IAEA-TECDOC-774

Guidance for the application of the leak before break concept

Report of the IAEA Extrabudgetary Programme on the Safety of WWER-440 Model 230 Nuclear Power Plants

INTERNATIONAL ATOMIC ENERGY AGENCY

The IAEA does not normally maintain stocks of reports in this series However microfiche copies of these reports can be obtained from

INIS Clearinghouse
International Atomic Energy Agency
Wagramerstrasse 5
P O Box 100
A 1400 Vienna Austria

Orders should be accompanied by prepayment of Austrian Schillings 100 – in the form of a cheque or in the form of IAEA microfiche service coupons which may be ordered separately from the INIS Clearinghouse

The originating Section of this document in the IAEA was

Safety Assessment Section
International Atomic Energy Agency
Wagramerstrasse 5
P O Box 100
A-1400 Vienna, Austria

GUIDANCE FOR THE APPLICATION OF THE LEAK BEFORE BREAK CONCEPT

IAEA, VIENNA, 1994
IAEA-TECDOC-774
ISSN 1011–4289

Printed by the IAEA in Austria
November 1994

FOREWORD

The IAEA initiated in 1990 a programme to assist the countries of eastern Europe and the former Soviet Union in evaluating the safety of their first generation WWER-440/230 nuclear power plants The main objectives of the Programme were to identify major design and operational safety issues to establish international consensus on priorities for safety improvements, and to provide assistance in their implementation

The scope of the Programme was extended in 1992 to include RBMK and WWER-1000 plants in operation and under construction The Programme complements ongoing IAEA activities on WWER-440/213 plants

The Programme is pursued by means of plant specific safety review missions to assess the adequacy of design and operational practices, Assessment of Safety Significant Events Teams (ASSET) reviews of operational performance reviews of plant design including seismic safety studies, and topical meetings on generic safety issues Other components are follow-up safety missions to nuclear plants to check the status of implementation of IAEA recommendations, assessments of all safety improvements implemented or proposed, peer reviews of safety studies, and training workshops The IAEA is also maintaining a database on the technical safety issues identified for each plant and the status of implementation of safety improvements An additional important element is the provision of assistance by the IAEA to strengthen regulatory authorities

The Programme is extrabudgetary and depends on voluntary contributions from IAEA Member States Steering Committees provide co ordination and guidance to the IAEA on technical matters and serve as forums for the exchange of information with the European Commission and with other international and financial organizations

The Programme, which takes into account the results of other relevant national bilateral and multilateral activities will provide a technical basis for safety related decisions to be made by the countries operating WWER and RBMK plants and by countries providing technical and financial support for upgrading the safety of nuclear power plants in these countries

The IAEA further provides technical advice in the co-ordination structure established by the Group of 24 OECD countries through the European Commission to provide technical assistance on nuclear safety matters to the countries of eastern Europe and the former Soviet Union

The present document provides guidance for the application of the leak before break concept, which is a generic safety issue of WWER-440/230 NPPs

PLEASE BE AWARE THAT
ALL OF THE MISSING PAGES IN THIS DOCUMENT
WERE ORIGINALLY BLANK

EDITORIAL NOTE

In preparing this document for press, staff of the IAEA have made up the pages from the original manuscript(s). The views expressed do not necessarily reflect those of the governments of the nominating Member States or of the nominating organizations

Throughout the text names of Member States are retained as they were when the text was compiled

The use of particular designations of countries or territories does not imply any judgement by the publisher, the IAEA, as to the legal status of such countries or territories, of their authorities and institutions or of the delimitation of their boundaries

The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA

CONTENTS

1. SAFETY SIGNIFICANCE OF THE APPLICATION OF THE LEAK BEFORE BREAK CONCEPT FOR WWER 440/230 NPPs

The first generation WWER-440/230 NPPs were designed in the late 1950s and 1960s and the design was based on regulations codes and standards in force at that time The main reactor components were produced as required in special documentation Requirements for the safety of NPPs were formulated for the first time in 1973 in the former USSR (OPB 73)

The safety concept of the WWER-440/230 NPP is basically preventive, ensuring high operational availability The design basis required that there should be no loss of primary circuit integrity resulting in significant deterioration of core cooling with severe core damage Therefore, the primary circuit was manufactured using forged parts with the exception of the bodies of the cast austenitic pump and the main isolation valves The primary piping was made exclusively from austenitic stainless steel On the basis of this and other provisions the plant was designed with an ECCS which is able to cope only with limited scope of breaks and without an appropriate confinement system

A large pipe break in a WWER 440/230 plant would result in the loss of two main safety functions cooling the fuel and confining the radioactive material Therefore, in the framework of the IAEA s activities to review the safety of WWER-440/230 NPPs, the applicability of the leak before break (LBB) concept was identified as an issue of major safety significance The leak before break concept is a tool to provide early warning before major break in primary piping could develop Successful application of the LBB concept is a must to justify further operation The LBB concept is required to restore some features of the original safety concept from the current point of view on maintaining primary circuit integrity It is the only feasible approach on providing reduction of the probability of primary breaks which the plant design is not able to cope with

Based on the high safety significance of the LBB concept for WWER-440/230 NPPs the IAEA has dedicated significant effort to this important issue in order to assist countries operating these first generation WWERs A status report on the Applicability of the Leak Before Break Concept was published as IAEA TECDOC 710 [1] in 1993

This document provides additional guidance on application of the LBB concept to WWER 440/230 NPPs and complements the IAEA TECDOC 710 The objective of the report is to describe in detail the elements of the LBB concept, the necessary support as well as the condition to be fulfilled, and the verification programme It should also provide a clear picture of all the activities and resources needed to implement the LBB successfully as a comprehensive concept

To apply the LBB concept, one has to demonstrate that crack growth is not unstable under the relevant load spectrum including seismic loads and additional ones which result from an extended spectrum of accidents to be coped with A comprehensive LBB analysis should be performed based on primary circuit stress and fracture mechanics recalculations Material data, in particular at critical sections of the primary circuit, have to be experimentally evaluated as well as assumptions on the component behaviour with cracks under dynamic load conditions validated An efficient in service inspection system based on non destructive methods has to be used to detect cracks in austenitic steel And, finally, leak detection systems have to be installed and calibrated

In addition, provisions should be taken to maintain the conditions of the concept during operation, i.e. in-service inspection, maintenance, and surveillance procedures need to be modified or developed where applicable and adhered to.

Successful application of the LBB concept to the WWER-440/230 NPPs will take time even if it is restricted to the most critical part of the primary circuit. Therefore, there is an urgent need to initiate activities related to the application of the LBB concept as a compensatory measure to justify further operation of WWER-440/230 reactors.

For major upgrading of the WWER-440/230 plants, benefit from successful application of the LBB concept may be taken into consideration. For this purpose the risk reduction potential of the LBB concept application needs to be evaluated. Leak before break behaviour of main piping may modify the load spectrum on which re-design of confinement should also be based.

It is important to note that breaks in primary piping not covered by LBB concept and in secondary piping could have a negative impact on the primary circuit integrity where the LBB concept applies. It is not a recognized practice to apply the LBB concept to secondary and small diameter primary piping, however, special care should be taken to demonstrate its integrity. This integrity demonstration should concentrate in particular on the sections in which a break would contribute most significantly to the risk.

Further, it has to be noted that this document does not substitute for a detailed work programme or procedure to implement the LBB concept.

2. BACKGROUND

The basis of the LBB concept is a demonstration that a primary circuit would leak significantly before a double ended guillotine break (DEGB) occurs. This is achieved by quantifying and evaluating the process of loss of integrity and accompanying leaks and prescribing safe shutdown of the plant on the basis of the monitored leak rate. A postulated through-wall circumferential cracks located at critical sites, usually welded joints, in the circuit are used in the analysis. A primary circuit which meets the LBB requirements [2–6] will have a low probability of a large LOCA (less than 10^{-6} per reactor year) [2].

It has been recognized that WWER-440/230 NPPs require modifications and backfitting in order to upgrade safety. In the primary circuit of these plants modifications are required of e.g. coolant leak monitoring, arrangement of viscous dampers and of supports to meet the 'leak before break' (LBB) status as defined in a US NRC document [2] or in the German RSK Guidelines [3] and more recently in a Japanese document [4].

