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

LEAK-BEFORE-BREAK AND OTHER CONCEPTS OF BREAK-EXCLUSION

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ABSTRACT

In the frame of knowledge management, it is important to transfer ideas and explanations regularly. Same terms can have several meanings and this can be misleading. For break exclusion several national concepts exist: LBB according to the US Standard Review Plan 3.6.3 (SRP 3.6.3) and Superpipe for MSL between containment penetration fixed point and MSV fixed point, Break Preclusion Concept (BPC) in Germany, French Break Preclusion Concept for EPR (FA3/TSN), High Integrity Component (HIC) e.g. for EPR in the UK. All concepts with almost the same goal: support demonstration of safety while removing of dynamic effects of break from the design basis and safety demonstration. The meaning of LBB will be recalled. The several concepts for break exclusion will be summarized. An overview of the main efforts of the previous different concepts will be given. Finally, an overview of past and actual R&D with focus on LBB will be shown as well as an outlook of success and remaining challenges.

HISTORY OF THE LEAK BEFORE BREAK AND THE PWR DESIGN RULES

Same terms can have several meanings and this can be misleading. For break exclusion several national concepts exist: LBB according to the US Standard Review Plan 3.6.3 (SRP 3.6.3) and Superpipe for MSL between containment penetration fixed point and MSV fixed point, Break Preclusion Concept (BPC) in Germany, French Break Preclusion Concept for EPR (FA3/TSN), High Integrity Component (HIC) e.g. for EPR in the UK. All concepts with almost the same goal: support demonstration of safety while removing of dynamic effects of break from the design basis and safety demonstration.

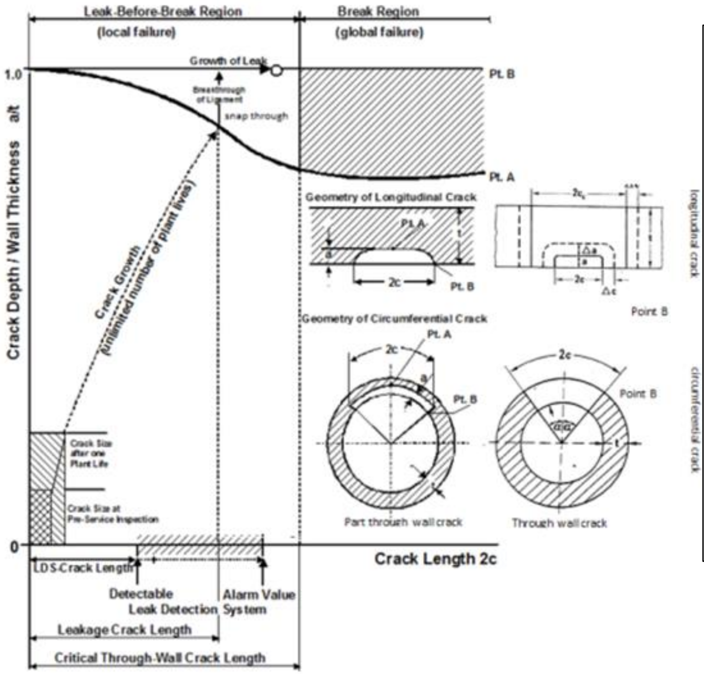
Short history, see Mir Sajjad Ali (2010), back in the 1960's, break of the reactor pressure vessel (RPV) was judged in the USA to be incredible. The hypothetical double-ended guillotine pipe breaks (DEGB) were postulated as "maximum credible accident" (MCA) and has been taken as the most severe reactor loss of coolant accident (LOCA) in nuclear power plant (NPP) design. The original purpose was to provide a limiting basis for the emergency core cooling and containment systems. However, the postulate was extended to the design of the high energy piping system, resulting in the construction of massive pipe whip restraints and jet impingement shields. The benefit of these devices is to limit pipe movement and avoid damage caused by impact of motioned defected pipe due to jet reaction forces into neighboring components as well as to avoid severe damage on neighboring safe-related components and other structure due to jet of water and steam leakage The DEGB postulate was further extended to the design for environmental qualification of safety equipment. Then, a "break everywhere" requirement was implemented in the General Design Criteria 4 (GDC4) to require protection against dynamic pipe rupture effects for some systems, including protecting against dynamic effects of pipe rupture. An associated difficulty arises for the demonstration of RPV internals integrity due to rapid discharge of fluid and depressurization waves during the DEGB event. In the 1980's the nuclear industry wanted to demonstrate that a DEGB is highly unlikely even under severe accident conditions, and that a LOCA based on DEGB is unnecessary and undesirable design restriction. Considering the improvement in the knowledge of fracture mechanics supported by the performance of piping and vessel testing, a new document, Modification of GDC4, was released by the US NRC (Safety authority), which defines the LBB case (based on fracture mechanics calculations) and assigns legislative consequences to the LBB status. To provide review guidance for the implementation of the LBB concept, the Standard Review Plan 3.6.3 (SRP 3.6.3) was issued. Following this implementation, relaxation to the design of NPP were finally achieved and protection against dynamic effects were removed. In parallel other concepts have been developed in Europe.

