld metals are very high, it is mandatory to verify whether the failure can occur by a mechanism other than ductile tearing. One possibility to investigate is plastic collapse, a situation in which the straight section of the pipe becomes completely plastic before fracture. The appropriate theory for this analysis is the limit load.

The limit load theory considers that failure occurs when the stress due to external loads on the section is equal to the flow stress, σ_f. This indicates that the toughness of the material is high enough to ensure that the failure mode is controlled by tensile properties. A detailed description of the analytical procedure to determine the critical crack length based on the limit load theory is available in the ASME code XI Appendix C (2010). The basic equations are

$$M_o = 2\sigma_f R^2 t\left[2\sin\beta - \sin\theta\right] \tag{8}$$

$$\beta = \frac{\pi}{2}\left[1 - \frac{\theta}{\pi} - \frac{P_m}{\sigma_f}\right] \tag{9}$$

with β, the angular location of the neutral axis in the cracked pipe, whose original position is changed by the presence of the crack, and P_m and M_o being the membrane stress and moment applied at the time of plastic collapse. The other quantities have already been defined.

The stability analysis is conducted with the minimum tensile properties of Table 2 and the normal operating loads combined with the accident loads shown in Table 3. To find the critical crack size a spreadsheet is used to solve Equations (8) and (9) simultaneously. The results for the base and weld metals are presented in Table 5, where the leakage crack size and critical flaw size are compared. Since the ratio between these quantities is greater than 2.0, step 6 of Section 2 is met and failure by plastic collapse does not occur.

Table 5 – Crack stability analysis (limit load method)

Through-wall crack location	θ/π_Q Leakage crack size	θ/π_{cr} Critical crack size	$\frac{\theta/\pi_{cr}}{\theta/\pi_Q}$
Base metal	0.0695	0.366	5.3
Weld metal	0.0695	0.412	5.9

As the numbers in Tables 4 and 5 show, the margins for limit load are smaller than those of the J/T method and, in this situation, the most likely failure mode is plastic collapse.

These results agree with what exist in most practical situations, in which for LBB applications in stainless steel pipes, whose toughness is high, the crack stability is controlled by plastic collapse (limit load theory). If, on the other hand, the steel is ferritic, or even austenitic operating at temperatures where the toughness may not be as elevated (about 300^{o}F), the stability is controlled by the ductile tearing (J/T method).

7 Further Remarks

The LBB procedure described in this chapter follows NRC documents originally published in the mid-1980s. Nevertheless, the basis established at that time remains valid for recent LBB applications, as are noticed for several plants in U.S., such as Surry 1 and 2 in 2019, D.C. Cook 1 and 2 in 2018, and Turkey Point 3 and 4 in 2018. In Brazil, Angra 1 adopted the same LBB procedure for the reactor coolant loop primary piping in 2010, and for the accumulator and surge lines, predicted to be implemented in 2022.

Although no modifications have been made to the calculation procedures, further refinements should be incorporated to demonstrate the feasibility of LBB. Some of these refer to the use of programs to determine leak rate considering a) probabilistic simulations or realistic models of the crack morphology; b) inclusion of dynamic effects and/or cyclic loads in the characterization of materials; and b) effects of residual stress in the calculation of crack opening displacement [Rahman 1997] and [NUREG/CR-6765 2001].

It should be noted that from the early 2000s, when primary water stress corrosion cracks (PWSCC) were detected in the Alloy 82/182 bimetallic weld that connect the ferritic components with those fabricated with stainless steel, the LBB procedures started to consider other important aspects, mainly those related to the leak rate analysis. For example, the leakage crack size for PWSCC at Alloy 82/182 weld calculated using the default values from PICEP is 28% greater than the number determined for fatigue. However, published data from 2003 provides a higher value for the crack size, with the crack half-angle for PWSCC 69% greater than the value obtained for the fatigue case. The discrepancy is explained by differences in the morphology of the cracks, which in case of PWSCC have lower surface roughness and sinuous path, as opposed to fatigue, which are straight through the thickness. In NUREG/CR-6765 [2001] and in Rudland et. al. [2003] there is a detailed description of how to include the effects of these parameters in the analyses.

