EUROPEAN COMMISSION

NUCLEAR SAFETY
AND THE ENVIRONMENT

EUROPEAN SAFETY PRACTICES ON THE APPLICATION OF LEAK BEFORE BREAK(LBB) CONCEPT
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The Nuclear Regulators' Working Group
Task Force on Leak Before Break

Final report – January 2000

Directorate-General
Environment

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FOREWORD

Leak Before Break (LBB) has been considered a priority area within the multi-annual programme (1996-2000) of the Nuclear Regulators Working Group (NRWG)\(^1\) of the European Commission.

During its meeting in November 1996 the NRWG set up a Task Force (TF) to compare and contrast the approaches taken by the safety authorities in the field of LBB for pressure retaining components of existing Nuclear Power Plants (NPPs). Existing practices are described in the report. The ultimate goal was to provide a set of good practices deemed useful by the members of the TF.

The group was made up of representatives\(^2\) from ANPA (Italy), AVN (Belgium), BCCN (France), GRS (Germany), SONS (Czech Republic) SKI (Sweden), STUK (Finland), VUJE (Slovak Republic) and URSJV (Slovenia, observer). The TF conducted its activities without a formal Chairman, and the representative from BCCN acted as co-ordinator for the whole report. Unit "Nuclear Safety, Regulation and Radioactive Waste Management" (DG ENV C.2) provided the TF with the corresponding Technical Secretary services.

The TF held five meetings and progress was reported to the NRWG at its plenary sessions.

The present report represents the work product of the activities conducted by TF. These activities were mainly concentrated on those aspects directly related with nuclear safety, bearing in mind the overall safety concept of defence in depth. All the other aspects linked with the methodology for the application of the LBB concept have been also considered but in a more general way. Chapter 6 "Conclusions and Recommendations" constitutes a brief synthesis of the discussions held by the group on key issues developed in previous chapters, and it is organised into the following sections: Impact on design basis, technical substantiation, limitations of LBB application, procedures and LBB implementation.

\(^1\) The Nuclear Regulators' Working Group is an advisory expert group to the European Commission and is made up of representatives of European Union member states and candidate countries to the EU. Switzerland participates as an observer.

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The documents published by the European Commission which relate to the implementation of the Council Resolutions of 22 July 1975 and 18 June 1992 on the Technological Problems on Nuclear Safety may fall into one of the following categories: current practices, good practices or consensus document.

(i) **Current practices document:**

A current practices document results from a review and inventory of current practices in different countries.

(ii) **Good practices document:**

A good practices document presents one or more different approaches to reach safety objectives.

(iii) **Consensus document:**

A consensus document stresses the degree of harmonisation achieved between practices and sets out the consensus reached in the NRWG.

The present document “European Safety Practices on the Application of the Leak Before Break (LBB) Concept” has been provisionally classified under the category of “Good Practices Document”.
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ABREVIATIONS
1 INTRODUCTION

The Leak-Before-Break (LBB) concept is associated with the nuclear power plant design principles as regards pipe failures and their safety implications. It has been introduced as a mean of partially relaxing the customary requirements concerning postulated double-ended guillotine breaks (DEGBs). During the past few years, LBB has received increasing applications as a criterion for assessing or upgrading the safety of existing plants whose provision against DEGBs presents deficiencies compared to current requirements.

Technically, the LBB concept, defined hereafter, means that the failure mode of a cracked piping is a leaking through-wall crack which may by timely and safely detected by the available monitoring systems and which does not challenge the pipe’s capability to withstand any design loading. The concept relies on experiences that DEGBs and other catastrophic failures of primary circuit piping are extremely unlikely. Various design, operation, inspection and monitoring aspects have been considered as prerequisites. From their differing contents and relative importance, other related concepts like the German developed Break Preclusion (BP) and Low Break Probability (LBP) have evolved. The definitions adopted for this study are given in Table 1. Since the safety goals are largely concurrent, the LBB concept will be mainly addressed in this report.

<table>
<thead>
<tr>
<th>Leak before Break (LBB)</th>
<th>Break Preclusion (BP)</th>
<th>Low break Probability (LBP)</th>
</tr>
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<tbody>
<tr>
<td>Design and operation principle according to which available ISI, maintenance and monitoring systems including leak detection, give early and reliable warning of a defect in piping component, so that necessary actions may be timely undertaken to avoid its failure as a consequence of any design basis condition.</td>
<td>Safety concept according to which advanced construction and operation practices, assured by measures to limit the bounding conditions, enable the local protection against pipe failures to be designed based on LBB behaviour.</td>
<td>Procedures required to demonstrate that the probability of failure of a piping component or pipe section is so low that the local transient effects associated with a postulated failure need not be included in the safety analysis.</td>
</tr>
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</table>

Table 1: Definition of concepts proposed to reconsider the pipe break postulates in nuclear power plant design basis

So far, the authorised relaxation of DEGB requirements by virtue of LBB has mainly dealt with local dynamic effects of broken pipes such as pipe whipping, jet impingement and missiles. Withdrawal of the pipe whip restraints has been consequently permitted, improving the In-Service Inspection (ISI) efficiency and also lowering the resulting radiation dosages. Among the global safety features whose design basis remains intact are e.g. the containment over pressurisation, safety injection system and residual heat removal capacities.

Additional industry arguments for LBB are that upgrading an existing plant with the necessary provision against DEGB is very costly and has also adverse effects. For all
these reasons, extensive research programmes have been underway in several countries since the mid-1970’s to enhance understanding of the fracture and leakage behaviour of degraded piping and to develop proven analysis tools for LBB licensing purposes. World-wide efforts have been taken to create failure databases substantiating the low probability of this event as one of the main arguments of LBB. Advances have also been witnessed in the areas of design, manufacturing, inspection and monitoring methodology and have become cornerstones of the proposed concepts, particularly of the BP concept.

The safety concerns felt by the nuclear regulators follow from the consequences of a possible large-diameter primary circuit pipe break to the global plant safety. Such incidents have not been reported and their realistic evaluation is prohibitive. The customary nuclear power plant design philosophy employs the concept of Defence-In-Depth, requiring several safety barriers to be provided against the Design Basis Accidents (DBAs). A standard measure is preventing the accident and mitigating its consequences at the same time, however small the probability. The DEGB constitutes a typical case and may not be allowed to jeopardise the next barrier, the containment, or the numerous other safety systems needed should it occur.

Few regulatory positions and documents have been issued on LBB so far. A potential for harmonisation and possible wider acceptance may be though expected since case-by-case applications of LBB seem to have been frequent. This report presents the results of such an undertaking, the Task Force on LBB, launched by the NRWG of the European Commission. Mainly prepared by the representatives of ANPA (Italy), AVN (Belgium), BCCN (France), GRS (Germany) and STUK (Finland), the report compares and contrasts the available regulatory approaches to look forward good practices for LBB application to existing plants.

The report consists of six chapters, the first being (Chapter 1) the Introduction. Chapter 2 addresses the impact of LBB on the fundamental design basis and safety features of LWR type nuclear power plants. A review of the technical substantiation with regard to operating experiences, experimental research programmes and analytical considerations is given Chapter 3, providing more detailed references. Chapter 4 considers in more detail the appropriate fracture mechanics and leak rate analysis procedures to be used in safety analyses justifying LBB for a particular application. Chapter 5 presents an overview of the experiences and positions of the participating countries as to LBB and arrives at a synthesis of the overall situation. Chapter 6 is devoted to the Task Force’s main conclusions and recommendations.

1.1 Definition of LBB concept

The LBB concept is associated with the nuclear power plant design principles as regards pipe failures and their safety implications. It has been introduced as a mean of partly relaxing the customary requirements concerning postulated DEGB. DEGB is used as a choice for designing safety systems.
1.1.1 Definition of LBB, according to the TF

Design and operation principle according to which available ISI, maintenance and monitoring systems including leak detection, give early and reliable warning of a defect in piping component so that necessary actions may be timely undertaken to avoid its failure as a consequence of any design basis condition.

It has to be noted straight at this point that many definitions might be found about LBB (e.g. in the E.U.R. document). Sometimes, due to national history, the weights of the different aspects (design, operation, inspection, monitoring, etc.) are not homogeneous.

1.2 Motivation

The LBB concept has received increased consideration, on the industry side, as an alternative criterion for elimination or reducing design provisions that have to cope with dynamic effects such as pipe whipping, rapid fluid transient phenomena that result from postulated high energy pipe ruptures. Therefore, it has to be understood, in a first step, as a decrease of the mitigating measures (for existing plants).

The implementation of the LBB concept might have positive impacts by improving the monitoring of the plant, the accessibility to non-destructive examination (NDE), or by reducing radiation exposure to plant personnel during ISI and maintenance, e.g. by removal of whip restraints and jet impingement barriers. The safety relevance of those impacts has to be assessed.

1.3 Limits

Limits to the application of the LBB concept might arise from different type of reasons: “pure” technical reasons linked with the pipework reliability, safety reasons linked with the expected margins on certain safety function, regulatory positions, global versus local effects choices.

1.3.1 a) Safety expectancies

Among the safety features designed to cope with the design basis accidents (e.g. safety injection systems (SIS), pipe supports, qualification of I&C equipment, control rod operability, etc.) regulators wishes to find appropriate means to mitigate the accidental conditions. For some of them the regulators might require to dispose upon increased margins, leading to limit the use of “realistic” approaches (versus conventional DEGB) as LBB, to justify them.

1.3.2 b) Regulatory positions

For plenty of reasons linked to historical or national aspects (particular, national relevant, feedback of experience on manufacturing or operation, etc.) regulators should be able to settle “arbitrary” limits to the extent of LBB use. (see chapter 5).
1.3.3 c) Global versus local effects

The analysis of a postulated break leads to global and local effects (definition in 1.5). Notwithstanding the consistency of the approach, the credit from the LBB (as it can be seen in part 5) might be limited to one category of effects or to part of it.

1.4 Effects of applying LBB

Independently of any LBB application, the defence-in-depth philosophy requires that several defence barriers be applied for a safe plant operation. We can distinguish:

- accident prevention measures (e.g. quality of design, behaviour of flawed structure, ISI, leak detection, etc.); and
- accident mitigation measures (e.g. safety injection system, containment, pipe whip restraints, etc.).

Introducing an LBB analysis, the general balance between the defence lines is influenced; the pipe whip restraints, which are mitigation measures, can be removed after an LBB application providing, for instance, knowledge on the behaviour of flawed pipes and enhanced leak detection, which are prevention measures.

The role of the safety authorities is to assess whether this changing is acceptable taking into account the technical substantiation for LBB (chapter 3), the procedure proposed for assessment (chapter 4) and the existing state of the plants.

1.5 Definitions

1.5.1 Defence Lines

The major lines of defence-in-depth in the frame of this topic are:

1. Quality of design and manufacturing;
2. Detection and correction of degradation of the pipes (flaws, loss of thickness, etc.);
3. Detection of leaks while still small;
4. Mitigation by SIS that protects core meltdown even if the most critical pipe should be broken;
5. Mitigation through the containment, even in the case some melting should occur.

1.5.2 Defence-in-Depth

The principle of defence-in-depth is firmly established in the safety design basis of nuclear power plants. It includes, as a general principle, design features providing for plant and public safety by the use of overlapping and redundant levels or “echelons” of defence. The basic idea is to provide several levels of defence so that failures in
equipment and mistakes by people will be covered.

The defence-in-depth philosophy requires that all lines of defence against a major nuclear accident be given proper attention.

1.5.3 Global Effects

Effects of the postulated pipe break affecting the plant system or circuits not directly in the vicinity of the break (e.g. blowdown effects on RPV internal, environmental conditions in the containment, mass flow to be compensated by safety injection systems, containment pressure).

1.5.4 Local Effects

Effects of the postulated pipe break affecting the vicinity of the pipe: pipe whip, jet impingement in the pipe area, flooding, efforts induced locally in the pipework and its supports (and/or snubbers).

1.5.5 High-Energy Fluid Systems

Any system or portion of system where the maximum operating pressure or the maximum operating temperature exceed certain threshold (e.g. 20 bar and 100°C), during normal plant operating conditions. Above these limits for only a relatively short portion (less than approximately two percent) of the period of time to perform their intended function, may be classified as moderate energy.

1.5.6 Loss of Coolant Accidents (LOCA)

Those postulated accidents that result in the loss of reactor coolant at a rate in excess of the reactor coolant normal makeup.

1.5.7 Main run

A pipe run that interconnects terminal ends.

1.5.8 Pipe rupture

The loss of pressure integrity of a piping run in the form of a circumferential break, longitudinal break or through-wall crack.

1.5.9 Pipe whip

Uncontrolled motion of a rupture pipe.
1.5.10 Pipe whip restraint

A device, including its anchorage, utilised for preventing pipe whip, or otherwise controlling the pipe motion within acceptable bounds following a pipe rupture.

1.5.11 Terminal end

That section of piping originating at a structure or component (such as vessel or component nozzle or structure piping anchor) that acts as an essentially rigid constraint to the piping thermal expansion. Typically, an anchor assumed for the piping code stress analysis would be a terminal end. The branch connection to the main run is one of the terminal ends of a branch run, except for the special case where the branch pipe is classified as part of a main run.
2 SAFETY OBJECTIVES

2.1 Safety implications by LBB application

2.1.1 Break postulates and design conditions

At first, the Task Force Members found that it was necessary to recall the role of the break postulates in the initial design of NPP. The safety position required to consider bounding loading conditions such as DEGB.