The LBB concept, according to the approach adopted by the former Czechoslovak Atomic Energy Commission, which issued respective regulatory requirements [5], has been applied to the WWER-440/230 Bohunice plant. The experience from this study and discussions with western experts were used as a basis for the first draft of this document, which aims at providing the overall strategy for development of the LBB status for WWER-440/230 plants.

The LBB approach was also considered at Kozloduy plant within the framework of international co-operation. At present the development of the procedure for application of the

LBB concept for piping is under way in Russia where it is planned to include it in the standards The LBB approach as outlined in this document is in principle also applicable to WWER-440/213 and WWER 1000 plants piping

The LBB approach described in this document consists of three programmes basic, supporting and verification

The basic programme provides for evaluation of the actual safety margins and their comparison with the prescribed safety margins [2] It is a good and proven practice to summarize the results in the format of a 'LBB Handbook' (see also Annex III) In addition it is required to demonstrate that there is no significant fatigue corrosion and other unspecified loading [2]

The input data for the basic programme analysis are provided by the supporting programme This means specifically material properties analysis of accident situations response of the pipework to the accidents in terms of local bending moments and axial forces and leak rate analysis This programme includes also the evaluation of leak rate diagnostics If the requirements [2] in terms of prescribed margins are not met hardware modification or other measures need to be implemented e g dampers

To validate the results obtained (e g presented in the LBB Handbook), a verification programme is outlined Both integrity and leak rate experiments with the full size models of identical materials and weldments are recommended to be included in this programme

The documentation resulting from this approach should be submitted to the regulatory authority with an application to grant LBB Status' to the primary circuit of the plant under consideration

Annex I to this report provides a summary of British Canadian French, German and Japanese views on the applicability of LBB concept Annex II provides detailed information on the contents of each of the LBB analysis elements

A practical illustration of the approach described in this document is given by a simplified example from the LBB project for the WWER 440/230 Bohunice NPP Unit 1, presented in Annex III

3. BASIC PROGRAMMES

3 1 METHODOLOGY

Essential part of the LBB programme is the evaluation of conservative estimates of margins with respect to specific types of crack advance that could lead to DEGB Only postulated through wall cracks should be taken into account in this analysis The resulting estimates could be presented in a comprehensive format (e g LBB Handbook) where, for each given critical section of primary circuit piping, a set of margins estimated should be summarized A preliminary list of critical sections should be established on the basis of conventional stress analysis and the knowledge of material properties In order to guarantee that all critical sections are included a broader list of critical sections should be considered initially in the evaluation The margins estimated should be compared with those given e g in the US NRC Standard Review Plan, 3 6 3 Leak Before Break Evaluation Procedures [2]

Evaluation of some additional margins is recommended to provide an insight into the behaviour of the components These additional margins are not part of the requirements specified in Ref [2] In Annex III an example is given in practical terms

The parameters to be presented for each critical section in the LBB Handbook are as follows

F^L(index) – ratio of the load for given type of crack advance to the superimposed normal operation condition (NOC) and safe shutdown earthquake (SSE) load The 'index' in brackets describes the type of crack advance (crack initiation after blunting and specific increments of stable tearing) to which the coefficient is related The following indexes should be considered

- i – crack initiation after blunting,
- g – crack growth up to the maximum valid J value when measured on the standard test specimens,
- m the smaller of the crack length up to the limit where the J resistance curve extrapolation is still valid and of the crack length at the onset of the instability after stable growth,

F^L(p) – seismic load safety factor, indicating how many times the SSE load may be increased (other load components being constant) until the plastic collapse load is reached,

l_{leak} – postulated through-wall circumferential crack length pertaining to the leak rate of 38 L/min under normal operation conditions,

l_p – postulated through-wall crack length pertaining to plastic collapse

It is recommended to use widely recognized and validated procedures for limit load, crack initiation and crack growth evaluation such as Refs [6–10]

In order to demonstrate the conservatism of the approach adopted it is further recommended to verify the results obtained using different approaches given in Refs [6–10]

For the leak rate calculation the use of a validated and qualified code is required (e g such as PICEP [11])

The following limits are obligatory

- a coefficient of 10 on the calculated leak rate This means that the leak rate of 38 L/min is considered instead of 3 8 L/min for the calculation of l_{leak} by the code above,

  $l_p/l_{leak} \geq 2$,

- $F^L(m) \geq 1$ or 1 4, according to the type of summation of loads (for details see e g Ref [2])

The conservatively estimated margins should be summarized in the LBB Handbook for two reasons First, to indicate whether the quantitative conditions required are met, e g

Ref [2] Second to document and illustrate criticality of the selected sections from the point of view of LBB, these sections may differ from those identified in the dynamic design analysis

3 2. FATIGUE DAMAGE ANALYSIS

It is required to demonstrate that fatigue crack growth is not significant

In the preselected critical sections a circumferential part-through crack should be postulated The aspect ratio of the crack is six and remains constant throughout the fatigue growth analysis The considered crack size should be taken as the maximum allowable crack size according to the IWB-3640 of Section XI of the ASME Boiler and Pressure Vessel Code

However, if other national standards or codes are used, it should be demonstrated that the results obtained are conservative as compared to the approach above

The maximum allowable crack depth after the growth is the smaller of

- 60% of the wall thickness, or
- the depth at which the plastic zone is equal to the remaining ligament

The ultimate length of the crack must be less than 1/2 of the plastic collapse crack length under the superimposed normal operation and accident loading

If these limits cannot be met, the LBB concept is not applicable to the system analysed

For the growth analysis of the postulated crack both the analytical loading cycles and the loading time history from the service should be taken into account The rain-flow method is recommended for the analysis of loading cycles The linear summation rule is used for the calculation of damage A detailed procedure for the fatigue evaluation is given e g in Ref [13]

3 3 CORROSION DAMAGE ANALYSIS

It is required to demonstrate that corrosion and stress corrosion effects do not contribute significantly to the total damage of the system analysed

Material tests must be carried out for all typical materials and material combinations of the system analysed base material, weld material and material compositions of dissimilar welds e g the RPV safe end In particular, it is necessary to demonstrate that

(a) There is either no crack initiation or the growth of the initiated cracks is negligibly small The crack growth rate is considered sufficiently small if the cracks do not reach the critical size between two regular inspections Typical acceptable rates are of the order of 10^{-10} to 10^{-9} m/s (see e g Ref [14])

(b) The growth rate of initiated cracks is not greater than 10^{-9} m/s for the stress intensity factors which pertain to the normal operation conditions and a crack length up to l_{leak}

(c) Crack growth under slow loading does not exhibit an instability for specimens loaded in the primary circuit water

(d) The dependence of crack growth on the cyclic amplitude of stress intensity factor of austenitic steels does not exceed the one assumed for the given component material and operational conditions To demonstrate conservatism consideration should be given to comparison of the results with the internationally recognized data Cycle asymmetry coefficient (R ratio) should be taken into account

(e) None of the materials is susceptible to intergranular corrosion cracking and the corrosion wear is negligible

For the above mentioned tests, analysis of the real operational water chemistry regimes for the system analysed is required The analysis must provide information about the number and the extent of deviations from standard values in pH and the concentrations of oxygen and hydrogen If the deviations are significant tests must be carried out in the standard chemical environment and in the extreme environment

4 SUPPORTING PROGRAMMES

The supporting programmes described in Sections 4 1–4 6 provide the inputs for the basic programmes

4 1 MATERIAL DATABASE

The material data required are the fracture resistance J Δa and the tensile properties both at room temperature and at the maximum operation temperature (where special care should be taken to ensure that the results are conservative for a given case) From these properties the following quantities are needed for the LBB evaluation

– the initiation and the maximum valid values of J as well as the best fit linear regression constants for J Δa curve

  yield stress and ultimate stress and the best fit linear regression constants for the tensile curve

Fracture mechanics and tensile tests shall be carried out according to recognized standards

The thickness of the test specimens for the fracture resistance J Δa tests must be sufficient with respect to the actual thickness of the pipe wall or its representativeness should be demonstrated (constraint effects) Material properties should be evaluated in two perpendicular directions

To obtain complete information about material properties complementary Charpy impact testing should be considered Material showing brittle type of fracture at operating temperature (impact energy below 49 joule) could not be accepted for LBB applications

Special care should be taken in order to evaluate properties of dissimilar welds Evaluation should include identification of the weakest section and should be based on tensile, charpy impact and fracture mechanics testing

It is also recommended to complement the evaluation of welds in particular by metallographic and fractographic examinations

