EUROPEAN COMMISSION
Community Research

SEVENTH FRAMEWORK PROGRAMME

ARCHER

Collaborative Project (CP)

Co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Seventh Framework Programme

Grant Agreement Number : 269892

Start date : 01/02/2011 Duration : 48 Months
www.archer-project.eu

Archer
Advanced Reactor for Cogeneration of Heat & Electricity-R&D

"Gap Analysis" Integrity Concept LWR-HTR

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ARCHER project – Contract Number: 269892
Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D
EC Scientific Officer: Dr. Panagiotis Manolatos

Document title	"Gap Analysis" Integrity Concept LWR-HTR
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Number of pages	28
Document type	Deliverable
Work Package	WP25
Document number	D25.21– revision 0
Issued by	Materialprüfungsanstalt Universität Stuttgart (USTUTT-MPA)
Date of completion	16/10/2013
Dissemination level	Restricted to the partners of the ARCHER project

Summary

This document contains the description of the LWR Integrity Concept including redundant measures covering quality assurance, design and manufacturing as well as monitoring and surveillance issues and the Basis Safety Concept (BSC). Based on this information and input from Deliverable 25.11 a gap analysis is given in order to conclude necessary steps which have to be addressed for an integrity assessment concept for various types of advanced HTRs.

Approval

Rev.	Short description	First author	WP Leader	SP leader	Coordinator
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Table of contents

1 Introduction

For nuclear power plants (NPPs) a high degree of safety is indispensable. To avoid the consequences of severe accidents that could lead to the catastrophic release of fission products, for safety relevant mechanical components the possibility of catastrophic failure (large break) must be ruled out. The application of break preclusion also reduces the costs because additional and very expensive safety measures like burst protection for the RPV and whip restraints for pipes are not needed anymore.

In the case of Light Water Reactors (LWR) in Germany the so called “Integrity Concept” (IC) has been developed in the last decades, by which a large break can be excluded for operation not only for new components but also for components already in operation. The IC is based on the German Basis Safety Concept (BSC).

For High Temperature Reactors (HTR) no such concept is available at present. The successful development and application of the IC for LWRs makes it likely to use this concept also for HTR components. The principles, on which IC is based, can be applied of course to the HTR components, but the differences in materials, geometries, design, operating conditions (temperatures, pressure) and cooling media (environment) must be carefully evaluated and taken into consideration.

Within the Collaborative Project “ARCHER” the objective of work package WP25 “Integrity Concept of the Helium Pressure Boundary” is the basic application of the “Integrity Concept” developed for LWR components, e.g. pressure vessel and piping, to HTR components or to components of other advanced nuclear reactors approaching the creep regime.

The aim of task 2.5.2 “Identification of open Questions” of WP25 was in a first step to describe the IC developed for LWR components. Based on this and on the information achieved from task 2.5.1 (Loading and Boundary Conditions for HTR Primary Pressure Boundaries, Experience from Licensing Processes), a gap analysis was elaborated, which identifies the additional steps that are necessary for the application of the existing LWR concept to HTR pressure boundaries taking into account the potential differences in gaps for the different pressure boundary designs, i.e.

- “cold” pressure boundary (operational temperatures as LWR or lower, low alloy fine-grained ferritic steel as 20 MnMoNi5-5 or similar; HTR-Modul, HTR-PM, PBMR) and a
- “warm” pressure boundary (operational temperatures at or in the creep range, e.g. high alloy creep resistant martensitic steel as mod 9Cr1Mo; NGNP designs by AREVA and GA, also cross-cutting to GFR).

The up to now experience with the application of IC to HTR pressure boundaries in licensing processes (HTR-Modul, PBMR 400) also will be summarized based on the results achieved in task 2.5.1 and open issues will be identified.