The break postulates, e.g. the postulate of double ended guillotine breaks, were introduced as a choice for the plant design and the accident consideration of nuclear power plants with respect to the protective aims (safety functions) as these are shutdown, residual heat removal and activity enclosure.

2.1.1.1 Break Postulates

The national safety concepts in the EU countries to use break postulates for the design of light-water reactors, for example see Table 1, follow to a large extent the safety concept as it was developed by the US AEC and the nuclear steam supply system (NSSS) designers in the USA:

2.1.1.1.1 a) Design of containment system

In this safety concept the sudden double-ended guillotine break in the largest high pressure coolant pipe was postulated as giving the bounding load for the containment system design with respect to temperature and pressure.

2.1.1.1.2 b) Design of emergency core cooling system

In the early sixties this postulated guillotine-type break was also taken as giving the worst case conditions for the core cooling. For the installation of an emergency core cooling system or SIS such a break was the basis for system layout, design aspects and safety analyses. However, more detailed investigation showed that the SIS performance had to be demonstrated for the full range of leak sizes (small leaks up to the guillotine type break) in the safety analysis. Furthermore, the postulate of a break was extended for all high-energy piping up to the first isolation valve or check valve.

2.1.1.1.3 c) Requirements for equipment qualification

Consequently, the leaking coolant required the protection or the design against humidity for the containment internal structures, neighbouring components and mechanical / electrical equipment.

2.1.1.1.4 d) Design for local, static effects due to fluid discharge

Furthermore, it became a plant design requirement that the leaking coolant should not flood the different components and equipment in their installation rooms and that the
supports of the main components should withstand the forces due to fluid discharge.

2.1.1.1.5  e) Design for local, dynamic effects due to fluid discharge

Furthermore, the break also results in a decompression of the fluid in the pressure-retaining boundary; the component internals as well as the connecting piping should absorb the effected dynamic loading. Especially the dynamic loading types, as these are decompression, pipe whipping and fluid jet, influenced strongly the piping design.

2.1.1.1.6  f) Design procedure for effects due to pipe whipping

But the consequent design against the dynamic loading would result in great effort. Therefore, for a defined absorption of the dynamic loading constructional measures are normally preferred. To assure the function of the neighbouring structures and components in the case of pipe whipping, the pipe motion has been limited by adequate pipe restraints but only arranged at the locations of postulated breaks. Furthermore these pipe restraints will reduce the free cross-sectional area of the failing pipe and besides the loading due to the decompression and fluid jet.

Among those six points, one can check the existence of global and local effects type of design.

2.1.1.2  Design Considerations

In general, break postulates are only a choice for the plant design and the accident precaution of nuclear power plants with respect to the protective aims as these are:

- reactivity control: to shut down the reactor and maintain it in a safe shutdown condition for all operational states or accident conditions;
- core cooling: to provide for adequate heat removal from the core after shutdown, including accident conditions;
- activity enclosure: to contain radioactive materials in order to minimise their release to the environment.

For this purpose break postulates are used in the system design as well as in the design against leakage effects on the single structures, components, equipment and piping for the formulation of:

2.1.1.2.1  a) design loading concerning the

- containment system, to guarantee activity enclosure;
- containment internals, to avoid subsequent failure;
- electrical equipment, to guarantee accident resistance;
- component support, to avoid subsequent failure;
- reactor pressure vessel internals, to guarantee shut-down and residual heat removal;
- component internals and piping, to guarantee residual heat removal;
- jet and reaction forces, to avoid subsequent failure.
2.1.1.2.2  b) capacity requirements concerning the

- safety injection system to guarantee core cooling;
- residual heat removal system, to guarantee core cooling.

The design consideration of the break postulate with its extreme loading, as these are decompression, jet and reaction forces, did result in the arrangement of pipe whip restraints and thus in consequences in the design of piping by decreasing their:

- flexibility for compensation of thermal expansion;
- accessibility for surveillance and inspection;
- efficiency of thermal isolation due to additional supports.

Considering break postulates in principle would suggest that the break can occur at every location of every high-energy piping. For design considerations it was agreed that breaks of pipes were to be postulated at weld locations. This decision was based on arguments being valid at the time, (e. g. that the welding was the manufacturing step with the highest probability of introducing defects and limitations of non-destructive examination methods) as has been shown by piping failures in conventional power plants.

For that reason breaks at circumferential as well as longitudinal welds had to be taken into account. In order to limit the design effort against the effects of pipe whip resulting from pipe breaks in a reasonable way, the number of break locations has been further reduced to the welds connecting the main components to the piping (therefore providing bounding values for blowdown) and some intermediate locations being subjected to higher stresses or usage factors.

Furthermore, it is presupposed that all the breaks are of perfect geometry and occur only in the weld regions. Consequently, mixed breaks as a combination of circumferential and longitudinal breaks are not considered.

In summary it can be stated:

- The postulate that the largest-diameter high-energy pipe in the primary system breaks was a simple criterion to define boundary conditions namely for containment and SIS design; this was justified at the time when it was introduced. Nevertheless, this is further on a sound basis of the presently used design criteria.

- The technical background concerning piping at that time had not the same level as for vessels: for piping of NPPs there were not many recognised codes and in conventional power industry piping failures have occurred more frequently than vessel failures.

- For practical purposes based on technical reasons the locations for the postulated breaks were selected using criteria, which resulted in most designs of Pressurised Water Reactors (PWRs) in a limited number of break locations.

- The design of pipe whip restraints is mainly based on highly idealised
assumptions about the fracture mode (guillotine type or split type break without branching of the cracks and possible variations of the direction of the maximum loads).

2.1.2 Examples of LBB Application

For the design of pressure and fluid retaining components, which demonstrate a LBB behaviour in case of an arising failure, some general design concepts have been developed in different countries, e.g. in the USA and in Germany. In this chapter only the changes related to the design principles described above will be reported. Other details are to be found in chapter 5.

2.1.2.1 Leak-Before-Break Application for NPPs in the USA

In the USA, it is permissible to eliminate the dynamic effects of the postulated high energy pipe ruptures from the design basis of the nuclear power plants, in the case the LBB concept is shown applicable.

Provided the adequate demonstration can be done, the following effects of break postulates might be withdrawn:

- blowdown load: the LBB concept was initially used to resolve the asymmetric blowdown load issues in PWRs;
- pipe whip restraints: the local dynamic effects of the postulated instantaneous double-ended guillotine breaks (in the large diameter piping of the PWR primary loop)

As an example, the LBB application permits the absence or the removal of the pipe whip restraints. However, the design for global effects remains unchanged (e.g. in Table 1):

- the containment must continue to be designed to withstand all global effects, such as pressure and temperature, resulting from ruptures up to and including the rupture of the largest pipe;
- the SIS must continue to be designed to accommodate pipe ruptures up to and including the rupture of the largest pipe.

2.1.2.2 Break Preclusion Application for NPPs in Germany

Break preclusion has been developed in Germany (Fig. 1), and is a general design concept for pressure and fluid retaining components. That design is aimed by a step by step procedure that the component will demonstrate during its whole operation time at worst case a LBB behaviour but never a catastrophic failure will occur (break preclusion, BP) or only with a very low probability (low break probability). For the better understanding of this procedure, estimated contributions of the different steps for the realisation of the low break probability concept are given in Table 2.

If a qualified LBB demonstration can be done for the plant (see Table 1),
- the design with respect to global effects with static loading has to continue to be based on the double ended guillotine break in the largest coolant pipe for the containment system and the emergency core cooling system;
- the design with respect to local effects with static loading has to be based on the double ended guillotine break in the relevant largest coolant pipe for the containment internal structures, the mechanical/electrical equipment and the main components support;
- the design with respect to for local effects with dynamic loading might be considered with postulates of smaller breaks or leaks for the compensation of decompression forces, jet forces and pipe whip forces.

A global view of the break and leak assumptions for the design of the different systems and components is summarised in Table 3.

### 2.2 Design Changes and Safety Benefits

In the following the design aspects discussed in chapter 2.1 will be addressed once more with respect to design changes and safety benefits.

#### 2.2.1 Design Changes

Among the whole range of design considerations it seems from point of view of the Task Force Members that some of the following aspects should remain unchanged (for example see Table 1):

1. Design of containment system: No benefit is given; the design of containment system will be maintained.
2. Design of emergency core cooling system: No benefit is given; the design of emergency core cooling system will be maintained.
3. Design for containment internal structures: No benefit is given; the design for containment internal structures will be maintained.
4. Requirements for environmental equipment qualification: No benefit is given; the requirements for the equipment qualification will be maintained.
5. Requirements for design of component support: No benefit is apparently given; the design of the component support will be maintained (with an equivalent static value that is not corresponding to the dynamic forces).

It seems that the current practices, for Western plants design, exclude the "global" effects with static loading (points 1 and 2) as well as the "local" effects with static loading (points 3 and 5) of the acceptable changes due to LBB application whereas the "local" effects with dynamic loading (points 6 to 8) are diversely addressed.

The Task Force Members recognise that this current situation is some kind of an arbitrary choice. Without formal approval some other design considerations are
judged to be possibly relaxed by the LBB application:

(6) Design procedure for effects due to decompression forces: Some benefits are given due to the effect that the leakage area is essentially smaller than the full area of a double-ended guillotine break. The dynamic loading due to decompression will decrease.

(7) Design procedure for effects due to fluid discharge: Some benefits are given due to the effect that the leakage area is essentially smaller than the full area of a double-ended guillotine break. The dynamic loading due to fluid jet will decrease.

(8) Design procedure for effects due to pipe whipping: Some benefits are given due to the effect that the leakage area is essentially smaller than the full area of a double-ended guillotine break. The dynamic loading due to pipe whipping will decrease. Dependent from the piping design, flexible or rigid, the pipe whip restraints can be reduced in their number and completely removed, respectively.

2.2.2 Safety Benefits

LBB application requires a very good knowledge of the real plant state concerning e.g. loading, material, geometry and degradation mechanisms and will allow the reduction or removal of installed pipe whip restraints. The former might push to introduce enhanced plant monitoring systems (e.g.: leak detection, load and displacement control, fatigue monitoring.). The later will result in the following advantages:

- no uncontrolled stiffening of the piping in case of thermal expansion: this means no additional forces and moments for the piping;
- improved accessibility for surveillance of piping and surrounding: this means a reduction of access time and dose rate for the plant personnel, and therefore an increased controllability;
- improved accessibility for repair and no need for removal of pipe whip restraints: this means a reduction of access time and dose rate for the plant personnel, and therefore an better replaceability, should component be replaced for safety reasons;
- no restriction or difficulties for performance of in-service inspection: this means a time reduction and results improvement of inspection.

2.3 Upgrading to Meet Present Requirements

For existing NPPs, the LBB concept application can be used to justify and by this to compensate existing shortcomings in the general design, e.g.:

- high energy piping design without installation of whip restraints, as the normal case (type N);
- containment design without consideration of bounding loading, as an
exceptional case (type E);
- emergency core cooling design without consideration of bounding loading, as an exceptional case (type E).

Existing piping can be upgraded to meet the requirements of an LBB demonstration (proof of high reliability) concept as laid down for example in Fig. 1. This concept can be used to compensate non-conservative design features which do not meet all the present requirement (for examples see in chapter 5). In general this may be given if during the plant design:

- on the one hand the break postulates concept has not been consequently considered for the layout of the components and systems, and
- on the other hand it has not been demonstrated in parallel that these components and systems show a low break probability.

Examples for such non-conservative design features, which have to be assessed individually, are:

- low containment design values (pressure and temperature) (type E);
- insufficient capacity of the emergency core cooling systems (type E);
- insufficient physical protection of neighbouring components (type N);
- missing / insufficient spatial separation of redundant piping (type N);
- missing pipe whip restraints in case of high-energy piping (type N).

These non-conservative design features can be justified by the demonstration that a low break probability is given for the considered piping. However, in case of the existence of non-conservative design features of type E it is strongly recommended to compensate these deficits by appropriate accident management measures.

If the existing pipework or surveillance system is not complying with the requirements, a thorough examination is necessary. Nevertheless, leakages have to be considered for the local design.