Adequate documentation on the evaluation, results, materials source (archive, equivalent, model), etc is required A computerized database is recommended for this purpose

4 2 STATIC AND SEISMIC ANALYSIS

The purpose of the analysis is to evaluate

(a) bending and torsion moments axial and shear forces,
(b) membrane, bending and shear stresses in all weldments
(c) the reactions (forces and moments) in hinges, supports and anchorages

In the static analysis, the internal pressure, deadweight and thermal expansion should be taken into account For the seismic analysis it is mandatory to take into account the safe shutdown earthquake intensity

Only verified codes should be used in order to meet the QA requirements The following values of input quantities are recommended for the seismic analyses

Ground response spectrum	84% non-exceeding probability of site specific spectrum
Structural model	Best estimate with soil-structure interaction
Soil-structure interaction	Develop expected parameter variation
Floor spectra generation	Frequency shifting of floor spectra rather than peak broadenings
Piping model	Complex dynamic model of loops Nos 1-6 including connected feedwater steam and other piping
Damping	5%
Modal combination	Square root of the sum of the squares
Closely spaced modes	10% method according to RG 1 92 [15]
Frequency range	Up to 30 Hz lower value is permitted if the calculated stresses are not influenced

The bending and torsion moments, axial and shear forces (item a) should be used as input data (see Section 3 1) The reaction forces and moments (item c) are needed for the assessment of heavy components stability (see Section 4 4)

WWER 440/230 NPPs were designed for SSE 5° MSK 64 At individual units seismic upgrading of the main circulating piping and all safety significant components is completed, under way or planned The unit specific seismic loads evaluation is recommended However, if this is not applicable, conservative generic approach could be used, e g the seismic margin assessment (SMA) methodology [2] for evaluation of components seismic capacity These procedures have been developed independently by the Lawrence Livermore National Laboratory (LLNL) under US NRC funding and by the Electric Power Research Institute (EPRI) The characteristic feature is the evaluation of the 'seismic margin' in terms of the high confidence of low probability of failure (HCLPF) capacity value' This is a conservative representation of capacity and corresponds to the earthquake level at which it is extremely unlikely that loss of shutdown capacity or core damage will occur From a mathematical point of view it may be defined as the mean peak ground acceleration (PGA) value for which there is 5% probability of failure at 95% confidence The HCLPF capacity is calculated for the components, systems and plant

For WWER-440/230 plants the EPRI methodology may be recommended The following steps have to be carried out for piping systems

- stress analysis as in item (b) above,

- screening of the maximum stressed welds

  - the reactor pressure vessel safe ends,
  - the steam generator hot elbow,
  - the pressurizer surge lines nozzles and safe-ends
  - the steam generator feedwater nozzle

  the evaluation of HCLPF capacity,

- the comparison of calculated HCLPF capacity with SSE peak ground acceleration value In the case when

$$HCLPF < A_{SSE}\ (PGA)$$

corrective measures in upgrading of piping systems are needed The symbol A_{SSE}(PGA) denotes the peak ground acceleration for the SSE.

4 3 ANALYSIS OF WATER HAMMER

Water hammer (WH) effect consists of hydraulic pressure wave effects caused by rapid changes in coolant flow The changes may be for example initiated by

(a) fast motor operated isolation valve action (not applicable to the WWER)
(b) sudden main circulating pump (MCP) shaft failure,
(c) phase changes from liquid to steam and vice versa

Water hammer caused by any of these conditions can be categorized into two groups *First, the anticipated or analysed group* In these cases, the effects are taken into account in the stress analysis as well as any LBB consideration

The second category is the unanticipated WH which should be addressed by evaluating the probability of occurrence If the probability of this event is extremely low WH can be neglected

For the WWER 440/230 type reactor only the anticipated WH is analysed and the above item (b) is taken into account An unanticipated WH for PWR plants is evaluated on the basis of accumulated operational experience only No unanticipated WH (item c) has been reported in the operational history of the WWER-440/230 plants therefore this event needs not to be considered

Prior to performing the analysis of the sudden MCP shaft failure loading, the event should be classified as normal, upset, emergency or faulted" Since the event falls into emergency or faulted conditions, there is, according to the ASME Code Section XI, no need for a fatigue flaw growth evaluation

For flaw stability calculations (Section 3 1) the following scenario is valid

water hammer on SSE	**load combinations**
non-concurrent	the larger of the SSE and WH loads
concurrent	1 5 times square root of the squares of the SSE and WH loads

The following method can be used for the evaluation of WH loads

- the solution of pressure waves propagation from MCP to the reactor in the nozzle and MCP to steam generator outlet nozzle directions,
- description of the RPV and steam generator motion,
- analysis of the attached primary piping induced stresses;
- comparison of the WH and SSE stresses,
- flow stability calculations if WH is larger than SSE

In general, the water hammer would occur after the seismic event has finished Also, since SSE loading is fairly large, the WH is not anticipated to exceed the SSE Note that this assumption must be submitted to verification before the events can be considered uncoupled in any analysis

4 4 STABILITY OF HEAVY COMPONENT SUPPORTS

The purpose of this analysis is to demonstrate that the events mentioned below are remote causes of pipe rupture under normal operation conditions and the SSE The events are

- RPV support failure,
- main circulating pipe support failure,
- pipe supports failure,
- pipe hangers failure,
- failure of snubbers or viscous dampers (if they are used)

The high confidence of low probability of failure (see Section 4 2) is recommended for the analysis The acting moments, forces or stresses must be taken from the complex model of the piping

The following elements and details are mandatory for the evaluation

RPV	the biological water shielding tank and reactor pressure vessel fixing elements The acting forces consist of two components — attached

	piping system (static and seismic parts) and reactor pressure vessel (only inertial forces and moments induced by SSE)
main circulating pump	all three legs of MCP casing
steam generator	capacity of installed snubbers or viscous dampers fixing screws,
pressurizer	all supporting legs, conical shell and weldments of fixing wedges If the viscous dampers or snubbers are used as clamping of the vessel, the capacity of it must be evaluated,
snubbers or viscous dampers	if used for piping upgrading, the capacity and the fixing screws must be evaluated

4 5 LEAK RATE CALCULATIONS

For the leak rate calculations a validated and qualified code should be used, such as PICEP [11] code described below

The PICEP code analysis uses the modified Henry non-steady flow model and the input parameters are in a range of subcooled water to two-phase mixture The expansion process for low vapor content is considered as non steady. The model takes into account crack face friction and the change of crack opening area from the internal to external pipe surfaces The decrease of pressure is caused also by the influence of crack kinking of 45 to 90 degrees which is also taken into account in the analysis The following simplifications are used in the calculation

- flow is assumed to be adiabatic and one dimensional,
- flow is assumed to be homogeneous
- heat exchange between the flow and the surroundings is neglected
- the liquid is assumed to be incompressible,
  non equilibrium "flashing" mass transfer between liquid and vapour phases are modelled

4 6 LEAK DIAGNOSTICS

Leak detection systems have an important role in the LBB concept The required response period should be 1 hour or less and the sensitivity of the detection systems 3 8 L/minute or less The leak detection systems are based on the processes that accompany leak i e vibration, increase of humidity due to the evaporated coolant, increase of activity

In order to provide reliable leak detection, a minimum of 3 independent leak detection systems, meeting the usual redundancy and diversity requirements, have to be installed The performance of these systems have to be validated for all regimes of operation

Detection systems already implemented in some of the WWER power plants are based on

(a) fluid level measurement in the drain
(b) radioactivity of the air
(c) condensate volume measurement in ventilation filters,

(d) measurement of temperature and humidity in hermetic boxes near the critical piping sections
(e) measurement based on the acoustic emission signal

The methods (d) and (e) are partially or well suited for the location of the leakage

5. VERIFICATION PROGRAMMES

The purpose of verification programmes is a demonstration that the estimates used for the evaluation (LBB Handbook) are consistent and conservative The verification should cover both integrity (i e crack behavior predictions and actual values) and leak rate (comparison of calculated and actual leak rates)

Examples of the verification experiments related to integrity are described in Sections 5 1 and 5 2 In this case crack opening displacement (COD) predictions are tested which are an input for leak rate calculation Section 5 3 describes the leak rate tests with cracks generated by fatigue