As a result, in cases where LBB is applied to dissimilar metal welds the PWSCC crack size associated with detectable leakage is larger than that determined for fatigue. For the same conditions as the example shown here, the size of the circumferential through-wall crack postulated for the stability is θ / π equal to 0.235, against 0.139, the number calculated for fatigue.

In step 1 of Section 2 it is stated that NUREG 1061 and SRP 3.6.3 requires that the piping candidate to LBB should not be susceptible to degradation, such as PWSCC. In nuclear plants it is demonstrate that the integrity of the piping during lifetime is not affected by the PWSCC if a mitigative measure is implemented. The choice of the industry are repairs, as those named mechanical stress improved process (MSIP) or structural weld overlay (SWOL), both adopted to provide a PWSCC resistant barrier to the Alloy 82/182 original welds. These mitigative repair process are applied to convert tensile residual stress in the inside surface of these welds into compressive residual stress field, thereby minimizing the probability to have initiation or propagation of PWSCC at the Alloy 82/182 material.

LBB can also be conducted in the form of boundary analysis curves approach. In this cases curves which correlate loads under normal operating and accident conditions are obtained to meet the required crack stability margin for specified leak rate, pipe, and material. Data presented in this format is very convenient during early plant design when the results of the piping layout is still preliminary, or stress analysis are not yet known. Later in the design phase, with P and M available, it is easy to verify for which combinations of the stresses the LBB is demonstrated. An example of boundary analysis curves in terms of the normal operating stress, σ_{op}, and maximum stress $\sigma_{op}+\sigma_{DBE}$, the superposition of normal and accident (DBE) stresses, involves the following steps:

a) For a stress under normal operating condition calculate the leak rate Q and crack size θ/π_Q curve. Repeat this analysis for various σ_{op} values;

b) If the plant monitoring system detects 1.0 gpm, and considering the margin of 10, obtain, for each level of σ_{op}, the leakage crack size for 10 gpm. Repeat this step to generate the curve σ_{op} and θ/π_Q;

c) For a value of the stress under normal and accidental operating conditions use the limit load method to calculate the critical crack size. Repeat this analysis for various stress values to obtain the curve correlating the maximum stress $\sigma_{op}+\sigma_{DBE}$ and θ/π_{cr};

d) Combining steps b) and c), and with θ/π_Q equal to half of θ/π_{cr}, determine the envelope curve σ_{op} and $\sigma_{op}+\sigma_{DBE}$.

Figure 7 schematically represents each of the previous steps and illustrates how the envelope curve for LBB validation is obtained. A numerical example is in Figure 8, which is a bounding analysis curve for a 12 inches pipe diameter, 1.312 inches thickness, forged stainless steel SA-376 TP316, operating at 653^{o}F and 2235 psig. LBB is demonstrated if the normal operating and maximum stresses, determined from the piping stress analysis, and represented by the various points σ_{op} and $\sigma_{op}+\sigma_{DBE}$, as presented in the figure, fall below or at the curve.

8 Conclusions

The example shows an application in the nuclear industry of LBB for a piping, the hot leg from the primary loop. The pipe is fabricated with a cast stainless steel, and it is assumed that the postulated through-wall circumferential crack caused by fatigue is located at the base metal or weld.