However, the low leak probability concept cannot be used to compensate a missing design for humidity or flooding due to the effect that a leakage cannot be precluded. Furthermore, there exist no realistic possibility to compensate with this concept unspecified service conditions or component ageing.
<table>
<thead>
<tr>
<th>n°</th>
<th>Plant design aspect</th>
<th>significance of the break postulate on the design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>break effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Design for global effects:</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>- containment system</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>- emergency core cooling system</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Design for local effects:</td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>- containment internal structures</td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>- mechanical / electrical equipment</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>- main component support</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>- compensation of decompression forces</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>- compensation of jet forces</td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>- compensation of pipe whip forces</td>
<td></td>
</tr>
</tbody>
</table>

**Abbreviation for break effects:**

- 10 support loads
- 9 temperature build-up
- 8 pressure build-up
- 7 radiation
- 6 humidity
- 5 flooding
- 4 decompression
- 3 fluid discharge
- 2 temperature of fluid
- 1 pressure of fluid
- postulated pipe cross-sectional area:

- A = area of main coolant line
- a = area of branching lines

here with $a/A = \text{ca. 0.1}$

**Table 1:** German example: Postulated pipe breaks for the Main Coolant Lines and Associated Effects; German Procedure for Designing NPPs
<table>
<thead>
<tr>
<th>Step</th>
<th>Aim</th>
<th>measures</th>
<th>estimated value that measures fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Basic safety: no detectable defects may exist or occur</td>
<td>- design/manufacture of components without detectable defects - component operation without relevant material degradation</td>
<td>$\cdot 1 = 10^{-4}$ 1/a</td>
</tr>
<tr>
<td>2.</td>
<td>Fracture mechanics (FM): non-detected but possible defects have to be assessed by FM</td>
<td>- during one plant-life, a defect will not penetrate the wall - after many plant-lives, penetrating crack will show LBB behaviour.</td>
<td>$\cdot 2 = 10^{-1}$ 1/a</td>
</tr>
<tr>
<td>3.</td>
<td>Component control: possible existing / occurring defects have to be detected</td>
<td>- continuous monitoring and surveillance of components - in-service inspection and preventive maintenance</td>
<td>$\cdot 3 = 10^{-1}$ 1/a</td>
</tr>
<tr>
<td>4.</td>
<td>Leak detection: all leakage due to possible defects have to be detected</td>
<td>- different leak detection systems with response on fluid - additional leak detection systems with response on noise</td>
<td>$\cdot 4 = 10^{-1}$ 1/a</td>
</tr>
<tr>
<td></td>
<td>Resulting value for having a catastrophic failure:</td>
<td></td>
<td>$\cdot_{res} = 10^{-7}$ 1/a</td>
</tr>
<tr>
<td>5.</td>
<td>Catastrophic failure: assumed, e.g. due to non-detected leakage, has to be governed</td>
<td>- break assumptions (core cooling, reactor shut-down, contain.) - limitation of effects due to physical protection and separation</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: German example :Required Steps with Estimated Contributions for the Realisation of the Low Break Probability Concept for Pressure Retaining Piping of NPPs
<table>
<thead>
<tr>
<th>Effects</th>
<th>Postulated pipe break size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>On due to</strong></td>
<td></td>
</tr>
<tr>
<td>• design for global effects:</td>
<td></td>
</tr>
<tr>
<td>o performance of safeguard systems, e.g.</td>
<td></td>
</tr>
<tr>
<td>– safety injection system;</td>
<td>loss of coolant</td>
</tr>
<tr>
<td>- residual heat removal system.</td>
<td>≤ 2 A (MCL)</td>
</tr>
<tr>
<td>o design of containment system</td>
<td>pressure build-up;</td>
</tr>
<tr>
<td></td>
<td>temperature</td>
</tr>
<tr>
<td></td>
<td>2 A (MCL)</td>
</tr>
<tr>
<td>• design for local effects:</td>
<td></td>
</tr>
<tr>
<td>o environmental qualification of equipment,</td>
<td></td>
</tr>
<tr>
<td>– instrumentation;</td>
<td>pressure;</td>
</tr>
<tr>
<td>- electrical components.</td>
<td>temperature;</td>
</tr>
<tr>
<td></td>
<td>flooding / humidity;</td>
</tr>
<tr>
<td></td>
<td>radiation</td>
</tr>
<tr>
<td></td>
<td>2 A (MCL)</td>
</tr>
<tr>
<td>o design of containment internal structures,</td>
<td></td>
</tr>
<tr>
<td>– reactor cavity;</td>
<td>flooding;</td>
</tr>
<tr>
<td>- missile shield;</td>
<td>differential pressure;</td>
</tr>
<tr>
<td>- compartments.</td>
<td>temperature;</td>
</tr>
<tr>
<td></td>
<td>support loads</td>
</tr>
<tr>
<td></td>
<td>2 A ³) (MCL)</td>
</tr>
<tr>
<td>o stability of support of main components,</td>
<td></td>
</tr>
<tr>
<td>– reactor pressure vessel;</td>
<td>fluid discharge forces</td>
</tr>
<tr>
<td>- main coolant pump;</td>
<td>P = 2 p A</td>
</tr>
<tr>
<td>- steam generator;</td>
<td>A (considered line)</td>
</tr>
<tr>
<td>- pressuriser.</td>
<td>p (operating pressure)</td>
</tr>
<tr>
<td>o design of internals of main components</td>
<td></td>
</tr>
<tr>
<td>/ MCLs, e.g.</td>
<td>dynamic effect of pressure</td>
</tr>
<tr>
<td></td>
<td>drop</td>
</tr>
<tr>
<td></td>
<td>the larger value of</td>
</tr>
<tr>
<td></td>
<td>0.1 A (MCL) and</td>
</tr>
<tr>
<td></td>
<td>a (branching line)</td>
</tr>
<tr>
<td>o design for thrust and reaction forces, e.g.</td>
<td></td>
</tr>
<tr>
<td>– surrounding walls;</td>
<td>jet impingement,</td>
</tr>
<tr>
<td>- target components;</td>
<td>fluid discharge forces</td>
</tr>
<tr>
<td>- piping support.</td>
<td>the larger value of</td>
</tr>
<tr>
<td></td>
<td>0.1 A (MCL) and</td>
</tr>
<tr>
<td></td>
<td>A (connected line)</td>
</tr>
</tbody>
</table>

³ consideration of guard pipes or restraints for pressure build up in reactor cavity.

• defence in depth:

o postulates for studies within the framework of severe accidents, e.g. consideration of a failure of the reactor coolant boundary, will be discussed in other working groups.

Table 3: German example :Postulated Pipe Breaks and Associated Effects for Main Coolant Lines (MCLs)
## Break Preclusion Concept

### Basic Safety Concept

<table>
<thead>
<tr>
<th>Principle of Quality Achieved by Design and Manufacturing</th>
<th>Principle of Controlled Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>use of optimised *)</td>
<td>organisational prerequisites:</td>
</tr>
<tr>
<td>o design</td>
<td>o plant personnel qualification</td>
</tr>
<tr>
<td>o materials</td>
<td>o experience feedback</td>
</tr>
<tr>
<td>o production / inspection measures manufacturer qualification</td>
<td>control of degradation / leakage:</td>
</tr>
<tr>
<td>*) restricted in case of older NPPs</td>
<td>o continuous monitoring/surveillance</td>
</tr>
<tr>
<td></td>
<td>o maintenance and ISI</td>
</tr>
</tbody>
</table>

### Additional Safety Assurance Measures

<table>
<thead>
<tr>
<th>Principle of Bounding Loading Conditions</th>
<th>Principle of Controlled Failure Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consideration of limiting design conditions with respect to:</td>
<td>analysis of LBB behaviour in advance by using:</td>
</tr>
<tr>
<td>o human error</td>
<td>o test results and / or</td>
</tr>
<tr>
<td>o system malfunctions</td>
<td>o crack growth analyses</td>
</tr>
<tr>
<td>o internal and external impact</td>
<td>under consideration of degradation</td>
</tr>
<tr>
<td>o corrosion</td>
<td>effects and bounding loading conditions</td>
</tr>
</tbody>
</table>

### Break Preclusion Assessment

<table>
<thead>
<tr>
<th>Break Preclusion</th>
<th>Low Break Probability</th>
<th>Retaining Break Postulates</th>
</tr>
</thead>
<tbody>
<tr>
<td>all principles are met in a balanced way</td>
<td>some principles are not met in a balanced way</td>
<td>some principles are not met at all</td>
</tr>
</tbody>
</table>

Assumption of Leakage Sufficient Assumption of Breaks Necessary

for Component Specific System - and Accident Analysis

---

Fig. 1: German example: General Concept of Break Preclusion for Pressure Retaining Structures of Nuclear Power Plants with Nominal Diameters of DN >= 150 mm
3 TECHNICAL SUBSTANTIATION

The impact of LBB on the fundamental nuclear power plant design bases imposes a serious need of its technical substantiation. The operating experiences and related research programmes are the most relevant data sources for this purpose. This chapter describes the state-of-the-art within each discipline mainly based on the review given in /KES 99/.

3.1 Operating experiences

Worldwide databases exist currently for exploring NPP piping failures /NYM 97/. No breaks have been reported in large-diameter Light Water Reactor (LWR) primary circuit piping and leakages are also predominantly limited to small bore piping. Most failures may be attributed to degradation mechanisms specific to the materials, service conditions and their combination:

- inter-granular stress corrosion cracking (IGSCC) of sensibilized austenitic stainless steels at Boiling Water Reactors (BWRs);
- erosion-corrosion at feedwater and wet steam conveying pipes made from low-chromium carbon steel;
- thermal fatigue due to mixing and stratification near junctions, tees and leaking valves.

Human factors relating to construction, operation, maintenance and the associated strategies are responsible for at least 20% of the failures. From the LBB point of view, the most exclusive degradation mechanism is apparently material loss due to erosion-corrosion, which accounts for most of the breaks. Thermal fatigue and IGSCC also present a potential for break via extensive crack formation but leakage has proved to be the governing failure mode. Vibratory fatigue is an important contributor to breaks but for small bore pipes only. The known degradation mechanisms have become increasingly understood and may be largely prevented or mitigated by proper construction, operating environment and monitoring. However, the localised and parameter-sensitive nature of some mechanisms causes a real challenge to the inspection and maintenance programmes if some chance for their presence exists. The old plants have a history of back-fitting against unexpected degradation at susceptible components; therefore progressive ageing trends and underlying new degradation mechanisms may not be excluded.

The scope of human errors is wide and has turned increasing attention to issues like operator training, experience feedback and modelling by safety analysis (PSA). Many relevant to LBB are faulty operating situations giving rise to excessive loading such as water hammer, which has been a marked contributor to pipe failures. But degradation mechanisms such as erosion-corrosion, IGSCC, thermal fatigue might be or have been significant to LBB, especially when combined with loading over the normal operation loads. Construction and maintenance errors may also cause malfunctions and excessive defects escaping detection, which might be particularly detrimental in case of a coexisting degradation mechanism.

From the above it may be concluded that abundant operating experience is available for establishing regulatory positions as to LBB in LWRs. However, large pipe breaks
are inherently rare events so supplementary experimental justification is needed to 
envelop degraded piping behaviour under bounding loading conditions. Extremely 
low break probability shall always be the goal when targeting the concept to measures 
affecting the global safety of NPPs. Therefore, LBB may not be unconditionally 
implemented as a design tool but several prerequisites are necessary as regards 
construction, operation, maintenance and the responsible organisations. At existing 
plants less options are available but a thorough plant-specific evaluation of the as-
built configuration and past histories may be conducted to justify the LBB concept 
implementation.

3.2 Experimental programmes

Experimental programmes have been going on in several countries since the late 
1970s to enhance understanding of the fracture mechanics and leakage processes in 
cracked piping components and the conditions for their timely detection. The basic 
fracture mechanics experiments with single components have mainly consisted of:

- four point bend tests on circumferentially cracked straight piping;
- burst tests on axially or circumferentially cracked end-capped pipes and vessels;
- mechanical loading tests on cracked elbow, T-joint and nozzle assemblies.

Combinations of the above types have been frequent. Some tests with wide plates 
have been also done. The experiments have represented the monotonic and cyclic 
pressure, bending, thermal and corrosive loading conditions characteristic of LWR 
plants. The typical primary circuit piping materials and diameters have been covered.

These experiments have served establishing the bounding conditions between failure 
modes (leak or break) in terms of pipe material, main dimensions, initial crack size 
and stress level. The well-defined set-ups have also enabled evaluation of the fracture 
mechanics estimation schemes and FEM procedures considering the observed weld 
and base material toughness characteristics. Much of the interest has focused on 
whether the circumferentially cracked pipes, made from ferritic and austenitic 
stainless steels, will attain a maximum load predicted by the limit (net-section 
collapse) load theory. Cases with prior unstable crack growth have been reported, 
suggesting that this is not a general rule.

Arrangement of realistic loading and boundary conditions is an inherent difficulty of 
tests on single piping products. The potential for break may depend largely on factors 
like static and dynamic response of the entire piping, compliance of the loading and 
retaining the system pressure at the onset of large leakage. Considerable insight into 
these aspects has been gained from internationally organised full-scale experiments on 
piping facilities containing sections with artificial circumferential through and part-
through cracks /WIL 98/. Seismic events and blowdown situations with isolation 
valve closure, as well as thermal transients and thermal stratification phenomena have 
been simulated by these facilities. These experiments have made clear that pipes with 
crack sizes far beyond acceptable still possess a marked residual strength. A possibly 
contributing factor in case of fairly long cracks is their interaction with the piping 
system deformations which tends to increase the apparent stiffness of the cracked 
component and hence the critical crack size. However, a similar effect occurs during
normal operation, resulting in a smaller crack opening and a more stringent requirement for leak detection.