2 Break Preclusion for German LWR Components

2.1 General Remarks

The assurance of the integrity of the pressure containing components (PCC) is a very important issue for the reliable and safe operation of NPPs. In the case of safety relevant mechanical components a catastrophic failure shall be ruled out. To achieve this in Germany the “Basis Safety Concept” (BSC) was developed and adopted in principle by the German Reactor Safety commission (RSK) in 1977 and became legal in 1979 (RSK Guidelines for Pressurized Water Reactors, 2nd Edition, 1979). The 3rd Edition of 1981 was supplemented by several revisions [1]. As shown in Figure 1 the elements of the BSC are the “Basis Safety” (BS) and the so called Independent Redundancies, [2] to [4].

The BS is the realization of the "quality through production principle", this means optimization, control and qualification of

- Design
- Material and
- Manufacturing.

The requirements of BS will provide the pressure-retaining boundary with a basic safety that will preclude any disastrous failure of a plant component as a result of manufacturing defects, [2] to [4].

The further development of the BSC taking into account possible degradation mechanisms due to operation resulted in the Integrity Concept (IC) that assures the integrity of the component during operation taking into account plant specific operational conditions. The IC is incorporated in the legal framework for nuclear installations in Germany within the nuclear codes and standards. An outline of the legal framework and the main features of the IC for LWR components is described in the following chapters.

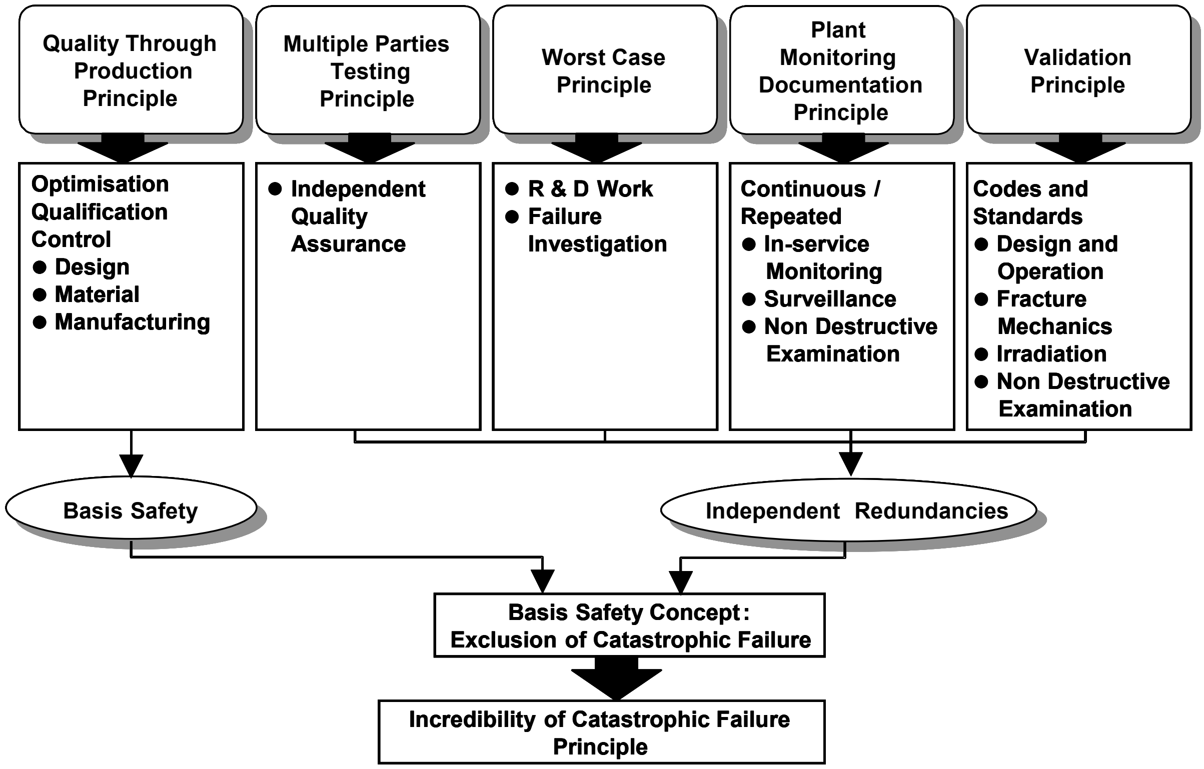

Figure 1: Summary of the "Basis Safety Concept" (BSC), schematic, [2] to [4]