For each crack, two types of analyses are performed: a) leak rate analysis; and b) crack stability analysis. In the first case, the crack size associated with the detectable leak rate

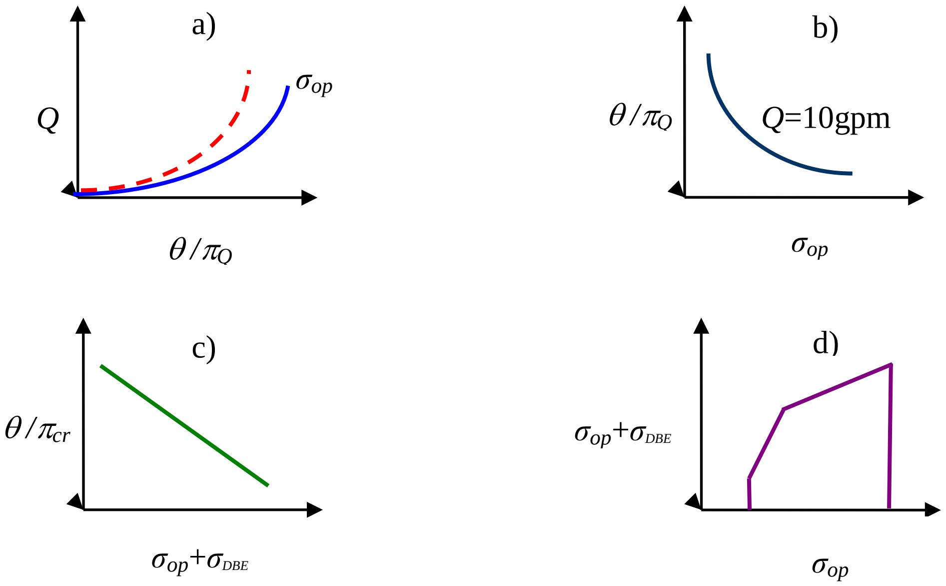

Figure 7: Schematic representation to determine the boundary analysis curve

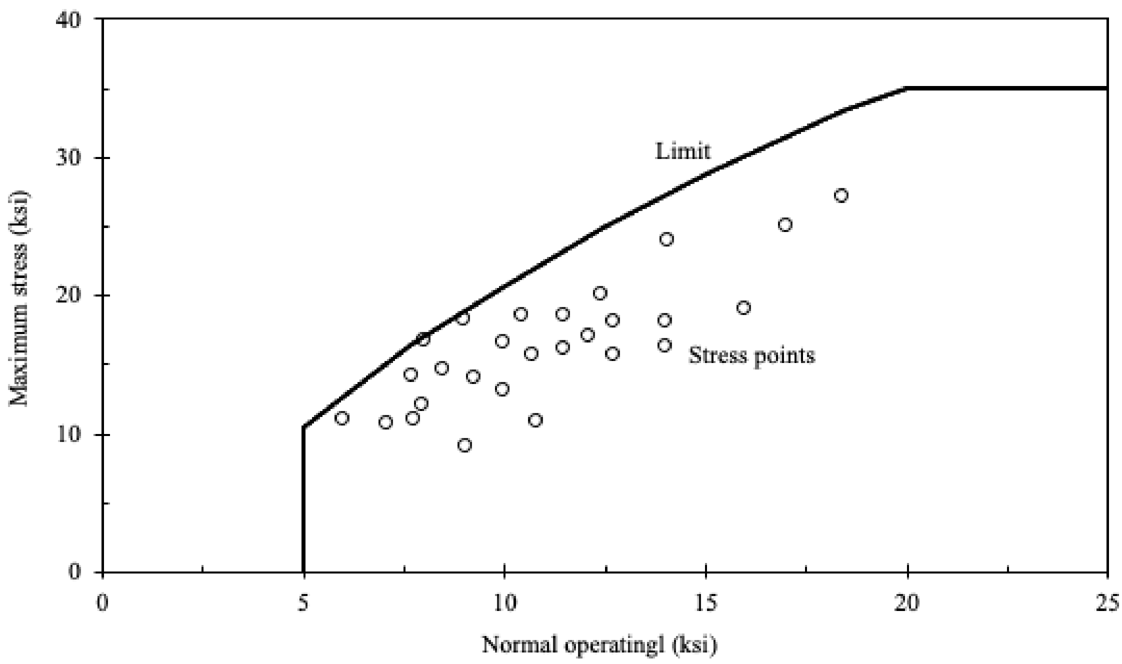

Figure 8: Typical boundary analysis curve for LBB validation

is obtained. Once this size is determined, the stability of the crack is verified, using the J/T method (ductile tearing) or the limit load theory (plastic collapse).