The efficiency of crack detection by Non-Destructive Testing (NDT) has been the subject of several international research programmes such as the PISC III exercise. Procedures exist for effective detection of relevant defect sizes in wrought steel pipes. However, the metallurgical structure limits the performance for welds and cast stainless steels. In any case, characterisation of the type of the defect may be regarded as unreliable and application of the same procedure by different teams presents marked scatter. A general need to enhance the NDT system performance by qualification therefore exists.

Investigations into the leak detection effectiveness have in turn made clear physical uncertainties in the amount of leakage discharging from service induced cracks. Among them are possible plugging due to particles, the true surface morphology and frictional effects as well as the local (residual) stress fields affecting the leak area. International benchmark tests have resulted in large scatter bands /GRE 95/ and the reported post-analyses of real events have been successful only after a careful investigation of the influential local conditions. On the other hand, sensitive monitoring systems, using well diversified principles, are currently available so under favourable conditions, detection of leaking cracks of reasonable size should not be a problem.

It may be summarised that the fracture mechanics experimentation of vessels and single piping products for LBB application has reached a considerable maturity. A fair understanding exists as to the failure mode (leak or break) following a given combination of materials, pipe dimensions, initial crack configuration and service conditions. Availability of reliable information on these aspects will be crucial in making real safety cases. The full-scale experiments undertaken on complex piping systems have indicated their ability to withstand large cracks under severe loading conditions. Additional safety margins may result from system interactions but are specific to each application and would require a detailed analysis. The detectability of cracks and leaks continues to be an area deserving further effort, such as NDT system qualification and more post-analyses of real leakage events to justify the safety margins needed in safety analysis.

3.3 Analytical considerations

The analytical research activities regarding LBB have centred around probabilistic approaches and development of analysis procedures for practical licensing applications.

Considerable justification for the low pipe break probabilities has been obtained from PSA studies where pipe breaks are treated as initiating events. These estimates are mainly based on operating experiences. Failure data of fossil power plants as well as statistical correlations between their leak and break frequencies have been also used, recognising that only leaks have occurred in large-diameter NPP primary circuit piping. Such approaches were adopted in the German Risk Study phase B and yielded estimates of 1.7x10-3 to 10-7 per reactor year for pipes of respective diameters 25 mm
to 250 mm. The lower limit has been generally used to justify the German Break Preclusion concept.

Advanced fracture mechanics methodology is currently available for evaluating the probability of making an LBB case. Taking the input data from empirical statistics of physical variables governing the leakage and fracture after break-through, extensive parameter studies have been carried out showing the break probability dependence on pipe diameter, service stress level, material (ferritic vs. austenitic stainless steel), crack location (weld vs. base material) and leak detection limit (PWR vs. BWR). In case of a given cracking mechanism (IGSCC), an overall break frequency evaluation has been possible as the probability of crack initiation and escaping detection by ISI and leak monitoring while extending to a size unstable under the specified service loads. The analytical predictions have fallen in some cases considerably below the inputs for PSA.

A clear lesson from the real pipe leak and break events is that a case-by-case analysis, based on a proven procedure and qualified methodology, shall be carried out for each licensing application using LBB. Typical issues, to be addressed in more detail in Chapter 4, are:

- consideration of failure mechanisms;
- location and type of postulated cracks;
- loads and stresses to be considered;
- weld and base material characterisation;
- leak area and rate analysis;
- crack growth and stability analysis;
- NDT and leak detection sensitivity;
- safety factors.

Affected by the applicable regulations, operating and research experiences and other regional conditions (seismic activity etc.), the approaches adopted in different countries vary. Comparative benchmark activities have indicated wide scatter bands, which may be partly attributed to disparate basic assumptions and definitions.

Consideration of the failure mechanisms, possibly excluding LBB, may be in some cases a decisive step and, in absence of exact screening criteria or analysis methodology, will be more or less based on engineering judgement. Different prioritisation of the basic mechanisms has in some cases led to conflicting national preferences as to plant and material types qualifying for LBB. Postulating circumferential through-cracks at welds with worst combination of material properties and service stresses is becoming a standard approach; however, risk-based alternatives, adopting locations with highest break consequence rather than probability, have been proposed. The options in preparing data for the analysis are numerous and attention has been recently given to aspects like:

- load condition and critical crack definition for stability analysis;
- configuration of the postulated cracks;
- accounting for the residual stresses and weld property mismatch;
- safety factors, particularly on leak detection.
The bulk of the procedures consists of fracture mechanics and leak area analyses of postulated through-wall cracks. Several estimation schemes, with various basic assumptions and limitations, have been proposed for treating standard geometry and loading situations while rigorous FEM techniques are available to analyse complex products like elbows and T-connections /IKO 95/. For making the leak rate analysis, internationally recognised thermal hydraulic computer codes exist, featuring detailed crack morphology and thermal hydraulic descriptions. Procedures have also been presented for postulating part-through cracks and demonstrating either insignificant fatigue crack growth during the remaining lifetime or a consequent LBB case, should the operation continue until breakthrough.

It may be concluded that empirical and analytical models exist on how pipe break probabilities depend on the key parameters relevant to LBB. The break probability is a strongly decreasing function of the pipe diameter. The bare figures are though hardly representative enough to justify LBB alone, but more refined estimates should be striven for, e.g. by advancement of the world-wide relational failure databases. The LBB procedures act a key role in justifying LBB for particular applications and, compared to the efforts undertaken in the area of involved methodology, some convergence of the definitions and aspects accounted for is yet to be seen. An overall consideration of the possibly exclusive failure mechanisms is an integral part of the procedure and depends on the skills and experience of the reviewer.

### 3.4 Current status

Since its birth some two decades ago, the LBB concept has undergone a development from a probabilistic fracture mechanics argument into a multi-disciplinary safety technology relying on:

- operating experiences;
- construction technology;
- load and environmental monitoring;
- fracture mechanics;
- non-destructive testing;
- analysis and detection of leaks;
- full-scale experiments;
- probabilistic safety analysis.

Intense research programmes have been going on in several countries. A principal understanding has been created on: 1) under which conditions and how frequently pipe leaks and breaks occur; 2) how these conditions can be prevented and mitigated and 3) how meeting the LBB criterion may be evaluated for each particular application.

Considerable substantiation of the LBB concept may be deemed to result from these developments, particularly in case of large-diameter primary circuit piping. No breaks have been reported and the pipe size effect is well supported by analytical considerations. Such components also have to meet stringent standards and regulatory control in the different areas of construction. Advanced designs and manufacturing technologies have been introduced to minimise the potential for break.
Monitoring of the loading and environmental conditions of the primary circuit is customary and facilitates managing the degradation mechanisms. Independent leakage monitoring systems, using diversified principles, are provided inside the containment and have been specified with regard to unidentified leakages /AZO 95/.

After these efforts and developments, it may be yet recognised that the positions as for the LBB concept are not fully established within the nuclear community. The definitions, basic assumptions and methodology employed in the national LBB procedures do vary, and the associated benchmark exercises have consequently resulted in large scatter bands. Concerns have been also presented regarding technical aspects like the detectability of cracks and leaks under real plant conditions. The previous benchmark exercises suggest that NDT procedures currently used for in-service inspections enable detection of defect sizes relevant to LBB from wrought steels only. The metallurgic structure limits performance for welds and defect characterisation may be generally regarded as unreliable. Experimental evidence also exists in case of leak detection that its effectiveness depends on unpredictable local physical phenomena which may limit the amount of leakage discharging from service-induced cracks. Post-analysis of real leakages has been successful only after a careful investigation of the crack. The significance and implications of these considerations may be evaluated as follows.

**LBB procedures**

A wide range of analysis methodology is available for the LBB procedures. The points to be emphasised are qualification against applicable benchmarks and the analyst’s familiarity with the basic limitations particularly when it comes to material toughness. The positions on failure mechanisms as well as the choice of loads, stresses, material properties, safety factors and postulated cracks are largely responsible for the diversity. Noteworthy risk-based alternatives, underlining the consequence rather than probability of breaks, have been proposed for locating the postulated cracks. Evaluation of the potential for harmonisation of the procedures is clearly desirable and has been initiated by the WGCS /AEA 97/.

**Non-destructive testing**

The role of NDT in case of LBB concept implementation is to enable early detection of slow part-through cracking mechanisms whose configuration might cause a potential for break. A thorough consideration of such mechanisms and exclusion from LBB concept application when excessive is also part of the procedures. In case of fatigue crack growth analysis, a sufficiently large initial part-through crack is postulated to ensure detection by NDT. These evaluations should become informed of the local conditions for NDT performance at each weld. The same is true for the strategies of choosing the postulated through-wall cracks which currently place most emphasis on the stresses and material properties. A candidate permanent solution would be following the NRWG common position on NDT system qualification strictly in case of LBB concept application /CEC 96/.

**Leak detection**
NPP operating experiences speak for that, under favourable conditions, detecting leaking cracks of relevant size inside the containment were not a problem. Based on benchmark test findings, a high safety factor has been yet found necessary in LBB analysis against uncertainty of leak detection. This results in large postulated crack sizes and difficulties to meet the LBB criteria particularly for small to intermediate diameter piping. Increasing the leak detection sensitivity may be alternatively considered in such cases. Probabilistic analyses, based on morphology data from service-induced cracks, have been also undertaken to justify a smaller safety factor. Further justification may result from considering the system interactions in LBB analysis. More experience with realistic benchmark tests and post-analyses of real leakage events would be also needed to enlighten the reliability of practical state-of-the-art leak rate analyses.

### 3.5 Discussion

A general conclusion from the above considerations is that large-diameter LWR primary circuit piping breaks are very unlikely events and indisputable substantiation exists to re-consider their treatment in the NPP design bases. This statement relies largely on the reported operating experiences, full-scale piping experiments and advances in various areas of construction and monitoring. For giving much credit to detectability of cracks and leaks, a critical survey of the benchmark findings suggests that some progress should be still foreseen in the areas of NDT and leak detection. The challenge in both cases is that the performance to be expected depends on physical micro-scale aspects and the available information on them. Improved management of these uncertainties may be expected to result from advancement of the LBB procedures.

From the LBB point of view it may be consequently interpreted that meeting the prerequisites rather than the computational LBB criteria often constitutes the actual safety margin. This places a high responsibility on the construction, operation and maintenance practices and the associated organisations. Under these circumstances, supplementary analysis procedures would be worth considering to signify adequate component reliability and maintaining the global plant safety in LBB concept implementation, irrespective of crack and leak detection. A more refined modelling of the LBB candidate piping in the PSA would be one alternative. To this end, worldwide relational failure databases as well as probabilistic fracture mechanics methodology, incorporating the effect of in-service inspections and leak detection, are currently available. Component proximity considerations and other plant-specific safety features affecting the break consequences should receive attention in such an analysis.
3.6 References


4 OVERALL METHODOLOGY

4.1 Basic principles and limitations of the LBB application

4.1.1 Basic principles and limitations of the LBB application

Most of the nuclear piping systems are made of ductile materials. Due to their high toughness, those materials are known to be fracture resistant. The ductile behaviour of the materials in nuclear power plant piping gives so a satisfactory account of the basic assumption of the LBB concept, i.e., the possibility for a through-wall defect of a limited length to be stable under the specified loading conditions. It is therefore evidence that LBB would not be applicable to piping systems made of material showing non-ductile failure mechanism or insufficient ductility.

An initial surface crack can grow through the pipe wall by several potential mechanisms such as fatigue, tearing or any other process due to service loading and environment (called hereafter degradation mechanism). Crack growth through the wall thickness comes to an end at the time when the remaining ligament fails. If the defect length at breakthrough or even during its growth exceeds the limiting (or critical) crack size, the conditions of crack instability are met and the catastrophic failure of the component due to rapid crack extension will occur should a high loading transient arise. If the defect length at breakthrough is less than the critical crack size, the now fully penetrating crack can keep growing in size, possibly leading to a detectable leak, until the limiting size is reached.

A first range of LBB procedures, that could be named «conventional» procedures, have been based on a deterministic analysis procedure where: (1) through-wall cracks with straight fronts, perpendicular to the pipe surface, are postulated at zones with least favourable combination of loading and material properties, (2) computational demonstration is given to that the resulting leakage under normal operating conditions will be detected long before that the crack reaches a size that would be critical under the worst specified loading conditions. Different safety factors have been prescribed to conduct such analyses. In some cases, additional consideration is given to that a part-through crack of the largest permissible size will not grow markedly during the lifetime of the plant by slow mechanisms like fatigue. An alternate type of procedure to account for these aspects is described in point 4.7 and the respective advantages and drawbacks discussed in 4.8.

An obvious prerequisite for the «conventional» approach, stipulated in the underlying regulatory documents, is to exclude from its scope cases where (i) crack growth mechanisms may introduce flaws whose geometry may not be bounded by the postulated (stable) through-wall flaws, and (ii) when high but not quantified loads are expected to be imposed on the component. Under (i) is for instance the preclusion of the LBB application to piping components prone to stress corrosion cracking, as intergranular crack growth can lead to very long surface defects. More generally, shall the kinetic and/or the degradation mechanism not be well known and described, is the (i) not satisfied. As an example for (ii), it is recognised that the risk of water hammer loading in piping containing high-energy fluid can preclude the application of LBB, unless the peak loads are considered in evaluating the limiting crack size. It is
also considered that where there is a significant risk of damage to piping from impacting objects (missiles or dropped loads) or equipment failure, LBB procedure should not be applied.