2.2 Legal Framework in Germany

The safety of high-performance conventional steam generating and chemical plants is achieved by applying conventional codes and standards, like e. g. the standards for steam boiler TRD, the standards for unfired pressure vessels AD-Merkblätter, the standards developed by the German Institute for Standardization (DIN) or the harmonized European standards (EN) for pressure parts and related materials of the European Committee for Standardization (CEN). These standards were developed over decades. The knowledge and methods on which these standards are based is of course also used in nuclear technology, but the special potential of degradation for nuclear installations needed additional measures. For nuclear technology extensive investigations were carried out since the late sixties concerning the strength and fracture behaviour especially for welded components, placing special emphasis on the defined requirements for materials, construction manufacture, non-destructive examinations and the evaluation of tolerable flaws. Also the basics and the proof of safety against burst of the reactor pressure vessel (RPV) and other safety-relevant mechanical components of LWR were covered.

In the following a short description is compiled of important requirements from Guidelines, Codes and Standards, containing statements to avoid potential degradation and failure of mechanical systems, structures and components (SSC).

The legal frame for the use of nuclear energy and the safe operation of all nuclear installations in Germany is given by the Atomic Energy Act (AtG).

Principles for the safety-related requirements taken as a basis for the design of NPPs, especially with respect to the state of the art in science and technology are compiled in the so called "Safety Criteria for Nuclear Power Plants [5]. These "Safety Criteria" were first published in 1977 by the Federal Ministry of the Interior (BMI). Today the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) is responsible. The Safety Criteria are in force for LWR without any exemption.

- Criterion 1.1: "Basic Principles of the Safety Precautions"
  Requires that NPP shall be designed and operated such that at all times during specified normal operation and during incidents the reactor facility can be safely shut down and kept shut down, the residual heat can be removed and the radiation exposure of the personnel and of the environment can be kept, in accordance with the state-of-the-art in science and technology, as low as possible.
- Criterion 2.1: "Quality Assurance"
  Requires that the quality of each plant component of a NPP shall be in accordance with its safety-related significance.
- Criterion 2.2: "Testability"
  Requires that plant components shall be adequately inspected prior to their commissioning and thereafter at regular intervals in accordance with their safety-related significance or function.
- Criterion 4.1: "Reactor Coolant Pressure Boundary"
  Requires that systems which contain the reactor coolant shall be in such a condition and so arranged that the occurrence of dangerous leaks, fast growing cracks and brittle fractures can be precluded as of the present state-of-the-art in science and technology.

BMI-"Safety Criteria" and "RSK-Guidelines" were replaced in 2012 by the BMU "Safety Requirements for Nuclear Power Plants" [6].

2.3 Basis Safety Concept

2.3.1 Basis Safety

2.3.1.1 General Remarks

The evolution in conventional engineering was the basis and a crucial factor in decision-making related to the procurement of nuclear power plant pressure vessels and piping. The on-going advances in science and technology have increased the standards for the construction and operation of the plants especially as concerns the safety against catastrophic failure of pressurized components and systems. Analyses of the operational behaviour of high-quality pressurized components and systems as well as flaw and damage analyses have shown that proven and well-defined principles exist to reliably attain and maintain high quality. In Germany therefore the BSC was developed for break preclusion of pressurized nuclear components [2], [3], [4], Figure 1.

As illustrated in Figure 1 the **"Basis Safety" (BS)** is provided by the optimization of design, material and manufacture (RSK guidelines [1], Appendix 2). This implies that a stringent and well-documented process control and qualification is carried out at each and every step of the manufacturing process, throughout the history of the materials, using in-process monitoring and qualification testing. If all these features are guaranteed, the BS will preclude any disastrous failure of a plant component as a result of manufacturing defects. In the following aspects concerning the design, the material, the manufacture and the operation are pointed out in more detail.

BS basically requires that the quality of the components have to be guaranteed during the production process (design, material, manufacture), so-called "quality through production principle". The essential requirements are implemented in the "General Specification Basis Safety" (Appendix 2 of [1]). If they are fulfilled, the components will attain a basis safety level that will preclude any disastrous failure of a plant component resulting from degradation caused by manufacture.