THE MEANING OF LEAK BEFORE BREAK

According to G.Wilkowski (2000), the term LBB has been used for half a century in reference to a methodology that means that a leak will be discovered prior to a fast fracture occurring in service (see . The earliest technical approach was described by Irwin in 1960 using linear elastic fracture mechanics methods to investigate flaw propagation for missile weapon applications. Another approach was developed in 1965 to describe fracture behavior as a function of temperature for naval application by Pellini who suggests to apply it to piping flaws, this approach was quite useful to differentiate between catastrophic brittle failure versus ductile tearing. This latter point being also one of the reasons why a pressure retaining component should be operated at temperature well above the nil ductile transition temperature (NDT) of the weakest material. However, the term leak-before-break was not coined at that time but later on, perhaps at the Battelle Memorial Institute Columbus Laboratories (BMI) during test campaign between 1960 and 1970 on gas pipes with flaws oriented along piping axis or by Bartholomé and Dorner (1972) using “LBB-flaw” in the frame of Break Exclusion demonstration of a reactor pressure vessel RPV.

There are several technical definitions for LBB. For instance, LBB can occur for an axial flaw in a pressurized pipe where the penetration of the wall thickness will result in a stable axial through-wall crack. This is LBB under load-controlled conditions. LBB could also occur for a circumferential crack in a pipe with high thermal expansion stresses. This can be considered as LBB under compliant displacement-controlled conditions. Finally, LBB might occur when the flaw is stable under normal operating conditions and remains stable when there is a sudden dynamic event such as seismic loading. This can be termed as a time-dependent inertial LBB analysis.

For nuclear power plant (NPP) Industry, the schematic of LBB is given in Figure 1. LBB ensures that a tolerated flaw (lower left corner) does not grow significantly during the plant life (point A of crack should not cross the thickness t) and that a through-thickness flaw (with length 2c) can be sub-critical to instability (cloud delimited bold line) under all operational and accident loadings) and that a leak arising from such through-thickness flaw is on the contrary large enough to generate a detectable leak (leakage from crack length $2c_{LDS}$) in time during normal power generation operation and does not grow quickly to reach instability.so that intervention of plant operation (like shutdown) is ensured before global component failure occurs.



Legend for Figure 1:
TWC: through wall crack is a defect in the piping with a crack path connection between inner and outer surface which can lead to a leak if the piping is under sufficient tensile stresses to open the crack mouth and let it leak;
PTWC: part-through-wall crack is a defect in the piping without fully extent through the thickness;
Flaw or crack: postulated or non- or detected defect

Figure 1 LBB diagram

SEVERAL CONCEPTS FOR BREAK EXCLUSION

US LBB concept: summary of the US NRC guidance for LBB Application (Standard SRP3.6.3)