The main steps of the “conventional” LBB procedure include:

1. Material characterisation and piping stress calculation
2. Determination of critical through-wall crack lengths (incl. crack location assessment)
3. Calculation of crack opening area
4. Evaluation of leak rate
5. Assessment of results

4.2 Material characterisation and piping stress calculation

The fracture mechanics analysis techniques applied in the LBB procedure require to know the tensile and toughness properties of the piping material (base material, weld, heat affected zone) at service temperature, and taking into account, where relevant, the degradation of these properties during service. The available data should be sufficient to characterise the variability of these properties for the steels to be found on the plants. Sufficient data should also be available to demonstrate the corrosion resistance of the materials. Validated test procedures, conform to applicable standards, shall be followed in fracture mechanics characterisation. The specimen type and size shall provide adequate capacity with regard to the energy release rate and amount of crack propagation relevant for the analysis. Validated extrapolation techniques shall be applied when necessary.

Application of the LBB procedure also requires knowing the stress state in the piping under the relevant operating conditions. In order to ensure this requirement, the piping geometry and the as-built supporting system should be available in order to generate a model of the piping system suited to a conservative stress analysis. Where substantial difference in the as-built state compared to high quality standards is known, it shall be taken into account (weld mismatch, component support in contact, welds without post-weld heat treatment). The static and dynamic loads applied on the piping system under the relevant plant operating conditions should be sufficiently specified to allow the piping analysis to be performed.

4.3 Determination of critical through-wall crack lengths

The critical crack length is the limiting length at which a through-wall defect at a postulated location would become unstable under the applied loads.

4.3.1 Crack location

Determining the crack location requires assessing the potential flaw locations and the least favourable combination of stress and material properties. Experience shows that the welds with the heat affected zones are the preferred areas for flaws, whether they
are induced by the manufacturing process or they are initiated during service. Nevertheless, for the latter, detrimental conditions such as high cycle thermal fatigue might create also flaws in the base metal. Limiting the postulated flaws to the weld locations should however be considered with great caution as the occurrence of specific phenomena during plant operation can initiate crack-like defects at other locations in the base material. So, other factors of choice can be introduced such as: location where pipe interaction with some type of supports can occur (if the gap between support and piping might be not sufficient to allow all thermal expansion displacements), and locations with high risk of manufacturing flaws. Locations with high safety impact may also be considered (PSA driven criterion).

Experience with piping stress analysis also indicates that, due to the effect of the bending moment, the axial stresses are generally higher than the circumferential stresses (in straight parts) and so the circumferential cracks are generally more severely loaded than the axial ones. As a consequence, circumferential through-wall cracks are generally postulated only at the circumferential weld locations along the piping system and at the connections with the heavy components. An exception can be found in some old nuclear power plants in which elbows fabricated with longitudinal welds may have been installed. Special attention should also pay for in cases where T-junctions are encountered. Another point has to be kept in mind, is that on a pure safety point of view, a longitudinal crack opening with intermediate flow leakage on the primary system might generate a small break LOCA that could be more penalising for the reactor pressure vessel than a DEGB.

4.3.2 Applied loads

The objective of the critical crack length calculation is to ensure that unstable fracture is not a concern. The critical crack length should therefore be calculated under the most critical service conditions. The relevance of the loading considered has to be checked, taking into account the piping system layout (e.g.: in the vicinity of a fixed point there is a potential elastic follow-up effect).

4.3.3 Calculation Methods

The critical crack length depends on the crack geometry orientation, the component geometry, the material properties and the loading conditions. Several methods are currently available to determine the critical crack length, from the elastic-plastic fracture mechanics to the fully plastic fracture mechanics. Detailed descriptions of the existing fracture mechanics assessment methods can be found in the literature. Commonly used methods include the limit load (net section collapse) analysis, the moments method, the J integral/tearing modulus (J/T) approach, the crack opening displacement (COD) method, the R-6 approach and the failure assessment diagram. It should be pointed out that all these methods have their limitations and that particular care should be taken when selecting a particular method for a specific application. This is most true for the limit load type methods. Evidence exists that even for ductile stainless steel pipe that the ideal plastic conditions may not be reached because of the onset of stable crack propagation. The true toughness depends e.g. on the welding procedure and possible post-weld heat treatments and shall be evaluated in each case.
4.4 Calculation of crack opening area

The crack-like through-wall flaws considered in the LBB procedure are assumed to be closed when no loads are applied on it. (One should be aware that residual stresses may limit the opening behaviour of tight cracks). Loading is therefore required to open the crack and so develop a leakage area. Leakage area calculation consists in evaluating the extent to which a through-wall crack opens under the relevant loading conditions. More specifically, the crack opening area depends on the crack geometry (length, orientation), the component geometry, the material properties and the loading conditions.

The crack opening displacement is commonly used to calculate the crack opening area by assuming that the crack opens into a conventionally elliptical shape. Analytical methods for calculating crack opening displacements are limited to simple cases, for instance a straight pipe under internal pressure. For more complex geometries and/or loading, crack opening displacements have been obtained by finite element calculations. The results available in the literature make possible their use for specific cases by interpolation. The methods do generally consider the effect of plastification to reflect the crack opening area larger than foreseen by elastic modelling. For most applications however, for well designed piping systems, the plastification is limited. Residual stresses may limit the opening behaviour of tight cracks.

4.5 Evaluation of leak rate

The LBB procedure requires evaluating the leak rate through a crack at a postulated location under the relevant loading conditions. The leak rate calculation aims at evaluating the detectable leakage crack length, i.e., the length of the crack associated to the minimum detectable leak rate, given that the whole leakage occurs through this crack. The leak rate depends mainly on the crack opening area, the thermodynamic conditions of the fluid and the crack morphology variables (surface roughness, numbers of turns, discharge coefficient, actual crack path/thickness,).

Due to the thermodynamic conditions of the reactor coolant (subcooled water), a two-phase flow of water is to be considered. Several models have been developed to describe this highly complex physical phenomenon. A model commonly used is the Henry-Fauske model aiming at calculating the two-phase critical flow and accounting for nonequilibrium effects between the phases. Homogeneous equilibrium models are also available.

The development in chapter 3 shows that, although efforts have been made in the leak rate calculation methodology, uncertainties remain quite high.

4.6 Assessment of results

The LBB argument is that, should a through-wall defect arise, the resulting leakage will be detected before the defect «grows» to a limiting length. Practically the «conventional» LBB analysis demonstrates that a component showing a full penetrating flaw (of a sufficient size to be detected via leakage) still has a sufficient
load-carrying capacity to resist the relevant specified loading conditions. The «conventional» LBB procedure so requires comparing the detectable leakage crack length to the critical crack length.

Specified normal operating loads are commonly assumed to avoid under-predicting the detectable leakage crack length. On the other end, in order to ensure conservatism, the worst specified loading conditions are generally considered to calculate the critical length of the through-wall defect.

The «conventional» LBB procedure is a deterministic analysis based on the principles of fracture mechanics and thermo-hydraulic analyses. So, fluctuation of applied loads, variability of crack morphology parameters and material properties, and uncertainty in analytical models contribute to question the conservatism of the analysis.

In a first attempt to ensure the required conservatism, the calculations of the critical crack length and the detectable leakage crack length are traditionally performed using the worst-case values of the material properties. Lower bound material properties provide conservative estimates of critical crack length. Best estimate material properties are generally recommended to calculate the crack opening displacement, as it should not be over-predicted.

Furthermore, for licensing purpose, several safety factors are included in the analysis. As the «conventional» LBB analysis is essentially done in terms of the associated crack lengths, a prescribed safety factor should exist between the calculated critical crack length and the calculated detectable leakage crack length. This safety factor is intended to account mainly for the uncertainties inherent in the analysis.

The definition of the detectable leakage crack length should also include a safety factor for accounting all those features making the modelling of the leak detection rather coarse. The required factor should consider first the global performance of the leak detection system. That includes the uncertainties related to the type of leakage measuring systems, their sensitivity and their accuracy. It also includes human factors such as the availability for the plant operators of the reliable information and procedures to interpret the measurement data.

4.7 Alternate LBB procedures

A characteristic, if not a drawback, of the «conventional» LBB procedure is the lack of the time dimension. Adding the time dimension would lead to consider the time of detection and the crack growth. In addition to the «conventional» LBB procedure, other procedures have been developed which consider somewhat the time dimension.

So some procedures, rather than postulating a full-penetrating defect, consider the development of the crack prior to breakthrough and between the breakthrough and the growth to the limiting size. Those procedures differ from the «conventional» LBB procedure mainly by the flaw assessment and the growth analysis.

First the postulated or actual part-penetrating defect is to be characterised. Then the defect length at breakthrough has to be estimated. The shape development of the
characterised defect arises from fatigue or other potential crack growth mechanisms under normal operating conditions. (This suggests that the driving mechanism is known and analytically modelled). For pure mechanical damage, the stress distribution is so the major parameter controlling the defect shape development.

The calculation of the defect length at breakthrough is the most delicate part of the flaw assessment as it determines whether the initial ligament failure results in a leak or break. Indeed, if predicting the crack shape as it grows through the wall thickness indicate that unstable growth in length direction can occur before the defect has grown fully through the wall, stable breakthrough of the part-penetrating defect cannot occur and a LBB case cannot be made.

One of the acceptance criteria of those alternative procedures is to demonstrate that the crack length at breakthrough is less than the critical crack length.

4.8 Discussion between the conventional and alternate LBB procedures

Historically the «conventional» LBB procedure was the first one to have been applied. The «alternate» procedures can be seen as an answer from the industry to describe more precisely the behaviour of the flawed pipe structure. Nevertheless, due to the accuracy and confidence achieved in different parts of the «alternate» procedure, the «conventional» procedure still presents advantages for the regulators. The following table aims at identifying the advantages and drawbacks from the both types of justifications.

<table>
<thead>
<tr>
<th></th>
<th>“Conventional” LBB procedure</th>
<th>“Alternate” LBB procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>- a careful application of the prerequisites is required, among which the knowledge of the loading and degradation mechanisms is one of those, as the growth mode is not assessed</td>
<td>- identification of the preferred growth direction (and eventually track down flaws growing preferentially in length) =&gt; can lead to identify crack shape and location that might be unstable without having grown through wall</td>
</tr>
<tr>
<td></td>
<td>- the robustness of the pipe (load carrying capacity of the flawed pipe) is a key element</td>
<td>- possibility to introduce complex growth mode, provided that there exists an adequate and conservative modelling</td>
</tr>
<tr>
<td></td>
<td>- a limited number of identifiable safety factors is used</td>
<td>- quantified idea of the time of growth between leakage size and limiting size</td>
</tr>
<tr>
<td></td>
<td>- only simple justifications (calculation procedures) are needed</td>
<td></td>
</tr>
<tr>
<td><strong>Drawbacks</strong></td>
<td>- no estimation of the evolution of the flaw shape</td>
<td>- procedure linked to a specific type of crack growth mechanism</td>
</tr>
<tr>
<td></td>
<td>- no formal link between growth rate and time of detection</td>
<td>- bursting phase (final growth phase) is not assessed correctly</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- assessment of the initial flaw size is a critical step</td>
</tr>
</tbody>
</table>

It appears from this comparison that there is much room for a case by case discussion between the regulatory body and the industry on the choice of the type of procedure.
5 REGULATORY APPROACHES TO LBB

5.1 Situations in different countries

After having discussed the general concepts and methodologies used in the frame of LBB analysis, this chapter’s role is to give a general overview of the regulatory practices in the different countries taking part in this task force. The position of the USA has also been reminded, because of the historical background, and also because many countries establish their requirements based on the USA position.

The purpose of the chapter is not to give a detailed view, mainly because a synthetic chart was preferred in the preparation of the table of content. The data were provided through the task force members who answered a general questionnaire analysed during the second task force meeting.

5.1.1 Safety Objectives

For this point, the table of comparison shall follow the frame put in place for the corresponding second part of the report, namely:

- the role of the DEGB concept, the way it might be affected by the LBB approach and the expected gain for safety;
- the role of LBB in the toolbox of the safety authorities to upgrade the old plants in order to meet the present requirements;
- the way the LBB approach can change the balance in the global safety assessment for changed service conditions (design changes and safety benefits).

This point might be the one which has been the less reported in the countries’ contributions, mainly, according to the group, because the LBB approach and use seem to be a kind of case that is proposed to safety authorities for approval, and very seldom a recommendation from the safety authorities to utilities.

Furthermore, so far as no member of the US-NRC took part to the TF’s work, the chart filling for the USA position shall be taken with care because no validation was possible. Nevertheless one NRC/NRR staff member reviewed it informally and his remarks have been taken in account.

5.1.1.1 The DEGB concept

Please note that here, a gain has to be understood as an advantage/improvement of the design of the plant with regard to safety, on the point of view of the regulator.