5 1 LARGE SCALE EXPERIMENTS STAGE I

Stage I experiments refer to crack initiation and to real loading conditions The objective of Stage I is to demonstrate for a circumferential through wall crack located at a critical site, with a calculated leak of 38 L/minute and at normal operational conditions that there is no DEGB under the superimposed safe shutdown earthquake loads The through wall crack is introduced into a full size model of the real material The geometry and loading conditions of the models tested must be close to those of the plant In particular, internal pressure and bending moment must be applied simultaneously, if possible at plant operating temperature The through wall crack is sealed in such a way that the crack tip field is not influenced The model is heated and pressurized up to the normal operation pressure Subsequently, the bending moment is increased up to the predicted response to the SSE On safety grounds the test is terminated when crack initiation occurs even if the required bending moment was not reached The crack initiation should be indicated by the direct current potential drop and/or acoustic emission methods

The crack opening displacement is measured by the use of special gauges up to the load levels of normal operation conditions This information is useful for the verification of the crack opening area estimates The temperature and stress distributions are checked by thermal and strain gauges

5 2 LARGE SCALE EXPERIMENTS STAGE II

Stage II experiments focus on stable crack growth to quantify the safety margins Stable crack growth may represent a significant margin between crack initiation and the DEGB A conservative estimate of this margin is given from the $J_{\Delta a}$ fracture resistance curve measured on standard test specimens

The real crack growth data are obtained from through wall cracks machined into the critical section of the models (for practical reasons slightly longer than in Stage I) The model is quasi statically loaded by an applied bending moment up to 40 mm or more of stable crack growth The crack length versus load data are recorded The conservatively predicted and actual crack growth are compared and documented in the failure assessment diagram of the R6 method [7]

5 3 LEAK RATE TESTS

The purpose of the test is a comparison of the calculated predictions with the measured leak rates and verification of reliability of the commercial leak rate testing systems which are to be used at the plant as a part of the LBB concept

The US NRC Standard Review Plan [2] requires three independent leak rate measurement systems to be applied to the primary pipework Although other leak detection systems exist (see Section 4 6), only the acoustic emission (AE) method appears to be sufficiently sensitive both to crack location and to leak rate measurement Before applying a system to a plan pipework, verification tests must be carried out In these tests, the AE gauges are applied to a representative model without the verifier (operator) being informed of the exact location and size of the crack

6 FORMAT OF THE LBB DOCUMENTATION

The objective of the LBB documentation is to present to the regulatory authority the case for granting LBB status to the primary circuit of the nuclear power plant considered The format of the documentation should be such that it presents the relevant information, conclusions and supporting evidence in a clear and concise manner

The document should contain the following sections

(a) description of the pipework for which the LBB status is requested
- description of the materials and the tensile and fracture properties,
- description of fabrication of the pipework, including details of the weldments
- defect inspections and their results
- description of anti seismic measures

(b) conclusions on site specific seismic studies

(c) corrosion damage

(d) fatigue damage

(e) a document summarizing evaluated and prescribed safety margins (LBB Handbook),

(f) leak rate diagnostics, description, sensitivity assessment and calibration,

(g) quality assurance documentation

The document should also be provided with an annex containing all the final reports from the basic, supporting and verification programmes

Annex 1

SUMMARY OF VIEWS OF VARIOUS COUNTRIES ON APPLICABILITY OF LBB

CANADA

The LBB concept has been successfully used for the large diameter pipes in the primary heat transport circuit of the Darlington NPP (CANDU) to obviate the need for pipe whip restraints

FRANCE

The LBB concept is not used formally Existing regulations are designed to ensure either that fracture will not occur (RPV and superpipe) or that the rupture of a large diameter (500 mm) pipe can be handled (pipe whip restrain systems and ECCS) The former case is supported by periodic inspections

GERMANY

The general concept for break preclusion, simmilar to but not identical to LBB, is used for nuclear piping systems It consists of two elements namely basic safety and independent redundancies The applicability of the concept was discussed and accepted by the German authorities

JAPAN

The regulatory body has completed the discussion on LBB guideline to be applied to stainless steel pipe of the primary heat transport circuit in both PWRs and BWRs This guideline has not yet been arranged as the open regulation However, the regulatory body approved the application of this guideline to some PWR plants The purpose is to allow removal of pipe whip restraint structures There is no plan to apply LBB to BWRs at present, although regulatory guidelines will apply to both For carbon steel pipes LBB guidelines have not yet been drafted

UNITED KINGDOM

The LBB concept has been used in the case of the Magnox reactors to justify plant life extension particularly in respect to the RPVs For the Prototype Fast Reactor LBB is used on a case by-case basis as one of several safety arguments to justify continued operation of components where cracking is known to have occurred The UK has played a prominent role in developing LBB methodology as part of the design envelope for the European Fast Reactor

Annex II

ELEMENTS OF AN LBB ANALYSIS

In the following, information on the necessary elements of the LBB analysis is provided For each of the elements required scope of the analysis is given along with related recommendations Those cases, where approaches in Member States differ considerably or relevant information is not available, are discussed for each element in the subsections "Aspects of non-compliance The cases where plant specific aspects have to be taken into account, are also indicated

II 1 STATIC AND DYNAMIC CALCULATIONS

II.1.1. Scope

1 Seismic fragility assessment procedure
2 Verification of computer codes used
3 Number of static and dynamic models with and without anti seismic measures
4 Floor response spectra
5 Number of eigenfrequencies shape loadings
6 Frequency range
7 ZPA (zero peak acceleration) effect
8 Summation of very near shape loadings

II.1.2. Recommendations

1 SMA/HCLPF seismic fragility assessment procedure should be used

2 By using IPIRG 3rd Round Robin Problem No 2 to predict the response of experimental pipe loop

3 Following models are suggested
MCL + SL (3) + FWL + StL
MCL + SL (2) + FWL + StL
MCL + FWL + StL with respect to symmetry (2)

Without anti-seismic measures to determine
Static expansion F, M + Fatigue damage
Dynamic F, M → Seismic fragility SMA/HCLPF
LBB assessment

With anti seismic measures to determine the same as above, include possible influence of seismic dampers change of characteristics (stiffness) (also applies for hangers)

To provide optimization of seismic dampers distribution

4 Floor response spectra has to be justified[1]

---

[1]The recommendation is for best estimate procedure with medium + σ deviation which represents 85% probability of non-exceedance

5 Number of eigenfrequency shape loadings should be determined later

6 Frequency range should be determined later

7 ZPA effect — no comment

8 Summation of very near shape loading — no comment

II.1.3. Aspect of non-compliance

For items 5–8 above, information from Japan and other countries will be extremely valuable

II.1.4. Plant specific aspects

1 Site specific seismic situation

2 Changes in pipe layout MCL, SL FWL, StL

3 Disposition of hangers

4 Anti seismic measures used (Kozloduy, Japanese amortizers, Bohunice, GERBs Kola Novovoronezh none)

II 2 FATIGUE DAMAGE ASSESSMENT

II.2 1. Scope

In order to perform fatigue damage assessment it is necessary to evaluate

1 Design features of the system concerned (layout supports, etc , including all plant specific modifications)

2 Applicable loads

3 Material characteristics

4 NDE results (stress concentration and fracture mechanics assessment)

II.2.2. Recommendations

1 LBB concept is applicable only for pipelines, residual lifetime of which has been evaluated using fatigue damage assessment

2 The fatigue damage assessment has to be plant specific and should take into account possible deviations (non-compliance) from the original design

3 Evaluation of loads resulting from operation and external events should be based on both operational experience and analytical data

4 The evaluation of damage due to flow stratification has to be performed on a plant specific basis Experimental verification (strain, temperature measurements) should be included

5 Material characteristics should be based on plant/component specific certificate data, ISI and other results Ageing effects should be taken into account

6 Probabilistic approach in evaluating material properties distribution and defects distribution has to be applied using validated methods

7 Comprehensive NDE programmes have to be established and adhered to

8 For the fatigue damage assessment validated methods and approaches have to be used

II.2.3. Aspects of non-compliance

According to the US NRC only those pipelines with low fatigue damage could be included in the LBB concept

II.2.4. Plant specific aspects

The assessment is plant specific in general The use of generic information or transfer of data from other plants should be justified