First of all, a screening of the pipe to be eligible to LBB application, the apparatus must be operated in ductile fracture domain, the LBB approach cannot be applied to piping that is subject to brittle fracture or to active degradation mechanisms such as any type of stress corrosion cracking, erosion, corrosion, erosion/corrosion, large fatigue due to unspecified stratification/mixing, creep, water/steam hammer due to condensation (see chapter LBB requirement and restrictions). Details of the LBB procedure are given in Chapter 5 of NUREG-1061, Vol.3 (original technical basis document). The general methodology requires to calculate the critical flaw size under normal operation loads combined with earthquake (with some margin on loading) and to prove that the leak resulting from this critical flaw size is 10 times greater than the minimum leak rate that can be detected by the monitoring systems during power generation operating condition. The critical crack size at a given condition of loading and temperature means that a pipe with such a crack size will not be able to subtend the given loading condition without producing an instable crack growth. On the contrary, a shorter crack can may be stable without substantial further crack growth (safe) or with stable ductile crack growth (safe up to critical crack size). The criteria of the described methodology can be verified in different ways for the different materials, especially by the following methods: limit load (net-section-collapse), fracture mechanics J integral / tearing modulus, failure assessment diagram (FAD in the meaning of the English R6 methodology). Due to the inherent toughness of wrought austenitic stainless steel (austenite primary crystalline structure is face centered cubic), its failure analysis is controlled by limit load / net- section collapse behavior. However, for casting or ferritic steel (body centered cubic crystalline structure) with lower toughness and potential for brittle failure mode, the other fracture mechanics approaches are relevant. A typical plant licensing submittal (according to U.S. NRC Standard Review Plan 3.6.3 (2007) requires an evaluation of the leakage detection system to demonstrate conformance to U.S. NRC Regulatory Guide 1.45 (1981, revised in 2008) "Reactor Coolant Pressure Boundary Leakage Detection Systems", in addition to the loading analysis. There should be three diverse leak detection systems (humidity monitoring, sump level, activity monitoring) with a sensitivity of at least one gallon per minute (3.8 l/min) within one hour. Leakage from certain components is routed to collection tanks with a monitoring system that reports the total amount of this identified leakage. The applicable technical specification limits identified leakage to 10 gallons per minute. Other leakage collects in the containment sump as unidentified leakage. To distinguish water that leaked through the pressure boundary from water that leaked through valve packing and flange gaskets is difficult. In the US the technical specification limit of 1.0 gpm of unidentified leakage allows a licensee to operate its plant up to this limit and that some unidentified leakage might later be determined to be through the pressure boundary. Requiring plants to make unnecessary shutdown each time a small amount of unidentified leakage is detected would not have a safety benefit. In the 2008 revision, the state of the art capability of new leakage detection system have been considered (Framatome FLÜS™ is explicitly named). These methods also permit identification of the general (if not exact) location of a leak and, therefore, are able to monitor critical components. In addition, acoustic emission systems may permit monitoring the progression of material degradation. The leakage detection system is one of the key component of the LBB concept in the US. The calculation of leakage rate include the determination of the crack opening area as well as thermal-hydraulic assessment covering sub-cooled water to critical steam

European definition of BPC

The European Utility Requirements (EUR) document (European Utility Requirements for LWR Nuclear Power Plants, (Vol. 2, Chap. 4,Section 5.10), Rev. C 2001) provides the following clear and precise definition of break preclusion concept: “Break preclusion is a concept, implemented during the design phase, to deterministically rule out the catastrophic failure of any important coolant line (e.g. Main Coolant Line) from the list of the design events considered for structures and components”

German Break Preclusion Concept (BPC)

This concept is based on basis safety (“Basis Sicherheit”) production quality) and independent redundancies, it was first named the Basis Safety Concept (“Basissicherheitskonzept” BSC) by Kußmaul (1979) and is illustrated in Figure 2. Only the application of the whole concept allow break exclusion (“Bruchausschluss”). The integrity concept (IC) see Roos (2001) is a further development of the BSC by taking concrete measures and verifications for safeguarding the quality required for the integrity of a component or system over its total operational lifetime. The integrity concept comprises of: a) proof of the as-required quality upon design and manufacture (basis safety), b) proof of the existing quality upon previous operation, c) safeguarding of the required quality for further operation. The assessment of LBB behaviour is only one independent redundancy in this concept. All steps for performing the LBB assessment considering postulated flaw are described in the German Standard KTA3206 (2014) Break Preclusion Verifications for Pressure-Retaining Components in Nuclear Power Plants.

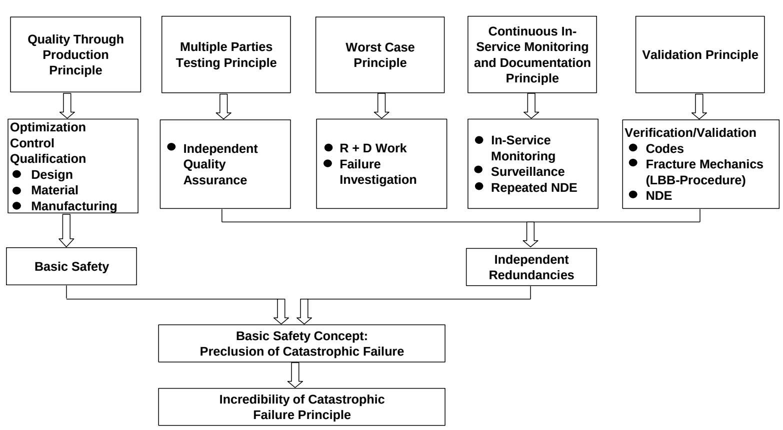


Figure 2: Principle of basis safety concept for break exclusion

Crack growth, leakage area and leakage rate include implicit margins and no structural factors is required. All design loadings are considered for critical crack size (not only SSE). The In-service inspection (ISI) interval is part of the assessment. In the presence of manufacturing defect, structural factors (on loading) of US code ASME XI are applied. As such, the LBB section of the BPC forms a "defence in depth" argument for the prevention of pipe failure; which will be accompanied by preclusion of other failure mechanisms and other detection and prevention measures. Investigated locations are welds, sections of increased load or material degradation and geometric features. It generally consider a three tiered approach with increased level of conservatism and decreasing level of complexity.