<table>
<thead>
<tr>
<th>Country</th>
<th>DEGB concept and expected gain from it's evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>DEGB concept: stems from the «classical» design (Design Basis Accident as defined in App A to 10 CFR 50 incl. GDC 4): used to design engineered safety features to cope with accidental conditions; verify that these conditions do not lead to any aggravation of the postulated accident; all these studies are done in a conventional way (SFC, ...). All aspects of</td>
</tr>
<tr>
<td>Country</td>
<td>DEGB concept and expected gain from it’s evolution</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Belgium</td>
<td>Original concept: same as in the USA. The methodology applied is the general US one plus additional requirements. Only the dynamic effects are «removable». The advantages: no particular advantage is foreseen within the global objective to keep the same global safety level by reaching the former acceptance criteria for the proposed new conditions.</td>
</tr>
<tr>
<td>Italy</td>
<td>No major differences with the DEGB original concept. The evolution, as in the USA, is based on advanced FM, probabilistic evaluation of pipe breaks; but the support of ISI is also expected. The advantages concern only the dynamic effects (pipe whipping and jet impingement) but not the blowdown loads on internals. Radiation dose to the workers is expected to be reduced during ISI and maintenance.</td>
</tr>
<tr>
<td>Finland</td>
<td>Original concept: same as in the USA (GDC 4) In case of Loviisa NPP (VVER 440), dynamic consequences of the main coolant loop DEGB’s were fully considered and provision against other high-energy DEGB’s was supplied after commissioning. There is a principal preparedness for LBB concept application to new plants, stipulated in a draft regulatory guide YVL 3.5. A plant-specific validation of the concept would be then required prior to construction considering experience, quality, probability, ageing, monitoring, physical separation etc. aspects. For existing plants, LBB analyses have served justification of defect and global safety assessments as well as leak detection system optimisation (SG tubes) case by case. Among the advantages of LBB are a sounder layout of the reactor building, increased efficiency of ISI systems and lower maintenance personnel dosages.</td>
</tr>
</tbody>
</table>
| Sweden  | As the first reactors in this country are quite old (some were built before the issue of the GDC 4 and reg guide 1.46, for instance with external recirculation loops), the rule for design bases changed with time. Generally speaking, the DEGB effects were rather considered for the global effects (on fuel behaviour, on mitigation systems, ...) but not for the local effects (pipe whipping), which are considered on a case by case basis. Advanced technology is expected on the three fields in order to start an LBP analysis and action: FM, leak detection systems and NDE (ISI) programmes. Currently known LBB criteria have been judged inconsistent when applied directly, but SKI might consider safety assessment based on LBB principle. The gains expected are not clearly expressed as the demand is coming from the utilities; e.g. the avoidance of stress arising from prevented heat expansion not taken into account in the stress analysis. For the commonly
<table>
<thead>
<tr>
<th>Country</th>
<th>DEGB concept and expected gain from it’s evolution</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>given arguments such as dose reduction or ISI conditions improvement, Sweden consider that other means enable to achieve these goals (such as automatization of NDE techniques) The general target is to satisfy the Safety report (FSAR) objectives, whatever the means.</td>
</tr>
<tr>
<td>Czech R.</td>
<td>Original concept : same as in the USA The advantages; The «as built» provisions (WWER 440/213 NPP) and design provisions (WWER 1000/320 NPP) to mitigate consequences of a main circulation line break were not appropriate, thus affecting level 1 and 2 of protection. Dynamic effects associated with a main circulation line DEGB could lead to damage of safety related equipment, components and structures and impair the performance of all related safety functions. The LBB concept was used as a compensatory measure.</td>
</tr>
<tr>
<td>France</td>
<td>The first series of 900 MWe was directly taken from the Westinghouse design, and therefore, the GDC-4 was applied. Later on, for the 1300 and 1450 MWe series, the break postulates requirements were expressed in the Basic Safety Rule IV-2-a (21/12/84) and in the code RCC-P, but are quite near to the original ones. No LBB regulation is intended for the moment for existing plants mainly because the utilities haven’t produce any comprehensive approach for that topic.</td>
</tr>
<tr>
<td>Spain</td>
<td>Among the current NPPs in Spain, the oldest ones are designed according the original GDC 4 with the «classical» break postulates. Two more recent NPPs are designed with the amended GDC 4 (by the generic letter 84-04), that is to say taking into account the American methodology and criteria for LBB (from the beginning). The technology used in the USA to support LBB application has been recalled before and is mainly based on FM considerations. For the application to S.G. tube bundles, extensive review was also carried out for leak detection and ISI. The gains expected by CSN are : * simplification of ISI (physical and radiation) * show some conservatism in the initial safety analysis, e.g. for the reactor cavity pressurisation.</td>
</tr>
<tr>
<td>Germany</td>
<td>The break postulates are regarded as design requirements on safety systems. The Basic Safety (BS) Concept, which is a global concept in Germany for supporting the Break Preclusion (BP) Concept (Fig. 1, ch. 2), requires the consideration of the following two principles : - Principle of Quality Achieved by Design and Manufacturing ; - Principle of Controlled Operation. The aim of the BS is the general improvement of the quality of the installed structural components and their safe operation mainly sup-ported by comprehensive monitoring and inspection measures. To successfully demonstrate BP, two further principles have to be also considered : - Principle of Bounding Loading Conditions ; - Principle of Controlled Failure Mechanisms. The benefit of the BP approach is the renunciation of large break openings for the local component/structure design which allows to avoid pipe whip</td>
</tr>
</tbody>
</table>
The DEGB concept and expected gain from its evolution:

**Slovenia**

- Original concept of GDC 4 is applied as in the USA NPP was originally designed against global and local effects of postulated DEGB.
- The proposed advantages from NPP are reducing doses to the workers, facilitating improved ISI by removing part of the mechanical restraints and snubbers and decreasing the challenge of pipes overloading due to snubbers failure. The current authority position to change the plant design basis by LBB concept introduction and snubber reduction for the only existing plant is negative.

**Slovak R.**

- On the base of the Regulation Act No.1/1991 was applied original LBB procedure. The main advantages from LBB concept application are:
  - For the older VVER 440/230 units: optimisation of anti-seismic equipment
  - For the new VVER 440/213 units: removing pipe whip restraints and jet impingement constructions

### 5.1.1.2 Assessment of global safety (design changes and safety benefits)

Under this general assumption shall be understood actions or analysis taken in order to maintain the global safety assessment and the defence-in-depth barriers in case of service conditions not taken into consideration at the design stage. In this sub-paragraph again, only the relevant countries have been pointed out. It is already possible to say that even countries having no general LBB policies have considered ‘LBB type’ (in a broad sense) analysis for assessing specific threats, deficiencies or ageing phenomenon arising to components or systems in the service conditions.

### Country | Case considered under an ‘LBB type’ analysis
--- | ---
**Belgium** | It’s rather for assessing new service conditions (removing restraints after SGR or power up-rating justification) that LBB has been introduced. But use of the LBB analysis made the global case acceptable, which would not have been the case by using the conventional methods. To keep a globally acceptable safety level, additional requirements were put in addition to the USA standard procedure: alternative LOCA postulates (SG manhole cover rapid opening), complementary loads to SSE analysis (SLB), slow break area of 1A

**Finland** | Following a replacement of IGSC cracked BWR shut down cooling system piping by resistant material, STUK rejected a request for LBB application but accepted reduction of a few intermediate whip restraints as justified by the SRP 3.6.2.

(please note that SRP 3.6.2. requires whip restraints at terminal ends and
Applications have already been submitted to SKI, but none was authorised successfully. In Sweden, risk-informed ISI is already done, and there are still some doubts about the possibility to implement effective leak detection systems with appropriate procedures.

Spain

Some of the old SG tube bundles susceptible to IGSCC for some type of defects were applied LBB concept, balanced with heavy ISI and a sensible and devoted leak detection system. For the other applications (snubbers or whip restraints removal), if the margins shown are sufficient (with regard to SRP 3.6.3), no balance is sought.

Germany

The Break Preclusion Concept (Fig. 1 chapter 2), is a global new balance in the safety assessment of high-energy components.

Czech R.

Assessment of global safety
LBB is a part of the structural integrity safety case.

Slovenia

Case considered under an LBB type analysis:
There is no approved LBB type analysis except the in the framework of steam generator tube plugging criteria, where specific type of LBB application are licensed and implemented.
Plant submitted the LBB concept and its application for snubber reduction currently with steam generator replacement and power uprating was rejected by the authority.

Slovak R.

Global safety level improvement is one of the goals for the safety authorities in Slovak Republic

France

For information: for new plants (EPR project): the DFD has accepted the feasibility to demonstrate the Break Preclusion concept for the Main Coolant Lines, under certain conditions to be defined in the early design phase by the project, such as material and design quality, leak detection, ISI programme and feed-back of experience evaluation.

5.1.1.3 Upgrading to meet present requirements

This criterion was quite seldom used in the questionnaires’ answers to justify the introduction or acceptance of an LBB type approach or analysis. This is mainly due to the fact that the demand is most of the time originating from the utilities and linked for instance to changes in the exploitation conditions (stretch out, less ISI, reduced maintenance, ...). Therefore, the next chart only counts the countries that used LBB as a «tool» to require upgrading actions or analysis. For instance, it cannot be the case for countries which have not given a regulatory status to the LBB approach. (This does not mean that the countries not present hereafter do not require upgrading actions from their NPPs !)

<table>
<thead>
<tr>
<th>Country</th>
<th>Upgrading to meet present requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>The solving of the USI A2 case can be interpreted as an upgrading action. Some shielding have been installed resulting from LBB introduction (see</td>
</tr>
</tbody>
</table>
### 5.1.2 Limitations adopted in the different countries

For plenty of reasons such as potential threats to vital safety functions, in service encountered prohibitive degradations type, knowledge of unpredictable loads or fear of unpredictable events leading to critical situation, or inadequate quality of material or construction, the regulators have decided to set limits to their actual or intended LBB policy.

#### 5.1.2.1 Threats to vital safety functions/design changes

This point considers mainly the benefits to be awaited from the LBB analysis in terms of design requirements. In other terms, here are listed the engineered safety features or equipment that, regardless the result of the LBB analysis, are still designed with the DEGB.

<table>
<thead>
<tr>
<th>Country</th>
<th>Limitations due to safety functions or design principles</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>In the «classical» DEGB concept, the containment design, the ECCS design, the environmental qualification of safety equipment, ... are not impaired by the LBB analysis. Only the dynamic effects such as pipe whipping restraints, RPV (blowdown) and SG internals (divider plate, tube plate), asymmetric pressurisation of RPV cavity are considered</td>
</tr>
<tr>
<td>Country</td>
<td>Limitations due to safety functions or design principles</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Belgium</td>
<td>See USA. Keep the physical separation is also required. Heavy components supports and whip restraints are concerned, but also the blowdown effects on the RPV internals.</td>
</tr>
<tr>
<td>Italy</td>
<td>Environmental qualification, blowdown loads on RPV and SG internals, pressurisation load of the RC are not impaired by the LBB analysis</td>
</tr>
<tr>
<td>Finland</td>
<td>Damage due to global effects (LOCA, over-pressurisation, pressure differentials, flooding, humidity, temperature). Local mechanical damage and leakages of impacted other components that would challenge the success of consequently needed safety functions like reactor trip, emergency cooling, residual heat removal and containment isolation.</td>
</tr>
<tr>
<td>Sweden</td>
<td>The so-called global effects of DEGB cannot be addressed by an LBB analysis (containment, emergency core cooling, core geometry, ...). Only local effects could be considered (jet impingement, pipe whipping, ...)</td>
</tr>
<tr>
<td>Spain</td>
<td>Allowed applications are: pipe whip and jet shields, snubbers, core coolability (RPV supports and internals), RC pressurisation. But not: ECCS, containment design, or radiological evaluation of the analysed accidents</td>
</tr>
<tr>
<td>Germany</td>
<td>The Break Preclusion Concept (Fig. 1) is used for the main piping of the pressure retaining boundary and the main secondary piping installed inside the containment. the following design loads have to be used: - the DEGB (2<em>A) is maintained for the design of containment and its internal structures, ECCS and equipment qualification; - a static load of 2</em>A<em>p, with p as internal pressure, is used for the support design of the main components, e.g. RPV, SG and MCP; -leakage due to an opening area of 0.1</em>A is considered for internal pressure waves and the piping surrounding (shields loads and reaction forces, no whip restraints needed) as well as for the system and accident analysis.</td>
</tr>
<tr>
<td>Slovak R.</td>
<td>By LBB application are addressed: - the pipe whip and jet shields - the heavy components supports too.</td>
</tr>
<tr>
<td>Slovenia</td>
<td>Limitations due to safety functions or design principles: No application. The submitted application follows the US regulation requirements. That means that the LBB application considers only dynamic effects. Containment design (global effects), ECCS design, qualification of safety equipment are not impaired by the LBB analysis.</td>
</tr>
<tr>
<td>Czech R.</td>
<td>Same as in the USA – only local effects are considered.</td>
</tr>
</tbody>
</table>