II 3 WATER HAMMER

II.3.1 Scope

1 Assessment of the operational experience with respect to water hammer occurrence

2 Postulation of hypothetical worst case to develop water hammer situation

II.3.2. Recommendations

1 Up to now no serious water hammer occurrences have been reported

2 Possible hypothetical worst case situation could arise from sudden failure of main circulating pump (MCP) shaft Possible water hammer should be conservatively analysed in particular at the RPV safe end and at SG elbow

II.3.3. Aspects of non-compliance

Not applicable

II.3.4. Plant specific aspects

Not applicable

II 4 STABILITY OF HEAVY COMPONENTS SUPPORT

II.4.1. Scope

The following heavy components support has to be checked

1 Reactor pressure vessel (RPV)
2 Support flange of the RPV

3 Pressurizer
4 Main circulating pump (MCP)
5 Steam generator

II.4.2. Recommendations

The assessment of all heavy components supports by determination of seismic fragility in terms of HCLPF values should be provided

1 RPV HCLPF value against rotation
2 RPV HCLPF value against vertical axis change
3 RPV support flange HCLPF value against vertical axis change
4 Pressurizer HCLPF value of the support tubes
5 Pressurizer HCLPF value of the dampers/amortizers
6 MCP HCLPF value of all support legs
7 Steam generator HCLPF value of the dampers/amortizers

II.4.3. Aspects of non-compliance

Not applicable

II.4.4. Plant specific aspects

Seismic fragility assessment is based on results of dynamic calculations with or without anti seismic measures As most of the anti seismic measures will be directly or indirectly connected with heavy components or with their supports, the assessment is plant specific

II 5 MATERIAL DATABASE

II.5.1. Scope

The objectives to develop material database are

- to guarantee that material properties will cover the mechanical and metallurgical requirements for the nuclear structural materials, and

  to provide the basis for structural integrity assessments based on fracture mechanical approach or LBB evaluation scenario

From the above viewpoint, material database should provide the following data for all the relevant materials including weld metals

1 Basic material properties data

  - chemical composition,
  - tensile properties at operating temperatures (yield stress, ultimate stress stress–strain curve),

    Charpy impact data at low temperature to upper shelf region

2 Fracture mechanics data

  - fracture toughness at operating temperatures (initiation, J–R curve)

- corrosion/fatigue data under the mechanical and chemical conditions equivalent to reactor operating conditions (crack propagation rate da/dN vs stress intensity factor range)

II.5.2. Recommendations

It is recommended that the following items are required to develop the reliable and non biased database and to gain the international consensus on the developed database

1 Testing method tests should be conducted in accordance with the validated standards

2 Material information the following material information should be additionally described

   - manufacturing process (heat treatment welding conditions, etc),
   - historical details (if the test pieces are taken from the components of nuclear plants)

3 Data treatment database should be treated by qualifying statistical method or appropriate sensitivity analysis It is important because test pieces taken from the degraded components may show the scattered date due to the historical conditions

4 Dynamic effects it is not clear that WWER materials are susceptible to dynamic strain ageing Dynamic strain ageing will degrade the material strength under seismic loadings (In the IPIRG international program by the US NRC, remarkable dynamic strain ageing was observed for A106 carbon steel piping) For materials used in WWER, it will be important to evaluate the effects of dynamic loadings on material properties

II.5.3. Aspects of non-compliance

Not applicable

II.5.4. Plant specific aspects

Not applicable

II 6 LEAK RATE CALCULATIONS

II.6.1. Scope

The scope of this section is to provide information on the aspects required to evaluate leak rate calculations Three separate aspects are required These are

1 Crack shape development following breakthrough of a surface crack propagating through the wall
2 Crack opening area evaluation
3 Leakage rate evaluation

II.6.2. Recommendations

1 Crack shape development following breakthrough

Experimental studies of through wall growth of surface cracks by fatigue have indicated that breakthrough to the back surface only occurs locally such that the crack length on the back face is initially substantially smaller than the crack length on the front face As further fatigue crack growth occurs the crack length on the back face will usually increase at a greater rate than that on the front face, but depending on the type of loading and geometry, there may always be a difference between these two lengths A method of calculating post-breakthrough front face and back face crack length in a conservative way is thus required in order to ensure a satisfactory leak before break argument

The method proposed is as follows

(a) For a given size of crack (length 2c and depth a) determined from NDE information, perform fatigue calculations until it attains a value just less than that of the thickness t (e g until a = 0 95 t)

(b) Taking crack depth as a_{BT} and crack length as $2c_{BT}$ at breakthrough, fix the crack aspect ratio at the value corresponding to a_{BT}/c_{BT}

(c) Maintaining the same crack aspect ration evaluate crack depth a of a pseudo semi-elliptical crack having a front face crack length $2c_{FF}$ equal to the critical crack length (factored by a suitable value) The corresponding back face crack length should be calculated by a simple construction method based on the pseudo-crack geometry

(d) Crack opening areas and leakage rates should be evaluated as outlined below

2 Crack opening area

Information on crack opening area solutions is for example given in Annex 9 of the R6/Rev 3 document [7] This states that if through wall bending stresses are absent or can be ignored, a conservative approximation for the crack opening area A, is given by

$$A = \alpha(\lambda) \frac{2\pi\sigma_m}{E} \left(1 + \frac{1}{3}\left(\frac{\sigma_m}{\sigma}\right)^2\right)$$

Where
σ_m is membrane stress
E is Young's modulus, and
σ is flow stress (=(UTS + yield stress)/2)

The term in brackets represents a first-order correction for the effects of crack tip plasticity The factor $\alpha(\lambda)$ is a correction to allow for bulging in cylindrical shells in terms of the shell parameter λ

$$\lambda = [12(1 - \delta^2)]^{0\,25} c/(Rt)^{0\,5}$$

Where
δ is Poisson's ratio
R is pipe radius, and
t is wall thickness

For axial cracks in cylinders

$$\alpha(\lambda) = 1 + 0.1\lambda + 0.16\lambda^2$$

Valid for $\lambda \leq 8$

For circumferential cracks in cylinders

$$\alpha(\lambda) = (1 + 0.117\lambda^2)^{0.5}$$

Valid for $\lambda \leq 5$

Whereas the above equations have been derived for straight fronted through-thickness cracks, they are intended for use in these procedures for cracks which have a through wall variation in length as outlined above

It is thus required to treat the crack as straight fronted of length, $2c_{FF}$, when evaluating front face crack opening areas A_{FF}, and, to treat the cracks as straight-fronted of length, $2c_{BF}$ when evaluating back face crack opening area A_{BF}

3 *Leakage rate*

Recommendable information on leakage rate evaluation is also given in the R6/Rev 3 document [7] For two phase flow of steam/water mixtures, PICEP and SQUIRT are two codes that can be used to calculate leak rates through a variety of cracks The two programmes are similar and use the same thermal hydraulic model for the flow In PICEP, the leaking fluid can be steam or initially sub cooled or saturated water SQUIRT requires initially sub-cooled or saturated water The programmes allow the crack shape to be elliptical and the crack opening area to vary linearly through the wall thickness, both required for this approach Friction losses due to surface roughness are included and additional losses due to path tortuosity can be included in an indirect manner Some information on friction factor values can be given based on experience in the UK, but the database for this is very limited and is based on single phase flow experiments for a crack which has been grown fully in fatigue in ferritic steel parent material This limited data suggests that a mean valve for friction factor is about 0 35, with a good upper bound being 1 0

As noted below further validation of the PICEP and SQUIRT codes is required before full confidence in their utilization can be gained Other approaches could be also used however, special care should be taken to validate the methods used

II.6.3. Aspects of non-compliance

1 Crack shape development following breakthrough

Further experimental work is required to fully understand the behaviour of crack shape development following breakthrough, particularly when there is a large through-wall bending stress component present

2 Crack opening area

The information given in Section 3 2 on crack opening area solutions assumes minimal through-wall bending If through-wall bending is known to be present then guidance could be obtained from the R6/Rev 3, Appendix 9 [7]

No information seems to be available on how to evaluate crack opening areas in weldments and sensitivity studies are required here in order to assess the most conservative case Experimental validation of this aspect would be beneficial, however The information in this document only applies to relatively straight pipe sections and further work is required for elbows and flange regions Further work is also required to obtain crack opening area solutions for values of λ outside the relevant ranges This aspect is actually being considered in a work programme within the UK Information is also required for evaluating crack opening areas for cracks loaded under negative bending moment which is relevant to seismic loading