"Super pipe" concept

The origin is the US-Approach (considering design criteria of ASME III – NE 1120 + Branch Technical Position 3.4) for steam line system between containment penetration fixed point and MSL valves station fixed point. It is applied in French plants as "tronçon protégé" considering optimized design, stress after RCC-M C3650, reinforced in-service inspection. An overview of the main efforts of the previous different concepts is given in Table 1 (from the point of view of the author).

Table 1 Base Principles behind the different concepts to exclude a full break scenario

	High level of quality, Ductility	In-Service-Inspection	Leakage detection system	Fracture mechanics analysis and testing
US LBB	+	+	++	+
German BPC	++	++	++	+
French BPC	++	+	-*	++
HIC	++	++	-*	+++
Superpipe	+	+	-	-

Legend: - none ; + low ; ++high ; +++ very high ; * LDS available even if not connected to break exclusion assessment

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French LBB for experimental reactor (codification RCC-MRX)

The approach is similar to US LBB concept with more detailed fracture mechanics evaluation and approach to estimate length at snap through.

LBB in England (routine R6 approach)

The approach contained within R6 is based on two methods: 1) determination of the crack required for detectable rate and 2) the calculation of the final defect size at the end of component lifetime. The second of these is more complex and involves crack growth calculations through life for an initially part-penetrating defect. Critical crack size are determined following two criteria method. The two-criteria method is used for assessing the failure behavior of components between the limiting cases of linear elastic and fully plastic material condition in a closed concept. The consideration of the fracture-mechanics characteristic values makes assessments possible with regard to crack initiation, stable crack propagation and crack instability. The two-criteria method was developed by CEGB (Central Electricity Board, Great Britain) and transposed into Routine R6 by British Energy. The R6 approach is heavily based on sensitivity analyses within deterministic calculations and does not apply specific safety margins. It is no applicable in case of multiple defects. A part of the R6 approach has been considered in the realization of the break exclusion concept for the EPR under construction in the UK, the outcome of this other concept is given the integrity assessment High Integrity Component (HIC).

LBB in Japan

Methodology follows US LBB with some differences: a fatigue flaw growth analysis is performed based on an initial flaw size that is twice the UT inspection capability or ~0.2t with a flaw length of 1t (i.e. 5:1 semi-elliptical flaw). This surface defect is required to be performed beyond the design basis number of cycles until it grows through-wall, such that a flaw length can be established. Margin of minimum 5 is required on the ratio critical crack length and leakage crack length. For the flaw stability analysis, the loadings to consider are operating conditions I, II and III and/or combination of operating condition I with SSE loads. The flaw stability is based on net section collapse, with a required margin for flaw stability is only 1.

SEVERAL CONCEPTS FOR BREAK EXCLUSION APPLIED TO EPRS

Overview of system for which exclusion is precluded with respect to the applied concept is given for EPR in Table 2.

Table 2 Systems considered under break-preclusion

System / EPR	OL3	US	FA3	TSN	HPC	EPR2
Main coolant lines	LBB	LBB	BP	BP	HIC	BP
Surge line	-	LBB	-	-	-	-
Steam water lines	LBB	LBB	BP	BP	HIC	BP
Feedwater lines	LBB	-	-	-	-	-

EPR OL3 (Specific report)

The LBB analysis is conducted in accordance with Finnish Standard YVL and US SRP 3.6.3.

In order to increase LBB margins, a sophisticated leakage detection system hast been installed (FLÜS) on specific area of the main steam line.

EPR US (see PSAR and FSAR report)

The methodology follows SRP3.6.3. and a LBB windows concept was calculated to define a range of required loadings to achieve LBB. Although the US EPR design was later cancelled, it is important to note that the NRC Staff had accepted the LBB analyses for all three piping systems. The LBB windows approach used in the analyses (A.D.Nana (1994) was also successfully defended with the Advisory Committee on Reactor Safeguard (ACRS) body (by Framatome and NRC Staff) prior to withdrawal of the US EPR application. The LBB analyses were performed for these piping systems considering very high 0.3g seismic loadings with consideration of various soil conditions from soft to hard rock for potential plant sites practically anywhere in the USA.

EPR FA3/TSN (Specific report)

Break exclusion has been considered for the main coolant lines (MCL) and main steam lines (MSL), see Chapuliot et al. (2014). As a defense in depth, an assessment of large through wall cracks was performed (“Tolérance aux grands défauts”), which is performed in the spirit of the LBB assessment considering the same margin.