As the toughness of materials from the primary loop piping is high, the most frequent failure mode is plastic collapse. However, for cracks in ferritic or austenitic steels where toughness is reduced by thermal aging, failure by ductile tearing is more likely, especially with the system operating close to 300^{o}F.

When the feasibility of LBB is demonstrated, postulated break loads (LOCA) are eliminated from the design basis. The advantage of LBB is that components such reactor vessel internals and nozzles, primary loop equipment and supports, and piping need not to be designed to withstand LOCA loads. As an added benefit, pipe-whip restraints, and jet-impingement shields, both installed to protect critical equipment from the dynamic effects of the postulated breaks, are not necessary.

References

ASME American Society of Mechanical Engineers. ASME Boiler and Pressure Vessel Code. New York, 2010.

A. Zahoor. Ductile Fracture Handbook. NP-6301-D Research Project, Electric Power Research Institute, 1989.

D. Rudland, R. Wolterman, G. Wilkowski, and R. Tregoning. Impact of PWSCC and Current Leak Detection on Leak-Before-Break, Presentation from NRC Conference on Vessel Head Penetration Inspection, Cracking, and Repairs, September 29 - October 2, 2003.

EPRI. Leak-Before-Break Evaluation for PWR Alloy 82/182, Materials Reliability Program, MRP-140, Report 1011808, Electric Power Research Institute, November 2005.

NUREG. Evaluation of Potential for Pipe Breaks, NUREG-1061 Volume 3, US Nuclear Regulatory Commission (NRC), 1984.

NUREG. The Application of Fracture Proof Design Methods Using Tearing Stability Theory to Nuclear Piping Postulating Circumferential Through-Wall Cracks, NUREG/CR-3464, US Nuclear Regulatory Commission (NRC), 1983.

NUREG. Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems, NUREG/CR-4513R1, ANL-93/22, US Nuclear Regulatory Commission (NRC), 1994.

NUREG. Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds, NUREG/CR-6428, ANL-95/47, US Nuclear Regulatory Commission (NRC), 1996.

NUREG. Tensile-Property Characterization of Thermally Aged Cast Stainless Steels, NUREG/CR-6142, ANL-93/35, US Nuclear Regulatory Commission (NRC), 1994.

NUREG. Development of Technical Basis for Leak-Before-Break Evaluation Procedures, NUREG/CR-6765, US Nuclear Regulatory Commission (NRC), 2001.

PICEP. Pipe Crack Evaluation Program (Revision 4), NP-3596-SR, Electric Power Research Institute (EPRI), 1992.

R.E. Henry and H. K. Fauske. The Two-Phase Critical Flow of One-Component Mixtures in Nozzles and Short Tubes, Journal of Heat Transfer, American Society of Mechanical Engineers Transactions, 1971.

R.E. Henry. The Two-Phase Critical Discharge of Initially Saturated ou Subcooled Liquid, Nuclear Science and Engineering, 41, p. 337, 1970.

SRP. Leak-Before-Break Evaluation Procedures, Draft Standard Review Plan 3.6.3, Federal Register Vol. 52 No. 167, August 26, 1987.

SRP. Leak-Before-Break Evaluation Procedures, NUREG-0800, Standard Review Plan 3.6.3, US Nuclear Regulatory Commission (NRC), 2007.

Westinghouse. Leak-Before-Break Evaluation of the AP1000 Piping, Appendix 3B, AP1000 Design Control Document, Westinghouse, 2007.