5.1.2.2  Limitations due to prohibitive degradations or unpredictable loading or event

The initial design, completed with the operational feedback of experience has identified some types of degradations: they can affect the material characteristics or
challenge the component in a way that disables the analytical prevision of the potential damage. One major argument supports this position: when the analytical study cannot be made, the probabilistic aspect that undergoes LBB looses his validation hypothesis. As a consequence, if a degradation mentioned below can be mastered analytically (kinetic knowledge, ...) the argument could be discussed again. The chart hereafter reports the position of the different countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>Limitations due to degradation mechanisms or unpredictable loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>Particular susceptibility to: IGSCC or other major corrosion effects, water hammer, mechanical or thermal fatigue with risk of excessive growth, risk of cleavage fracture, particular risk of piping failure occurring from indirect causes. BWR utilities have not provided yet arguments for it’s applicability.</td>
</tr>
<tr>
<td>Belgium</td>
<td>The pressuriser surge line where thermal stratification transients are known to occur has been excluded so far from the LBB analysis of the reactor coolant piping system.</td>
</tr>
<tr>
<td>Italy</td>
<td>Nothing specified.</td>
</tr>
<tr>
<td>Finland</td>
<td>Unpredictable loading in general shall be avoided: condensation, water hammer, corrosion, creep, erosion, fatigue, IGSCC, ... The understanding of the development of a through wall crack has to be sought</td>
</tr>
<tr>
<td>Sweden</td>
<td>A database on defects and failures from the feed-back of experience is wished, and as a general principle, the detailed knowledge on loads is required.</td>
</tr>
<tr>
<td>Spain</td>
<td>The BWR are excluded; IGSCC, water hammer, fatigue are excluded also; thermal stratification is not forbidden as such, but need a detailed analysis</td>
</tr>
<tr>
<td>Germany</td>
<td>The Break Preclusion Concept (Fig. 1) requires the consideration of the Principle of Bounding Loading Conditions for the component design. According to the Principle of Controlled Operation the observance of these bounding loading conditions is monitored.</td>
</tr>
<tr>
<td>Slovak R.</td>
<td>Like in other countries, the influence such a phenomenon as IGSCC, fatigue, damage, water hammer and erosion are excluded too. Thermal stratification is estimated and monitored.</td>
</tr>
<tr>
<td>Slovenia</td>
<td>Presently there are no additional (comparable to US requirements) specific limitations yet due to degradation mechanisms. Unpredictable loading due to seismic event could cause some specific limitations if the LBB application take place.</td>
</tr>
<tr>
<td>Czech R.</td>
<td>Same as in the USA plus thermal stratification (piping loads for stratified conditions).</td>
</tr>
<tr>
<td>France</td>
<td>no explicit rule; in the light of the SG tube bundles case, it can be derived that even a generally rejected damage mechanism such as IGSCC can be dealt with, provided that sufficient feed back of experience is gained (through ISI, experiments, expertise of extracted tubes and replaced SGs ...).</td>
</tr>
</tbody>
</table>
In France, the «Farley-Tihange» type case at Dampierre had a major impact on the topic, namely because it affected strait pipes (and not only welding) and because it illustrated the importance of unknown loading.

5.1.2.3 Limitations due to material uncertainties

The requirements on different sets of piping systems in NPP are rather different within the high-energy pipes (class 1 and 2). At the same time, the knowledge or the possibility to gain back this knowledge (through archive material or manufacturing documentation) is also at a different level depending on this class. The design is neither as complete (e.g. for the fatigue analysis in the secondary systems of PWR). The gains from LBB in terms of doses fall partly down when considering the ISI of secondary pipes. All these point can lead to limitations on the scope of the LBB approach. And last, but not least point than provides limitation is the diameter of the pipes, because the - not so huge - feed-back of experience of piping failures in LWR around the world give evidences for the LBP to be less applicable for small diameter piping.

<table>
<thead>
<tr>
<th>Country</th>
<th>Limitations of the scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>High energy lines and only ASME code level 1 and 2 are eligible</td>
</tr>
<tr>
<td>Belgium</td>
<td>Primary loop only, because of material quality and also because of the implicit margins in the design of the supports and structures</td>
</tr>
</tbody>
</table>
| Italy   | Class 1  
|         | Class 2 high energy pipes with diam > 4"  
|         | Material requirements : KCV energy over 100 J at service temp, low concentration of impurities (B, Mn, P, S), qualification of the manufacturing processes, double volumetric control (US + X-ray), ferritic steels used at temp > RTNDT + 33°C, austenitic steels with C<0.03% (sensitisation to SCC) and □-ferrite<20% (thermal ageing), heat treatment to limit strain ageing embrittlement for ferritic steels |
| Finland | Primary circuit only because : qualification of the manufacturing process of the components and defect detection capability (better ISI) |
| Sweden  | Minimum diameter (because of leakage behaviour sought) |
| Spain   | Primary circuit (incl. Connecting lines if diam > 6")  
|         | Material : qualified forged steel pipes austenite or ferritic, the latter with fracture toughness requirements (typically : Jic min = 750 in-lb/in2, Jic max = 2200 in-lb/in2, T=60, KCU=4,3 DaJ/cm2 and delta ferrite > 5 at 600°F) |
| Germany | The Break Preclusion Concept (Fig. 1) is used for the main piping of the pressure retaining boundary and the main secondary piping installed inside the containment, in general all those with a nominal diameter 150 mm (6"). The material requirements are set as to ensure a ductile behaviour starting |
with stable tearing of the defect and the application of the plastic collapse load concept. As an example for ferritic steels, the required ductility value is AV = 68 J (ISO-V-specimen) at a temperature TNDT + 33 K.

No application; For the new EPR reactor, the situation has been judged feasible at first for the MCL (Main coolant lines of the primary circuit), and has to be based on a high quality of design and manufacturing.

For the primary circuit and high-energy pipes. Ductile behaviour of postulated defects is assured by the materials property specifications.

Submittal application is referring only to the primary loop only, ASME code class 1 lines, > 6 inches diameter.

Primary circuit only (diameter larger than 150 mm). The materials must have sufficient ductility to meet LBB needs; specific attention must be given to ISI in the case of bimetallic welds.

In every case, when applying to existing LWR, the question of the knowledge of the as-built state is crucial. Sometimes it can be dealt with archive material, which is the ideal case, and sometimes material with the former technical specification has to be created (as for example recommended by the NUREG 1061 vol. 3).

### 5.1.3 Prerequisites

The difference between prerequisites and limitations is not always very clear. A tentative separation could be made by calling the latter as regulatory principles that make the case difficult to be presented to the safety authorities and the former as conditions, that have to be included in the demonstration in order to have a potential «acceptable» case.

<table>
<thead>
<tr>
<th>Country</th>
<th>Prerequisites</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>For leak detection, the approach does not include prescriptive positions, except that a case by case analysis shall be made and the reference shall be made to Reg. Guide 1.45. (this position takes into account the general redundancy requirement for leak detection systems The demonstration (made by Lawrence Livermore National Lab) was a master piece in the process because it contributed to root the LBB procedure on low break probabilities The way to establish the convenient material properties has been defined</td>
</tr>
<tr>
<td>Belgium</td>
<td>Application of LBB to Reactor Coolant Piping System has been approved for plants originally designed against the global and local dynamic effects of postulated DEGB. Apart from that general but important point, nothing specific different from the USA approach. Three redundant systems for the leak monitoring are available on the concerned NPPs.</td>
</tr>
<tr>
<td>Italy</td>
<td>A low break probability behaviour is required, based on design stress limits and the selection of materials (according to ASME III, in other terms, nothing specific to LBB).</td>
</tr>
<tr>
<td>Country</td>
<td>Prerequisites</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Finland</td>
<td>YVL 3.5 would require a general plant-specific justification of the concept for STUK before construction of new plants. This should cover experimental verification, quality, probability, ageing, monitoring, physical separation, etc.</td>
</tr>
<tr>
<td>Sweden</td>
<td>The ISI methods for flaw detection have to be qualified. Two sensitive, independent and qualified leak detection systems have to be used. The demonstration that physical means of protection (for ISI near restraints, ...) are not feasible has to be done (i.e. the demonstration that the expected gain from the LBP procedure cannot be achieved by other means)</td>
</tr>
<tr>
<td>Spain</td>
<td>ISI and leak detection: no special requirements if the safety factors are sufficient, except in the SG tube bundle case</td>
</tr>
<tr>
<td>Germany</td>
<td>The Break Preclusion Concept (Fig. 1) is based on the already mentioned four principles. Components of plants erected after the insertion of the Break Preclusion Concept have to meet all principles in a balanced way to realise Break Preclusion. In principle, components of plants erected before the insertion of the Break Preclusion Concept and re-qualified may not meet some principles in a balanced way; they will realise the criterion Low Break Probability.</td>
</tr>
<tr>
<td>France</td>
<td>No application. For the new EPR project, some of the prerequisites expressed by the DFD are: take into account explicitly the joint feedback of experience (France and Germany), implement the adequate provisions, notably leak detection and ISI programmes.</td>
</tr>
</tbody>
</table>
| Slovak R. | For the leak monitoring are for all four units under operation used three independent methods:  
- humidity measurement  
- activity of noble gas measurement  
- acoustic emission method. For the material properties characterisation archive materials were used, or the samples cut out from pipes (during reconstruction works). |
| Czech R.  | Nothing specific from USA approach but at least two independent detection methods are required which allow to detect a leak with quantification and at least one is required which allows to detect a leak without quantification. |

### 5.1.4 Procedures
This last part of the countries’ situation lists the procedures (roughly speaking) used for the LBB demonstration, including the main hypothesis, the special focuses (on special loading, on defect postulates, on propagation aspect, on leak evaluation, etc.) and the expected safety factors for the mechanical demonstration. The aim is not here to detail the technical aspects which can be found in the part number 4 of this report, but to point out the main orientations.

<table>
<thead>
<tr>
<th>Country</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>The SRP 3.6.3 (is still a draft document) and the Nureg 1061 vol. 3 give the LBB analysis procedure. It is a conventional analysis</td>
</tr>
<tr>
<td>Belgium</td>
<td>SRP 3.6.3 including safety factors plus complementary events, plus complementary loads (cf. 5.12.2.). The moment sum is the done by absolute sum. Crack growth assessment is required. Material properties: end of life (EOL), including thermal ageing, archive material preferably used. The safety factors are identical to the USA procedure</td>
</tr>
<tr>
<td>Italy</td>
<td>The procedure is similar to the USA, except: * the loads to be considered in the accidental condition are not limited to SSE * a lower bound of the stress limit is used for the calculation in Normal Conditions (NC), so to have a sufficient crack opening to flow detecting (Leak Condition (LC)); * an upper bound of the stress limit is used for the calculations in Accidental Conditions, e.g. SSE, SRVD, Maximum Thermal Stratification (TS) etc., so to have the stability of the through-wall crack (TWC).</td>
</tr>
<tr>
<td>Finland</td>
<td>SRP 3.6.3 plus or including: * cracks at «weakest location» * loading: normal + most severe conditions (whatever the worst, e.g. SSE) * LBB analysis: validated EPFM and leak rate analysis methodology with prescribed safety factors * material: archive material reliably characterised for the relevant energy release rate regime</td>
</tr>
<tr>
<td>Sweden</td>
<td>SRP 3.6.3 plus or incl.: * all relevant loading added (vibration, thermal loading, expansion, residual stresses) * explicit procedure for the leak monitoring with clear criteria</td>
</tr>
<tr>
<td>Spain</td>
<td>* Initial crack postulates: &gt; 1.5 * thickness and leak rate prediction (with safety factor of 10) * crack growth evaluation due to fatigue * final crack stability with loading: operating + SSE or operating + MSLB or FWLB * global collapse (limit moment study) and local failure (J/T approach) * safety factors on crack size: ? for «global» analysis and 2 for «local» analysis</td>
</tr>
<tr>
<td>Germany</td>
<td>The LBB procedure itself, participating to the Break Preclusion Concept (Fig. 1), is part of the Principle of Controlled Failure Mechanisms; this principle is not outlined in codes or standards.</td>
</tr>
</tbody>
</table>
For the plants erected after the insertion of the Break Preclusion Concept, the following Siemens procedure (see Fig. 2 this chapter) has been used;
- limitation to ductile material (> 45 J) required for the application of the plastic collapse load concept;
- reference defect, which is much larger than that detectable with NDT, postulated in highly stressed regions;
- this defect will grow after several plant lives due to fatigue propagation to a stable through wall crack (TWC) length for starting leakage, 2*cLS;
- estimation of the stable TWC length for detectable leakage based on the sensitivity of the installed leak detection system, 2*cLD;
- estimation of critical TWC length for the maximum load case, usually load due to normal operation and safe shutdown earthquake, 2*ccrit;
- comparison of stable TWC length for starting leakage with critical TWC length for the maximum load case, required : 2*cLS < 2*ccrit;
- comparison of stable TWC length for detectable leak rate with critical TWC length for the maximum load case, required : 2*cLD < 2*ccrit;
- for both comparisons no prescriptive safety factors are available; the results are justified on a case-by-case basis.

France

No application.
For the EPR case, the LBB evaluation procedure has been provided to the Safety authorities, but so far as no position is issued yet, it shall not be included here.
For its industrial purpose, Framatome has developed a procedure which is quite similar to the American one, with some specific complements (in defect assessment, leak rate technology and instability evaluation).

Slovak R.