EPR UK

The UK approach for High Integrity Components (HIC) has requirements for the demonstration of defect tolerance different from those of the conventional approach of the RCC-M. It imposes a margin between the End-Of-Life Limiting Defect Size (ELLDS) and the sum of the Qualified Examination Defect Size (QEDS) and lifetime fatigue crack growth (LFCG). It also explicitly requires consideration of residual stress fields in the Fracture Mechanics Assessment (FMA) of resistance welded joints. Thus, modifications to the RCC-M requirements are needed in order to meet UK requirements. The methods for FMA and LFCG comprise different levels of complexity; from complete analytical schemes codified in French codes to complex Finite Element Analyses (FEA).

IMPACT OF BREAK EXCLUSION ON SAFETY DEMONSTRATION

The benefits of LBB and BP are multifold, with maximum safety and economic benefits derived if the concept is increasing the structural reliability (quality) and is applied at an early design stages. The design basis for protection of light water nuclear power plants against the effects of postulated pipe rupture was given in the standard ANSI/ANS-58.2-1988 (withdrawn). The LBB and BPC concept have been also applied in a backfitting mode, for example by increasing the quality: feedwater lines and main steam water lines (made of conventional ferritic materials) were replaced with higher toughness piping in order to fullfill the requirement (basis safety) of quality through production. LBB has also been used as part of an overall safety assessments for leaving real or postulated flaws in service for some operating period. LBB is conducted to justify elimination from the design requirements of several effects:

Dynamic effects due to pipe rupture

This allows elimination of hardware, such as pipe whip restraints and jet impingement shields, which can impede the accessibility to pipes (critical for inspections) and increase radiation exposure during maintenance operation and in-service inspections.

Thermal hydraulic effects

Core cooling, sizing of emergency system, containment and qualification (to resist pressure, temperature, radiation doses) are impacted at design level, however some differences appears between concepts to the investigation of consequence to be performed, see Table 3.

Table 3 comparison of investigated consequences between concepts

	SRP3.6.3 LBB	**German BPC**	**French BPC FA3 / TSN**	**HIC**
Dynamic effects				
whiped piping	excluded	0.1A	excluded	excluded
jet forces	excluded	0.1A	excluded	excluded
reaction forces	excluded	0.1A	excluded	excluded
depressurization waves	excluded	0.1A, 15ms	excluded	excluded
sub-compartment pressurization	excluded	0.1A	excluded	excluded
Thermal hydraulic effects				
emergency cooling sizing	2A	≤2A	2a analysis realistic way	excluded
core cooling sizing	2A	≤2A	2a analysis realistic way	excluded
containment sizing against P-T	2A	≤2A	2a analysis realistic way	excluded
Qualification I&C against P-T	2A	≤2A	2a analysis realistic way	excluded

Color legend:
- (green) consequences taken into account (credited)
- (blue) Consequences not investigated (excluded), excepted breaks of connected lines

US LBB CONCEPT IMPLICIT REQUIREMENT AND RESTRICTION

The requirement of ductile failure mode is made: the system must operate at temperature excluding any risk of brittle fracture. This is generally the case during power generation. However, during startup and shutdown, the residual risk is higher.

An implicit assumption in the LBB SRP3.6.3 is also the LBB-behavior, assuming that a crack developing through the thickness is small in length compared to the critical crack length. This is not obvious since a large crack could develop and suddenly become a large through wall crack larger than the critical size. In the German BPC, this effect is also investigated considering an extension of the FCG beyond the specified load collective, in order to investigate the LBB-Behavior and the margin between the leakage crack size (even non detected) and the critical crack size. In this case, some unpredicted degradation mode may be prevented by the existence of the aforementioned margin. Recurrent in-service inspections with NDE can alleviate this risk.

Also following some concepts (German BPC as exception, see Table 3), local effects (jet) from flaw are not taken into account apart from junction with smaller adjacent lines not having break exclusion.

It must be demonstrated that the leak will be timely detected and that the plant will be systematically shut down. The implicit requirement is that the leak detection system is sensitive enough and that the reaction of the operator is adequate to evaluate the event in a break exclusion area.

The procedure is only applicable to an entire section of piping, not individual components or welded joints. The LBB approach cannot be applied to piping that is subject to active degradation mechanisms such as any type of stress corrosion cracking (relevant for Primary Water Stress Corrosion Cracking PWSCC in some DMWs), erosion (relevant for non-cladded ferritic piping), corrosion, erosion/corrosion, large fatigue due to unspecified stratification/mixing, creep. The reason is that this can lead to multiple cracking and that the mechanisms are time dependent leading eventually to large cracks.

Furthermore, large water/steam hammer (due to condensation) must be excluded due to the high dynamic loading on the piping and support.

The requirements to material are more stringent than the general rules for Class 1 piping.