The basis safety of a plant component will depend on the following.

- Use of high-grade material properties, in particular ductility.
- A conservative limitation of stresses.
- The prevention of stress peaks by way of optimized design and construction.
- The assurance of the application of optimized manufacturing and testing technologies.
- The knowledge and assessment of fault conditions.
- The consideration of the operating medium (environment).

2.3.1.2 Design

The design of the components shall be in conformity with the suitability for the intended function and the applied strength, the intended material, the intended manufacture (suitability for testing and manufacture) and with the suitability for a easy maintenance.

Optimized design according to BS is summarized by the following main features with respect of *suitability for the intended function and for the applied strength*.

- Low nominal and local stresses are achieved by using simple smooth shapes with minimum discontinuities, which produce stress concentrations.
- Using „integral design" shall reduce the number of welded joints.
- On principle seamless pipes shall be used for the straight legs of the pipes of the pressure-retaining boundary. Seamless pipe bends should be used wherever possible. Longitudinal welds must be avoided as far as possible (e.g. through the use of forged rings and piping instead of formed plates).
- Welded joints must be positioned to be remote from critical locations with respect to mechanical and thermal loading and irradiation exposure.
- Good access must be provided for non-destructive examinations.
- The layout of the piping systems shall be such that no unacceptable loads (including vibrations) will occur.
- On principle forged parts shall be used for pipe anchors having to cope with great loads.

Optimized design according to BS is summarized by the following main features with respect to *suitability for the intended material*.

- The requirements of codes and standards for the strength characteristics of the material shall be fulfilled.
- Toughness and ductility of the material (e.g. the absorbed energy shall attain at least 100 J in the upper shelf, low transition temperature) shall be guaranteed.
- Manufacturability, testability and repairability of the components shall be guaranteed.

- The selected material shall be corrosion resistant.

Optimized design according to BS is summarized by the following main features with respect to *suitability for the intended manufacture* (suitability for testing and manufacture).

- Welds shall be located so that surface crack examination, ultrasonic testing (UT) and/or radiography can be carried out with a sufficient degree of detectability.
- Reinforcements shall be located in the vessel or piping wall instead of in the nozzles.
- On principle fillet welds on pressure retaining walls are not acceptable. Attachment welds on pressure retaining walls shall be welded through to enable a non-destructive examination for the terminal weld.
- On principle all accessible weld surfaces on pressure retaining walls shall be ground level and all double-bevel welds shall be ground to show notch-free transitions.
- One-sided welding shall be avoided wherever technically possible. Exceptions shall only be acceptable if testability with non-destructive testing techniques is ensured.
- Product forms and wall thickness shall be chosen which ensure favourable preconditions for processing and non-destructive examinations.
- The number of welds shall be reduced to a reasonable minimum.

Optimized design according to BS is summarized by the following main features with respect to *suitability for an easy maintenance*.

- The implementation of recurrent tests and examinations shall be as easy as possible (good accessibility for testing and/or visual inspections, simple geometries in the areas to be subjected to non-destructive examinations as well as unmistakably defined and reproducible testing criteria).
- All those areas of the pressure-retaining boundary where recurrent test and examinations are impossible or restricted shall be so small that postulated defects of the size of these areas cannot result in a component failure whose consequences would be beyond control.
- Manholes and/or inspection holes shall be provided for the internal inspection of components to the extent this is required for recurrent test purposes.
- The exchange of wear parts shall be as simple and as fast as possible.
- The maximum operating nominal stress shall be 50 MPa for all components, which are accessible neither for recurrent tests nor for recurrent non-destructive examinations.

The design details that are of major importance for the BS of components shall be established as follows.