Except the SRP 3.6.3 application were in the analysis procedure included:
- the worst conditions of loading
- the postulated cracks in the critical parts and welds
- the lower bound of material properties values from archive material testing.

Slovenia

No applications.
LBB evaluation procedure has been done on the base of SRP 3.6.3 and has been provided to the Safety authorities. Safety authorities so far did not approve the implementation of the LBB concept. In the future, if the LBB would be licensed, additional to present US regulatory requirements is expected such as extensive material properties analysis, safety compensations demonstration, global safety benefits evaluation, unpredictable leak monitoring redundancy, improved ISI program, etc.

Czech R.

Same as in the USA.

5.2 Discussion of similarities and differences

This discussion wants to be only a summary of the orientations than can be derived from the above charts. It tries to be as neutral and factual as possible. The same structure will be kept for simplicity reasons, but the development of each subpart will be rather short. The general trends will be shown as well as the main differences.
5.2.1 Objectives

Generally speaking, the DEGB concept at the design stage (i.e. the one that was used for designing the plants to which an LBB analysis could be applied) is linked to the GDC-4. The advances in technology that sustain the acceptance of considering LBB cases goes from the sole aspect of fracture mechanics to the three pillars of LBB: fracture mechanics, leak detection and ISI. The leak detection part suffers from a evident lack of confidence that can be read from the high safety factors, even in the countries were a more detailed approach is used.

A very commonly expected gain is the dose reduction and the better physical access for ISI and maintenance. This point is of course more relevant for primary than for secondary lines. An implicit gain that was not cited in the questionnaires is the increase in the knowledge of the «real» plant state that is sought by a better understanding of the loading (see limitations) and a research for the «as-built» state of the plants (not for every country).

The re-evaluation of some conventional assumption of the safety analysis is rather belonging to differences, because there still are different opinions on the fact that «global» effects of the DEGB (such as blow-down on internals or reactor cavity) can be revised thanks to an LBB analysis. The lower bound acceptance is that, for countries accepting LBB cases, «local» effects can be dealt with.

None of the LBB cases applied were used for flaw assessment for indications effectively discovered during in-service inspections, and no regulatory position support this case. An explanation for this fact is that most of the discovered indications might challenge some of the hypothesis of the analysis (see limitations).

5.2.2 Limitations

For the sake of keeping the global safety, part of the regulatory does not accept that main safety functions can be impaired by an LBB analysis. This recall to the difference mentioned in the objectives about the «local» versus «global» effects that can benefit from an LBB case.

As a general rule, the regulatory bodies are willing to keep the physical separation, when existing. But the interesting question would rather be to know if an acceptable LBB analysis could replace this «hardware» defence against non aggravation of accidents.

Unpredictable loading is generally undesired (incl. non-mechanical «loading» that affect the components or material): water hammer, stratification, fatigue (e.g. Farley-Tihange type phenomena), erosion, corrosion. Some openings (e.g. for stratification or IGSCC) are done by some regulators under the strict assumption of mastering the process (loads or degradation mechanisms).

The most commonly adopted scope is the primary circuit, mainly because high quality of materials, availability of archive material or manufacturing data, important post manufacturing inspection programme were applied to the corresponding
components. The stress analysis is also more restrictive on secondary side (most of the time no fatigue analysis in the design basis). Maybe another factor is that the gain for the dose aspect is much lower on the secondary side.

5.2.3 Prerequisites

The whole range of position can be seen: from the position satisfied by the safety factors achieved in the LBB analysis with the existing systems to positions requiring sensitive means of leak monitoring and enhanced, qualified ISI or the need to report on the feed-back of experience or probabilistic aspects.

5.2.4 Procedures

Many similarities can be found such as: consideration of EOL properties, looking for high stress (or more seldom relatively weak material) regions, or the recommendations on archive material. The safety factors need can nearly be considered as a similarity, with most frequently the factor 10 on leak detection and 2 on crack size (between TWCC an LC).

But, behind these similarities, there are two main «schools» that distinguish a pure conventional approach, behind the SRP 3.6.3. (TWC with straight boards, conventional loading such as normal + SSE) and a more realistic one that add considerations to take other loading or the most stringent loading into account (compare with MSLB, add thermal stratification moments, ...) and that also add a part on the way the crack grows (through fatigue analysis).

At last, a difference also exists on the fracture mechanics schools between the global collapse and the local flaw instability (roughly speaking limit load analysis and J type approach).
input data for LBB analysis:
- material properties
- load collective
- geometry of piping & welds
- detectable crack size
- thermal hydraulic parameters
- leak detection system

Load histogram:
normal and upset condition

Crack growth of reference defect

Stable crack growth for one plant life

Through-wall crack after several plant lives

Minimum critical crack dimensions

Criterion for slow crack growth of leakage:

\[
2 \cdot c_{LS} < 2 \cdot c_{\text{crit}} \\
2 \cdot c_{LD} < 2 \cdot c_{\text{crit}}
\]

leakage detectable before reaching the critical crack length, i.e. LBB is demonstrated!

Fig. 2: Flow Diagram of the German LBB Analysis according to Siemens Procedure
6 CONCLUSIONES AND RECOMMENDATIONS OF THE REPORT

As defined in the final mandate of NRWG, this task force had for objective to establish, if possible, a “good practice document” on the application of the LBB concept (as an evolution in the design criteria) for existing plants. Therefore, the first task, which was not at all the easiest one, was to try and define this concept. After which, the usual DEGB design procedure had to be recalled in order to assess what were the possible design changes and benefits that could be derived from an LBB application. The technical substantiation was studied in a broad sense, taking into account the operating experience, experiments and analytical considerations. Although it is stemming from a regulators’ TF, the goal of this part was not to give rise to detailed acceptability factors. Then, highlighted by these considerations, the overall methodology was reviewed and the two types of procedures were identified and discussed. At last, as it is the first goal of a good practice document, the review of the current practices among several countries, including the TF members’ countries, were compared and described.

In this conclusion, the definition will not be restated; nevertheless, it will be reminded that LBB has parent definitions to be found in different countries, such as LBP and BP. The differences, that can be seen from the charts in chapter 5 for example, are of course due to historical aspects, but technically speaking, they are based on a different priority given by the regulatory body or the industry to certain aspects of the concept. (Prevention, mitigation, surveillance, ...)

It must also be noted that, as it can be seen from the detailed review of chapter 5, some countries have given a regulatory status to the LBB - or comparable - concepts, and some have not. As for the point mentioned here above, there are many reasons for these differences, not all of them being purely technical: no proposition from the industry side, propositions in different terms (use of the LBB application for operating aspects, which is different than using it for design basis changes), assessment in progress, conventional position taken by the regulatory body for plenty of reasons that can not be judged in the frame of this work. Therefore, the TF can only underline that there is a diversity in the regulatory status, that cannot be linked with the actual state of the plants.

6.1 Impact on design basis

The original design criteria for most western LWR plants treated the DEGB as an event, constituting the worst bounding condition for the design of safety systems and single components. This practice relied on contemporary knowledge and technology and prompted installation of massive hardware to protect safety-related components in the vicinity of the affected piping systems. DEGB as an initiating event in the plant has two type of consequences: locally induced effects (cope with “local” features such as whip restraints, physical arrangement and separation, jet impingement shields, ...) and globally induced effects (containment, safety injection system, environmental conditions).
Therefore, for plants not designed with DEGB, the application of the LBB concept can be regarded as a safety assessment of the design concept, and could lead to actions improving the actual plant safety.

The motivation of the LBB application is mostly pushed by the industry side: in the frame of re-assessments for making acceptable changed operating conditions or for changing maintenance conditions (whip restrains removal, snubbers’ reduction, gains in personnel doses and accessibility).

Applying LBB concept, for a given design, lead as a first consequence, to a decrease in the amount of mitigating safety features. Therefore, compensations must be acquired on the prevention side, namely that LBB “qualification” must be demonstrated through:

- a good knowledge of the state of the plant (as-built, as-operated, as-surveyed conditions);
- the verification of the coherence with the technical substantiation of LBB;
- a maintained attention on degradation mechanisms on the plant components.

If necessary, shall parts of these conditions not be met, the necessary modifications to physical circuits, surveillance systems or maintenance programmes shall be made.

The TF reminds that the general prevention/mitigation balance is the main tool to assess the acceptability of an LBB application and notes that this balance might stay acceptable under the enforcement of the adequate compensations and the observance of strict prerequisites.

Nevertheless, the LBB “qualification” cannot be used to allow leaks during operation, namely because leaks in the circuits might be safety challenging (e.g.: Small break LOCA is an initiating condition for pressurised thermal shock on reactor pressure vessel).

6.2 Technical substantiation

TF notes that, if high design and manufacturing standards are applied, a positive feedback of experience exists, the relevance of which increases with pipe diameter. Nevertheless, the assessment of the character towards LBB of a leak or break event shall be assessed very precisely on a case by case basis.

In the feedback of experience, degradation mechanisms not covered by the design codes play a significant role, meaning that attention has to be kept on the plant, (even after an LBB application). Always in this feedback analysis, the leak rate assessment of arisen events shows a great scatter.

From the miscellaneous experiments carried out worldwide, it was the opinion of the TF that high (proven) quality piping show a considerable load carrying capacity even when deeply flawed.
The TF underlined the interest for these experimental data, in particular to qualify the procedures in different loading conditions, and noted that reliable information was seldom available for organisation not taking directly part in the experiments’ groups.

6.3 Limitations of LBB application

The LBB concept is not a “miracle solution” suitable to cope with every type of deficiency. The TF has identified some kind of situations where it can not be reasonably recognised as applicable, e.g.:

- poorly defined service conditions;
- ageing mechanisms or crack growth not understood or not coherent with LBB hypothesis (e.g.: large crack growth extending circumferrentially before longitudinally).

Therefore, the TF thinks there is a need to identify properly in the feedback of experience the conditions that might affect LBB hypothesis such as new degradations, operator actions leading to unspecified service conditions.

With respect to defence-in-depth concept, the TF noted that for certain safety features (e.g.: safety injection system, containment) no credit shall be taken from LBB application. For local features (e.g.: whip restraints) a greater potential is seen, some countries wishing to keep different postulates in the changed designed basis.

6.4 Procedures

The TF has noted that, as regards the confidence on the reliability of the piping, main primary loop was the usual scope for LBB application.

The TF has identified two major types of procedures for LBB assessment. The first type is a “conventional” demonstration, based mainly on the load carrying capacity of the flawed pipe and the detection capacity of the systems. The second type “modified” roots on the assessment of the pipe degradation mode (mainly fatigue) and a more detailed description of the evolution of the potential flaw through the pipe before stability assessment. The choice among the two modes is not unique, the TF has provided in chapter 4 elements about their respective advantages and drawbacks, especially linked with the potential degradation modes.

6.5 LBB implementation

Taking into account all the aspects mentioned here above, TF estimates that a strict observance of all prerequisites already gives good implicit safety margins to an operating plant. Nevertheless, depending on the assumptions, safety factors would be preferably set. The current practice on this subject being to put them on leak rate and flaw size.
Concerning some of the hypothesis underlying those demonstration, the TF thought that it would be wise to require a leak detection redundancy, especially regarding the state of the art of leak rate calculation.

But, in every case, beside LBB procedures, in-depth knowledge of the plant stress state and thorough monitoring and ISI are important aspects to ensure the integrity guarantee throughout the life time of the plant.
**ABREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>BP</td>
<td>Break Preclusion</td>
</tr>
<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
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<tr>
<td>DBA</td>
<td>Design Basis Analysis</td>
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<tr>
<td>DEGB</td>
<td>Double Ended Guillotine Break</td>
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<td>EOL</td>
<td>End of Life</td>
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<tr>
<td>EPR</td>
<td>European Pressurised Water Reactor</td>
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<tr>
<td>FSAR</td>
<td>Final Safety Analysis Report</td>
</tr>
<tr>
<td>IGSCC</td>
<td>Inter-Granular Stress Corrosion Cracking</td>
</tr>
<tr>
<td>ISI</td>
<td>In-Service Inspection</td>
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<tr>
<td>LBB</td>
<td>Leak Before Break</td>
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<td>LBP</td>
<td>Low Break Probability</td>
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<td>LOCA</td>
<td>Loss of Coolant Accident</td>
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<td>MCL</td>
<td>Main Coolant Line</td>
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<td>NDE</td>
<td>Non-Destructive Examination</td>
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<tr>
<td>NDT</td>
<td>Non-Destructive Testing</td>
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<tr>
<td>NPP</td>
<td>Nuclear Power Plant</td>
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<td>NRWG</td>
<td>Nuclear Regulators’ Working Group</td>
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<td>NSSS</td>
<td>Nuclear Steam Supply System</td>
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<td>PWR</td>
<td>Pressurised Water Reactor</td>
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<td>PSA</td>
<td>Probabilistic Safety Analysis</td>
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<tr>
<td>RPV</td>
<td>Reactor Pressure Vessel</td>
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<tr>
<td>SG</td>
<td>Steam Generator</td>
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<tr>
<td>SIS</td>
<td>Safety Injection System</td>
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<tr>
<td>TF</td>
<td>Task Force</td>
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<tr>
<td>TWC</td>
<td>Through-Wall Crack</td>
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