- materials must remain in the ductile plateau for the lowest temperatures that could be encountered during transients, design basis incidents; a lower limit of 100J (Charpy V-Notch CVN) at 0°C has been required for ferritic piping under French BPC for EPR (stringent requirement compared to German BSC).

- the piping installation should allow easy access to all the exterior surfaces of the pipes; in-service inspection of welded areas must use effective methods.

Leakage from TWC must be large enough to be detected, the loading condition should be favorable (tensile) with regards to the crack location in order to induce a crack mouth opening large enough to allow flow rate. Therefore, loading must be within a certain range (see also LBB-window A.Nana 1994) for successful LBB assessment.

APPLICATION OF LBB WORLDWIDE

There are differences in the legislative status of the LBB concept in the OECD Member States, see Table 4.

Table 4 LBB status (LBB European research 2000)

Aspects of Regulatory Position	Applying in the Countries:														
	AC	Be	CS	Ger	Fin	Fr	Jap	SAf	SAr	Sd	Sp	Sw	UK	US	RF
Acceptance of LBB concept:															
- generally accepted			y	y									y	y	
- case-by-case basis	y	y				y	y		y		y	y			y
- under discussion					y			y		y					
Applied LBB procedure:															
- NRC procedure	y	(y)	(y)		(y)				(y)		y	y		y	(y)
- German procedure				y					(y)		y				(y)
- own national procedure		y	y	y	y		y		y	y					y
Reason for LBB application:															
- avoidance of installation of pipe whip restraints	y	y	y	y	y		y		y	y	y	y		y	y
- compensation of low design deficiencies (type L)			y						y		y	y			y
- compensation of high design deficiencies (type H)			y												y
Plants with LBB application:															
- total number of PWR units	16	7	14	14	2	58	23	2	5	3	7	3	1	76	29
- PWR units with LBB application	4	7	4	14	0	0	10	0	2	0	6	1	1	71	4
- total number of BWR units	6			6	2		28		2	9	2	2		37	17
- BWR units with LBB application	0			6	0		1		2	0	0	1		0	2

Key:
y = yes
p = partly
m = missing information
(y) = based on

AC Asian Countries (China, India, Pakistan, S-Korea, Taiwan), Japan separate
Be Belgium
CS Czechoslovakia
Ger Germany
Fin Finland
Fr France
Jap Japan
SAf South Africa
SAr South America (Argentina, Brazil, Mexico)
Sd Sweden
Sp Spain
Sw Switzerland
UK United Kingdom
US USA
RF Russian Fed. plus Ukraine, Lithuania & Armenia

Regulatory actions took place first in the US and Germany: standards (including the requirement to demonstrate LBB i.e. to achieve Break Exclusion) exist by law and can be submitted to regulator for acceptance. Efforts in other European countries (see details for French context) have not resulted to date in similar regulatory actions. The French safety authorities have validated the Break Exclusion Concept following the ASN Guideline 22 (2005). Some other NPPs with LBB application are given in table 5:

Table 5: NPPs with approved LBB lines (US, Germany, eastern plant studies performed by Framatome)

Plant System	Plant Type		
	Westinghouse	CE	B&W
Main Loop Piping	48	14	7
Surge Line Piping	23	1	0
RHR Piping	13	NA	NA
Accumulator Piping	19	NA	NA
Loop Bypass Piping	6	NA	NA
Main Steam Piping	2	0	0
Core Flood Piping	NA	NA	3
Shutdown Cooling/ Decay Heat Suction	NA	1	0
Safety Injection	0	1	0

Name of Plants	Begin of Commercial operation	Type	LBB - Status		
			A	B	C
Obrigheim	3 / 1969	PWR	+	+	+
Stade	5 / 1972	PWR	+		+
Biblis A	2 / 1975	PWR	+	+	+
Borssele (Netherlands)	10 / 1973	PWR	+		+
Unterweser	9 / 1979	PWR	+		
Biblis B	1 / 1977	PWR	+	+	+
Neckar 1	12 / 1976	PWR	+		+
Gösgen (Switzerland)	10 / 1979	PWR	+		
Grafenrheinfeld	6 / 1982	PWR	+	+	+
Grohnde	2 / 1985	PWR	+	+	
Philippsburg 2	4 / 1985	PWR	+	+	
Brokdorf	12 / 1986	PWR	+	+	
Neckar 2	4 / 1989	PWR	+	+	
Trillo 1 (Spain)	11 / 1988	PWR	+	+	
Angra 2 (Brazil)	12 / 2000	PWR	+	+	
Isar 2	4 / 1988	PWR	+	+	
Emsland	6 / 1988	PWR	+	+	
Brunsbüttel	2 / 1977	BWR	+		+
Philippsburg 1	2 / 1980	BWR	+		+
Isar 1	3 / 1979	BWR	+		+
Krümmel	3 / 1984	BWR	+		+
Gundremmingen B	7 / 1984	BWR	+	+	+
Gundremmingen C	1 / 1985	BWR	+	+	+

A - PWR: MCL; BWR: Feedwater- and Steamline
B - Other piping without backfitting
C - Other piping with backfitting (e. g. leak detection system, material evaluation, exchange of piping, etc.)