Analytical and experimental work is required to further improve the accuracy of crack opening area solutions particularly when there is a relatively large difference between front-face and back face crack length Such studies should be performed for various combinations of membrane and through wall bending applied stresses

3 Leakage rate

Although validation of the PICEP and SQUIRT codes has been carried out, this has only been with experimental data for flow in artificial cracks in the form of machined slots or parallel plates and flow through circular pipes

Neither programme takes account of any other flow reduction mechanisms such as blocking of the crack by particles or debris in suspension Uncertainties such as these may be partially compensated for by the choice of a pessimistically high friction factor but it is preferable to properly quantify and account for any such affects if possible

It is evident therefore that validation of the PICEP and SQUIRT codes for flow rates through realistic cracks is required as a priority

In relation to the above information on friction factor values is required for stainless steel

II.6.4. Plant specific aspects

Not applicable

II 7 PRINCIPAL SAFETY COEFFICIENTS

II.7.1. Scope

Not applicable

II.7.2. Recommendations

Not applicable

II.7.3. Aspects of non-compliance

There is currently no conformity in principal safety coefficient values between the practices of the various countries For example, in the USA a factor of 10 is specified for leak rate, a factor of 2 for crack length and a factor of 1 4 for loading stability

In Japan the effective factor on leakage rate results from LBB calculations performed for the diameter of pipe under consideration A leak rate of 5 gallon/minute for piping relevant to WWERs would be specified by such considerations, which in effect is a coefficient of 5, compared with the USA value 10

In the UK safety coefficients are not prescribed as such, but the R6 method specifies that detailed sensitivity studies on input data should be performed in order for confidence to be gained on the fracture assessment being performed

II 7.4. Plant specific status

Not applicable

II 8 FRACTURE MECHANICS ASSESSMENT

It is recommended to use the R6/Rev 3 method [7], however other approaches if properly validated and conservatism is shown could also be used In the following, information is related to this method

II.8.1. Scope

This procedure provides guidance on the evaluation of the integrity of cracked piping using the R6/Rev 3 method [7]

II 8 2. Recommendations

It is recommended that the R6 method, Ref [7] should be used in the following way to evaluate the integrity of cracked piping with the simplest and most conservative route being initially considered, followed by increasingly more complex and less conservative routes until an acceptable solution is obtained if applicable

(a) Option 1 generalized failure assessment curve with Category 1 through Category 3 analysis

(b) Option 2 material specific failure assessment curve with Category 1 through Category 3 analysis

(c) Option 3 material and geometry specific failure assessment curve (obtained by finite element analysis) with Category 1 through Category 3 analysis

In principle Category 3 full instability analysis is required for LBB Lower bound material properties as required in R6, should be used but a sensitivity analyses may be performed to assess the significance of different material properties on the result Care should be taken to ensure that all relevant stresses (including residual stresses) are included in the calculations

II.8.3. Aspects of non-compliance

Category 3 full instability analysis may be possible but since this involves extrapolating fracture toughness data beyond the J controlled limit, large scale validation experiments would be required Such experiments have been performed on 316 L stainless steel pipes and plates (including cracks in weldments) in the UK, France and Germany in support of the European Fast Reactor (EFR) programme and this work has indicated that Option 1 Category 3 analyses are generally conservative for the cases tested Similar validation is required for the WWER pipework if such a category is to be considered Alternatively, some limited validation testing could be undertaken in order to determine a satisfactorily prescribed amount of crack extension (Δa) for defining an enhanced fracture toughness value to be used throughout (For EFR 316 L stainless steel components, enhanced toughness corresponding to Δa = 3 mm has been specified)

Structural validation testing is also particularly required for transition weld regions

II.8.4. Plant specific aspects

This should be accounted for by taking account of relevant geometry local features (e g weld profiles) loading and material properties

II 9 LEAK DIAGNOSTICS

II.9.1. Scope

1 Requirements to leak detection systems from LBB analysis
2 Applicability of leak detection methods
3 Operational procedures for leakage measurement

II.9.2. Recommendations

1 Requirements

(a) Sensitivity, accuracy and detection time required for each plant should be clarified from LBB analysis

- Critical crack length and critical leakage rate would be different due to the piping design and a seismic design of each NPP

(b) The leak detection system is essential in order to apply LBB concept to WWER 440/230 which originally has a design basis accident 32 mm equivalent diameter pipe break The system reliability is very important for safe plant operation and should be the same as that of reactor protection system

Therefore leak detection system should have high reliability and redundancy

- Several different methods for leak detection should be adopted

- As for assessment of detectability of a system a single failure criteria should be considered for *WWER 440/230 leak detection system* (Example A nearest AE sensor from a leakage position may be ignored in the assessment)

- Surveillance tests during operation should be required to assure the function of leak detection systems Calibration of sensitivity of a detector and electric circuit function check may be required periodically

2 Applicability of leak detection methods

(a) Condensate flow rate monitor, atmospheric gaseous radioactivity monitor and moisture monitor in the confinement can be used as a leak detection system But these systems can not identify a leakage location and quantify with high accuracy and several hours are required before detection, if a leakage rate is small (~1 gpm)

(b) For the case of long non through wall cracks at the inside of a pipe the time available from the crack wall penetration to pipe break could be short

For this case, a fast response leak detection system should be provided

- Leakage sound detection with AE sensor or microphone is effective in this case These systems can make alarm within several seconds

(c) For localization of leakage position and high sensitivity and accuracy of leakage rate measurement, enough sensors should be installed at appropriate positions

(d) Sensitivity and accuracy of these sensors are dependent on the distance between leakage source and sensor piping configuration and background noise These parameters may be different in each NPP

Capability of leak detection system should be assessed and validated for each plant Implementation of more sensitive leak detection system should be conducted to meet the requirements from LBB analysis

(e) For detection of small leaks approx 1 kg/h, more sensors should be installed on the surge line Other detection methods, such as an infrared TV camera may be used to detect steam by image signal processing technique, etc

In case of small leakage around 1 kg/h, most of the leakage coolant will be steam which can not be seen if the room temperature is high

(f) For fast response leak detection over about 1000 kg/h (5 gpm), microphone leak detection system and normal TV camera can be used to support the AE sensor leak detection system This will give redundancy and reliability to AE leak detection system of WWER-440/230 to prevent large break LOCA

(g) State of the art technology should be applied to improve the system to be a highly reliable and also capable of detecting sufficiently small leaks

3 Operational procedures for leakage measurement

(a) Since the leak detection system in the WWER 440/230 NPP is significantly important to protect large break LOCA, this system should be carefully and properly operated and maintained during plant operation

(b) Spurious alarms will reduce confidence of operators to the system, and operators may ignore an alarm or bypass a signal

Reliability of leak detection system should be maintained and operational procedures for a coming alarm should be clarified and provided for operators for each NPP

(c) Maintenance procedures such as periodic surveillance tests fixing alarm setpoint, validation tests etc should be clarified and provided

(d) Man-machine interface should be considered to the system A long term trend recorder for leak detection system is useful for operators to notice easily small differences from normal condition before large leak

II.9.3. Aspects of non-compliance

1 Requirements such as sensitivity accuracy, etc to leak detection system for each WWER-440/230 NPP should be clarified from LBB analysis considering plant specific conditions

2 Further improvements for a more reliable and more sensitive leak detection system should be conducted to meet with the above requirements and be verified at each NPP specific condition

3 Operating procedures and maintenance procedures of the leak detection system should be clarified and provided for each NPP

II.9.4. Plant specific aspects

1 Requirements to leak detection system of each NPP may be different due to the site condition (seismic design), piping configuration of each plant, etc

2 Sensitivity and accuracy of the system of each NPP may be different due to the background noise level and piping configuration, etc

3 Therefore, leak detection system should be designed verified and properly operated on unit specific basis

II 10 LARGE SCALE EXPERIMENTS

II.10.1. Scope

1 To validate the assessment methodology and improve input data aspects such as crack shape development, crack instability, crack opening area and leakage rate should be addressed

2. *Components of the primary heat transport system, i e straight pipes, elbows and safe-ends*

II.10.2. Recommendations

1 The test requirements are linked to the fracture mechanics route employed These tests should be to simulate the reactor operating conditions (normal and abnormal) as closely as possible [2] Both monotonic and dynamic loading conditions should be considered

2 The material (weld) should represent the worst fracture toughness conditions as shown from small specimen tests

3 It would be desirable to have instrumented tests which would allow a calculation of J and J-R curves These should be compared with small specimen data