Name of plants	Year of LBB assessment	System
Greifswald 1 - 4 (VVER - 440 / V230)	1989 / 90	Aust. MCL , surgeline (reconstruction)
Bohunice V1 (VVER - 440 / V230)	1990 / 91	Auste. MCL (review)
Kozloduy 1 - 4 (VVER - 400 / V230)	1995 / 96	Aust. MCL, surgeline, RIS (PHARE program)
Novovoronesh 3 + 4, Kola 1 + 2 (VVER - 440 / V230)	1994 / 94	Aust. MCL, surgeline (TACIS project)
Paks 1 - 4 (VVER - 440 / V213)	1997 / 98	Aust, steam generator collector (PHARE program)
Smolensk 3 (RBMK)	1997 / 98	Ferritic MCL (TACIS project)

For the AP1000, the LBB concept has been applied and authorized by the NRC for a broad range of lines: MCL (hot legs, crossover legs, and cold legs), surge line, safety injection and residual heat removal lines, feedwater lines and main steam lines within the containment. Essentially, the AP1000 reactor design received NRC approval for all primary piping systems whose pipe sizes were 6-inches or greater. LBB is also widely applied for AP1400. LBB concept has been widely applied to VVER and RBMK plants and it is also applied to newer VVER1200 for main coolant lines.

Physically, several aspects support the break exclusion for several systems worldwide: the choice of material with regards to fracture mode (ductile for wrought austenitic stainless steel) and fracture toughness (high toughness for modern ferritic piping), the experience gained from existing plant for piping routing design, the increase of knowledge in the different degradation mechanism. Furthermore, the independent redundancies (like in-service inspections, monitoring, quality control, R&D investigations and validations) act as defence in depth.

FOCUS ON REGULATORY POSITION AND ACCEPTANCE IN FRANCE

In France, the ASN Safety Authority considers that the LBB concept does not demonstrate that the evolution of a leak leading to a large rupture is a sufficiently slow process that allows the reactor to shut down after leak detection and before the leak evolves into a pipe rupture. For EDF French plants, LBB concept is not validated by ASN, anti-whipping system are installed for main coolant lines and limited leaks (considering a restricted pipe whip) can be considered. The BCCN (now DEP) (Office of Control of Nuclear Boilers) member of the ASN, issued the following position on the occasion of the SPN (Section Permanente Nucléaire) from 21th june 2005 :

« ... The "leak before break" approach cannot be applied to predict the mechanical behaviour of breaches. Indeed, the assumptions justifying the stability of the breaches are not consistent with those justifying the evolution of defects until the appearance of the breaches. The demonstration that the performance of the leak detection systems allows the plant to be shut down before these leaks lead to complete pipe failures cannot be made. The application of the "leak before break" approach is not sufficient to justify not taking into account the effects of ruptures. ». According to ASN guide n° 22 produced jointly with IRSN, the choice of BPC may be considered acceptable only on the basis of a justification of major advantages for safety. To alleviate the statement on LBB for new plants, and in combination to the fact that LBB is not the main argument for break exclusion, it must be recalled that large progress have been made in terms of monitoring and that Framatome is already disposing of performant products allowing high sensitivy detection combined with the possibility to locate leakage (e.g. FLÜS™).

Regarding reactor designs for export, the customer or/and the Security Authority can request compliance with the US regulations (NUREG 0800 SRP3.6.3 2007), and in particular require the application of the LBB concept to validate the removal of anti-whip devices. This is currently the case for India and under discussion for Saudi Arabia. From a mechanical point of view (short-term dynamic effects) the application of the LBB concept is not a problem, on the other hand from a thermo-hydraulics point of view and in particular for the core cooling, the fact that DEGB of a primary loop is treated according to a conservative approach in the LBB concept (instead of a realistic approach in the French BPC concept), can pose a problem for compliance with the loss of coolant accident (LOCA) criteria especially when superimposed on the LOCA France reference. There are two main differences in LOCA analysis between the USA and France: assumptions for considering clad ballooning and fuel relocation effects, which are conservative in France ; extended application of statistical methods in the USA, in particular the break size is included in the statistic (forbidden in France). This approach is quite penalizing when compared to US Standards.