4 Both (a) circumferential and (b) longitudinal crack growth directions should be investigated

5 The number of tests for each component should be at least two, but may need to be more depending on the results, e g consistency with small specimen data and margin provided by the results

II.10.3. Aspects of non-compliance

Not applicable

II.10.4. Plant specific aspects

1 Material removed from the same, or closely comparable, reactor should be used Any relevant particularities of reactor component configurations should be accounted for

2 The material and geometrical condition of the test should be compatible with a specific plant

II 11 STATUS OF THE COMPONENTS AND PIPING

II.11.1. Scope

1 Design
2 Deviation from design during manufacturing
3 Maintenance
4 Modifications

II.11.2. Recommendations

Not applicable

II.11 3. Aspects of non-compliance

Not applicable

[2]Most importantly the correct loading conditions should be achieved

II.11.4. Plant specific aspects

Components and piping of WWER-440/230 type reactors were designed, constructed and manufactured following regulations and specifications valid in the former Soviet Union in the late 1960s Commissioning of this type of reactor were in the 1960s and 1970s During this commissioning period the layout, manufacturing and welding procedures were changed in some cases Therefore it is necessary to assess the components status and to examine if the actual status agrees with generic inputs of the applied leak before break approach, such as

- agreement between design and actual state,
- observed non regular structural features causing stress concentrations
- existing restrictions on the testability by non destructive methods

Restrictions on NDE are due to geometry and materials used These were produced e g during welding of semi-finished parts with different wall thicknesses or by oversized surface layers of welds (as required by regulations) or by dissimilar welds

II 12 ASSESSMENT OF THE OPERATING EXPERIENCE

II.12.1. Scope

Assessment of lifetime records

II.12.2. Recommendations

Not applicable

II.12.3 Aspects of non-compliance

Not applicable

II 12 4 Plant specific aspects

The assessment of operating experiences provides additional information concerning the operational behaviour of components and piping This will also provide important information on the efficiency of recorded measures taken against failure during design manufacturing and assembling stages of the components and piping These assessments should comprise

- general operating behaviour,
- observed shortcomings,
- results of recurrent inspections,
- results of non destructive testings,
- necessary repairs,
  improvements,
- corrosion attack
  wear and tear,
- restrictions due to inspectability,
- status of supports hangers and snubbers

Annex III

A SIMPLIFIED EXAMPLE OF AN LBB APPLICATION

The purpose of this annex is to illustrate the layout of the LBB analyses results presented for the case of Bohunice Unit 1 in the format of an LBB Handbook using an example of a primary circuit weld

The LBB Handbook summarizes conservative estimates of specific margins for which an obligatory minimum value is prescribed in the LBB status document [2] The prescribed margin coefficients are also defined in Section 3 1 The margins have to be evaluated for all critical sections of the primary circuit For each critical section a page, as shown in Fig 1 is to be evaluated The obligatory coefficients [2] are printed bold in order to be easily distinguished from the additional coefficients, which provide additional information about the safety case

Figure 1 shows a page of the LBB Handbook pertinent to the weld 112 in local notation In general, for each critical section more than one input parameter sets noted as numbered cases, may be required The lowest value of the margin is then considered for the critical section The weld considered in this particular case is between the RPV safe-end and the MCL located in cold leg of the loop with pressurizer of Unit 1

For the evaluation of the stress intensity factor the diameter D = 560 mm and wall thickness t = 33 5 mm are used Because the plastic deformation mechanism which is essential for the limit load may occur dominantly in a section out of the postulated crack, the diameter and the wall thickness D_{LL} = 560 mm and t_{LL} = 33 5 mm respectively, are given for the limit load calculation In this case, however, the dimensions for the limit load and the stress intensity factor evaluation are the same The welded joint is homogeneous, austenitic with the flow stress of the base material R_f = 332 2 MPa (dominant in the plastic deformation mechanism) and the initiation $J_{0\,2}$ = 121 7 kJ/m2 of the crack tip material The temperature for all materials involved is 265°C Internal and external pressure are respectively 12 65 and 0 1 MPa M_{NOC} = 450 643 Nm and F_{NOC} = 2 398 649 N stand respectively for the bending moment and axial force under normal operation The quantities include the effects of dead weight, thermal dilatations and pressure with respect of signs This load is used for crack opening and leak rate calculations M_{SUP} = 1 1 21 708 Nm and F_{SUP} = 2 549 355 N are respectively bending moment and axial force from dead weight thermal dilatations, internal pressure and safe shutdown earthquake (SSE) Square root of the sum of squares of SSE and NOC loads is taken into account All quantities are summed in their magnitudes, disregarding signs, i e components in the sense of the Cartesian coordinate system

To the leak rate of coolant of 38 L/min (10 gpm) corresponds a circumferential through-wall crack of the length l_{leak} = 131 4 mm under normal operation conditions Here the prescribed margin coefficient 10 is respected so that 38 L/min is computed and 3 8 L/min is prescribed for measurement The SSE component of the bending moment in M_{SUP} is 2 7 times less than the value associated with plastic collapse when other components of load remain constant, i e $F^L(p)$ = 2 7 As plastic collapse load is usually decisive for integrity failure, this is a valuable parameter even though not required in Ref [2] Crack length pertinent to plastic collapse is l_p = 523 2 mm The value of l_p/l_{leak} equals 4 which is greater than 2, prescribed in [2] This criterion is usually the most critical one throughout the LBB Handbook for plants with austenitic stainless steel piping

Description:

Weld: **112** Approximation **1**

Unit: *1 (loop with pressurizer)*

Cold leg

RPV nozzle weld of safe-end to primary circuit

Inputs:

D	=	560 0 mm	t	=	33 5 mm
D_{LL}	=	560 0 mm	t_{LL}	=	33 5 mm

Type of weld Homogeneous austenitic

R_f	=	332 2 Mpa	$J_{0.2}$	=	121 7 kJ/m²

Temperature 265°C

p_{int}	=	12 65 Mpa	p_{ext}	=	0 10 Mpa
M_{NOC}	=	450 643 Nm	F_{NOC}	=	2 398 649 N
M_{SUP}	=	*1 121 708 Nm*	F_{SUP}	=	*2 549 355 N*

Evaluation:

Crack length associated with 38 l/min leak rate under normal operation.	l_{leak} = 131 4 mm
Seismic load safety factor.	$F^L(p)$ = 2 7
Crack length associated with plastic collapse	l_p = 523 2 mm
Ratio l_p/l_{leak}	F^l = **4.0**

$F^L(index)$	–	ratio of M_{index}/M_{SUP}
M_{index}		bending moment pertinent to index type failure
Index i		crack initiation after blunting
Index g	–	crack growth within exclusion lines of J-R curve
Index m	–	described in the table

R6

$F^L(i)$	=	1 4
M_i[Nm]	=	1 527 521
$F^L(g)$	=	**1 6**
$F^L(g)/F^L(i)$	=	1 2
M_g[Nm]	=	1 830 846
$F^L(m)$	=	**1.9**
M_m[Nm]	=	2 103 202

m - instability

US NRC

$F^L(i)$	=	1 3
M_i[Nm]	=	1 443 599
$F^L(m)$	=	**1.8**
M_m[Nm]	=	1 969 603

m - instability

MPA/KWU

$F^L(R_{p0\,2})$	=	1.0
$F^L(R_f)$	=	1 4
$F^L(R_m)$	=	1 7

SSY - PL. STRAIN

$F^L(i)$	=	N/A
M_i[Nm]	=	N/A
$F^L(m)$	=	N/A
M_m[Nm]	=	N/A

SSY conditions not met

FIG 1 LBB Handbook format

The margin prescribed for the onset of unstable crack growth is equal to 1 (i e $F^L(m) = 1$ in the LBB Handbook notation) for the type of load summation described above $F^L(m)$ is defined as M_m/M_{SUP} where M_m is the moment pertinent to the minimum of crack growth instability and validity of the extrapolated J–R curve Which of the conditions is in force is given in the table in the analysed case $F^L(m)$ pertains to instability The $F^L(m)$ equals respectively 1 9 and 1 8 when evaluated according to the R6 [7] and US NRC [8] procedures There is no significant difference between both types of evaluation the former utilizing the FAL and the latter the J–T diagrams In some cases of rapidly changing wall thickness and pipe diameter the R6 and US NRC values of $F^L(m)$ may differ more profoundly in the LBB Handbook This is not because of a significantly different approach of the R6 and the US NRC but because of the use of different input data for the limit load In these cases the US NRC (as evaluated in the LBB Handbook) is overconservative and the R6 is to be taken into account as sufficiently conservative

An additional information about the margins, as defined in the above paragraph related to crack initiation after blunting, i e $F^L(i)$ is instead of $F^L(m)$, is useful, although not requested in Ref [2] Meeting the criterion $F^L(i) > 1$ adds strong additional argument for the final decision of the licensing authority This is the case here when $F^L(i)$ equals 1 4 and 1 3 respectively using the R6 and the US NRC approaches

Another additional useful margin parameter is $F^L(g)$ This is defined in the same way as $F^L(m)$ but it is related to the crack growth within exclusion lines of standard test specimens As expected $F^L(g) - 1$ 6 is between 1 4 and 1 9 The validity condition for this coefficient is $F^L(g)/F^L(i) \geq = 1$ 2 (for details see the R6 procedure [7])

The above defined margins are evaluated also in a SSY approximation when small scale yielding conditions prevail This is exceptionally the case in the analysed problems

The German MPA and KWU prefer to avoid J integral in the analysis The pertinent procedures compare a specific stress in the linear elastic body with yield, flow and ultimate stresses We can see in Fig 1 that the numbers 1 1 4 and 1 7 are in reasonable accord with the J integral based values

In the above paragraphs the content of the LBB Handbook was explained and demonstrated In addition to this document it must be demonstrated that fatigue and corrosion are not significant in primary circuit The procedure for this is described in Sections 3 2 and 3 3 of the main document

The LBB Handbook and fatigue and corrosion assessment require extensive input data related both to loading and to material properties The programme for obtaining the data is described in Section 4

Although only the results of Section 3 of this document are effectively required for the LBB status approval the Safety Case Document also requires documentation of the input data i e outputs of Section 4 of this document Validation of the most complicated cases of the LBB Handbook by large scale experiments supports the acceptance of the LBB case

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Applicability of the Leak Before Break Concept, IAEA-TECDOC-710, Vienna (1993)

[2] UNITED STATES NUCLEAR REGULATORY COMMISSION, US NRC Standard Review Plan, 3 6 3 Leak Before Break Evaluation Procedures, US NRC, Washington, DC (1986)

[3] GESELLSCHAFT FUER REAKTORSICHERHEIT, RSK Guidelines for Pressurized Water Reactors, 2nd Edition, 24 January 1979, including Appendices to Section 4 2, 3rd Edition, 14 October 1981, later changes of RSK Guidelines Sections 21 1 and 21 2, 1983

[4] IIDA, K 'Recent issues and researches on nuclear pressure vessel and piping', presented at 7th Int Conf on Pressure Vessel Technology, Dusseldorf, 1992.

[5] CZECHOSLOVAK ATOMIC ENERGY COMMISSION, Leak Before Break Procedure, CSKAE Requirements for Safety Case Reports and their Appendices, Prague (1991)

[6] ZAHOOR, A , Ductile Fracture Handbook, Volume 1 Circumferential Through-Wall Cracks, Rep EPRI NP 6301-D N14-1, Palo Alto, CA (1989)

[7] MILNE, I , AINSWORTH, R A , DOWLING, A R , STEWARD, A T , Assessment of the Integrity of Structures Containing Defects, CEGB Report R/H/R6 – Rev 3 1986, Int J Press Vessels Piping, **32** (1988) 3–104

[8] CHEXAL, V K , NORRIS, D.M (NSAC Project Managers), Applying Leak Before Break to High Energy Piping, NSAC-114, November 1987 (prepared by Robert L Cloud Associates, Inc for NSAC and EPRI)

[9] ROSS, E , HERTER, K H , JULISH, P , BARTHOLOME, SENSKI, G , Assessment of Large Scale Pipe Tests by Fracture Mechanics Approximation Procedures with Regard to Leak Before Break, Nucl Eng Des **112** (1989) 183–195

[10] BARTHOLOME, G , STEINBUCH, R , WELLEIN, R., Ausschluss des doppelendigen Rundabrisses der Hauptkuhlmittelleitung, presented at 7th MPA Seminar, 1981

[11] NORRIS, D M , CHEXAL, V , PICEP – Pipe Crack Evaluation Program, Rep NP-3596-SR, Electric Power Research Institute, Palo Alto, CA (1984)

[12] GABORČIKOVA, J , SAMOHÝL, P , BASLBB, Theoretical and Users Manual (in preparation)

[13] SAMOHYL, P , Fatigue Flaw Growth Assessment in the Primary Piping of Nuclear Power Plant V1, Rep UJV 9868 T (1993) (INIS B 22 30, E 22 00, E 17 00, E 32 00)

[14] KASSNER, T F , et al , Environmentally Assisted Cracking in Light Water Reactor, NUREG/CR-4667, Vol 9 (1989), Vol 12 (1991)

[15] UNITED STATES NUCLEAR REGULATORY COMMISSION US NRC Regulatory Guide 1 92, Combining Modal Responses and Special Components in Seismic Response Analysis, Revision 1, US NRC, Washington, DC (1976)

[16] BOHM, M P , et al , Application of the SSMRP Methodology to the Seismic Risk of the Zion NPP, Rep NUREG/CR-3429, US NRC, Washington, DC (1983)

[17] PRASSINOS, P G , et al , Recommendations to the Nuclear Regulatory Commission on Trial Guidelines for Seismic Margin Reviews of NPPs, Rep NUREG/CR-4482, US NRC, Washington, DC (1986)

ABBREVIATIONS

a, c	crack sizes
AE	acoustic emission
BT (index)	crack sizes at the point of wall breakthrough
BWR	boiling water reactor
CANDU	pressurized heavy water cooled and moderated pressure tube type reactor
DEGB	double ended guillotine break
ECCS	emergency core cooling system
EFR	European fast reactor
EPRI	Electric Power Research Institute
F	load
$F^L(p)$	seismic load safety factor, indicating how many times the SSE load may be increased (other load components being constant) until the plastic collapse load is reached
FWL	feedwater line
g (index)	crack growth up to the maximum value of the valid J integral when measured on the standard test specimens
GERB	viscous damper
HCLPF	high confidence of low probability of failure
i (index)	crack initiation after blunting
IPIRG	International Piping Integrity Research Group
J	J integral
LBB	leak before break
l_{eak}	postulated through wall circumferential crack length pertaining to the leak rate of 38 L/min under normal operation conditions
LLNL	Lawrence Livermore National Laboratory
LOCA	loss of coolant accident
l_p	postulated through-wall crack length pertaining to plastic collapse
M	bending moment
m (index)	the smaller of the crack length up to the limit where the J-resistance curve extrapolation is still valid and of the crack length at the onset of the instability after stable growth
MCL	main circulating line
MCP	main circulating pump
MSK64	seismic scale
NDE	non-destructive testing
NPP	nuclear power plant
OPB	former Soviet Union safety standard
PGA	peak ground acceleration
PICEP	leak rate calculation code
PWR	pressurized water reactor
R	loading ratio
RG	regulatory guide (US NRC)
RPV	reactor pressure vessel
RSK	German safety standard
SL	surge line
SMA	seismic margin assessment
SQUIRT	leak rate calculation code
SSE	safety shutdown earthquake
StL	steamline

t	wall thickness
US NRC	US Nuclear Regulatory Commission
WH	water hammer
WWER	Soviet designed PWR
ZPA	zero peak acceleration

CONTRIBUTORS TO DRAFTING AND REVIEW

Crochon, J P	WANO, France
Dragunov, Yu G	OKB Gidropress, Russia
Getman, A F	VNIIAES, Russia
Havel, R	International Atomic Energy Agency
Höhn, J.	International Atomic Energy Agency
Kasai, Y	ATR, Japan
Kashima, K	CRIEPI, Japan
Ovtcharov, R	Bulgarian Committee on the Peaceful Use of Atomic Energy, Bulgaria
Puls, M P	AECL, Canada
Sharples, J K	AEA Technology, United Kingdom
Shimomura, K	International Atomic Energy Agency
Wenk, W.	GRS Berlin, Germany
Zdárek, J	Nuclear Research Institute Řež, Czech Republic

Consultants Meetings

Vienna, Austria 9–13 November 1992,
29 November – 3 December 1993