Actual EDF/Framatome challenges with regards to concepts of Break Exclusion

The challenge is the removal of anti-whip devices for primary and steam main piping to benefit from the associated gains (installation, maintenance, in-service controls, costs) associated with the removal of the pipe guillotine rupture initiator in view of the short-term induced dynamic effects (decompression wave on the internals ...). The four concepts US LBB / German and French BPC-HIC allow these deletions as consequence of the quality. The French BPC is proposed for French reference export reactors. LBB is not accepted by the French Safety Authorities. However, it can be imposed by the local Safety Authorities for export purpose only. The HIC concept is imposed in the UK.

The imposition of the LBB concept on exports introduces a significant penalty of this study, with a difficulty of respecting the associated criteria, all the more difficult with the overlapping of the LOCA France reference (very penalizing).

The question is to have a design able to fulfill all the concepts criteria in a standard approach (even if amount of studies to be produced is different).

Overview of past and actual R&D with focus on LBB

Significant research program results are supporting and validating LBB. A non-exhaustive list is listed hereunder BINP, IPIRG, NURBIM, Investigation in the frame of Break Exclusion Investigations (worse to mention the break discharge rate experiment and blowdown experiments at KWU and “Heiss Dampf Reaktor” experimental reactor (HDR), experiment with large (ductile) dissimilar metal welds (DMW) (with stainless steel filler) BIMET, ADIMEW, with Ni-basis filler narrow gap EPR type within STYLE (see T.Nicak 2014) and MULTIMETAL (see Keinänen et al. 2015) to support characterization of DMW with test specimens.

Actually large ductile tearing prediction in cracked pipes (ferritic piping, austenitic piping with weld) is investigated within ATLAS+ (four point bending tests of pipes with crack at EDF Les Renardières, CEA and BZN in Hungary), which led to interesting results: blind prediction of ductile initiation by Finite Element Analysis (FEA) was validated by two experiments one with through wall crack and another one with an inner surface crack) however a fast fracture occurs after a few millimeter of ductile tearing of the surface crack.

OUTLOOK OF SUCCESS AND REMAINING ISSUES

Success:

excellent experience (no break) in piping system for which break-preclusion concept has been applied

Framatome can capitalize on results of actual fracture mechanics investigation on sacrificial pieces and actual R&D. Even if some requirement are not fulfilled, demonstration that integrity is not affected can be performed using direct fracture mechanics measurement.

The micromechanical material model (Gurson based) applied within STYLE is particularly suitable for simulations of ductile tearing problems. However, some limitations occur in cases where there is a smooth transition from ductile to brittle fracture regime, see also R&D ATLAS. The GFR model is promising to determine critical crack size (see dedicated Technical Break n°19 New analysis method of fast fracture resistance).

The amount of ductile crack growth is very important for the assessment of the critical crack size: under displacement controlled loading (restraint thermal expansion, weld residual stresses…), the growth of the crack tend to release stresses in the system leading to a global lower loading condition up to a stable equilibrium (crack stop). On the other side, the amount of ductile crack growth obtained from standard fracture mechanics testing is generally limited to a few mm due to the size of the specimen: extrapolation for large tearing is usually performed but in practice, a validation with real size component geometry is often required to demonstrate the representativeness of the considered material crack resistance obtained from specimen (scale and constraint effects).

Remaining issues:

Inherent toughness of the material is required and must be demonstrated (as for BSC). Direct fracture mechanic testing can be required to support correlation Charpy / material crack resistance curve (J-R).

LBB assessment of critical flaw size is usually performed considering normal operating condition (hot). Investigation at lower temperature on ferritic piping have also show a LBB behavior with ductile initiation and tearing followed by brittle propagation and subsequent crack arrest, findings from STYLE and ATLAS+ see S.Lindqvist et al. (2022).

Material crack resistance (J-R curve) for large tearing (not covered by standard) are required for evaluation of critical crack size if we choose to be accurate in the estimation.

Situation of corrosion at DMW (Ni-basis filler alloys 82/182), has occurred which led to extensive research program (Study of Extremely Low Probability of Rupture (xLPR) Events at Nuclear Power Plants to validate LBB considering this active degradation mechanism.

SUMMARY AND CONCLUSIONS

Investigation in the frame of break exclusion are still performed and acceptance by national regulatory body is not unique. This may evolve by keeping to increase our level of knowledge and capitalize benefits and findings from past research and events, especially in the metallurgy, mechanical, fracture mechanics, thermal hydraulic, ISI and monitoring field. The BPC as accepted by the French regulatory body do not rely on LBB.

Finally, Framatome dispose of several concepts (LBB, French and German BPC, HIC) to exclude DEGB impact at design using a deterministic approach.

In conclusion, the consideration of these concepts are crucial to new build by having a deep impact on design and the amount of studies to be performed. Framatome is able to justify its products not only according to old rules, but by developing our own knowledge and physical approach.

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