- A continuous wall thickness transition shall be provided when connecting shell structures of different wall thickness.
- On principle the basic shell in its entirety shall be reinforced in the case of nozzles having an inside diameter ≥120 mm and a wall thickness ≥15 mm. In this context favourable stress courses shall be observed. The wall thickness ratio between nozzle and reinforced basic shell should be as small as possible.
- Pressure vessel nozzles having an inside diameter ≥120 mm shall have a wall thickness that is at least two times that of the following pipes.
- On principle all weld-in nozzles shall be provided with counter-welds. Exceptions will be permissible if existing geometries do not enable any counter-welding. In such cases additional measures are indispensable.
- On principle pipes and bends for a nominal pressure >40 bar shall be seamless. Pipes with longitudinal seams (fusion welds) will be permissible for low-pressure lines (nominal pressure ≤40 bar) provided there is a great diameter v. wall thickness ratio (≥50).

- On principle pipe bends shall be designed to have straight pipe ends. This applies in principle whenever there is a difference in wall thickness between bend and adjacent straight pipe. The wall thickness transitions shall be designed so as to ensure clear-cut testing conditions for the connecting weld.
- The bend radius of pipe bends shall be ≥1.5 times the nominal bore.
- Welded connections on pipe walls for pipe hangers, pipe anchors or dashpots shall be made with through-type welds.
- Expansion joints (bellows) as parts of the pipes will only be permissible in justified exceptional cases.

Figure 2 comprises the description of the main features of application of optimized design, constructional aspects and limited and well-controlled loading.

BASIS SAFETY DESIGN
OPTIMIZED DESIGN • Minimization of the number of weldments • The number of longitudinal weldments is reduced by using forged components • Enlarged wall thickness (> 10 mm) • Confined tolerances in the preparation of circumferential welds of pipes
CONSTRUCTIONAL ASPECTS • Weldments are positioned to be remote from critical locations • Reinforcements are to be located in the vessel or piping wall and not in the nozzle • Elbows with large radius (≥ 1,5 D) and straight pipe ends • Accessibility for non-destructive examinations and recurrent testing
LIMITED AND WELL-CONTROLLED LOADING • Well-defined loading cases for normal, emergency and faulted conditions • Primary stresses shall be limited to the elastic region • The allowable primary and secondary stresses can produce plastic deformation (static, fatigue) • The secondary stresses and peak stresses are limited by means of optimized design and optimized system behavior • Application of advanced stress analyses • Stress analyses considering different postulated break locations

Figure 2: Requirements of the “Basis Safety” for the design and construction, [2] to [4]

2.3.1.3 Material

The selection of material and adequate structural design, welding and heat treatment shall assure a sufficiently ductile status of the material throughout the lifetime of the plant at all points of the pressure retaining boundary under all plant conditions which may occur during normal operation and incident conditions. For all mechanical components of the pressure-retaining boundary, only such materials shall be used as have been certified with regard to manufacturer, product form and manufacturing process, Figure 3. The ferritic materials shall have such properties, that for base materials, weld metals and heat-affected zone (HAZ), the reference NDT temperature is at least 33 K below the lowest operating stress temperature and the pressure test temperature. The material details which are of major importance for the BS of components shall be established as follows.

- The minimum value of the energy absorbed in an impact test shall be 68 J at a temperature not higher than N_{NDT}+33 K.

- The absorbed impact energy in the upper shelf (ISO-V transverse specimens) at the point where the specimen was taken shall attain at least 100 J in a depth of one-fourth of the section thickness (individual value).
- The minimum toughness and strength values of the weld metal shall correspond to those of the base materials to which they are allocated.
- The component ductility behaviour shall be analysed by means of large-scale specimens and component-like tests in consideration of degradations and defective material areas.
- In addition, the long-term influences of cyclic stresses and the corrosion effects resulting from static and cyclic stresses shall be investigated including the conditions under which stress corrosion cracking occurs.
- All investigations shall be performed on a sufficiently broad parameter basis.

BASIS SAFETY MATERIAL
APPLICATION OF IMPROVED STEELMAKING PRACTICE • Choice of material • Melting process • Casting process • Hot-working process
FABRICATION OF MATERIAL • Limitation of allowable materials • High purity and limitations of segregations • Homogeneity and isotropy • Control of heat treatment • Low sensitivity against all manufacturing processes especially welding
ENHANCED TOUGHNESS REQUIREMENTS COMPARED TO CONVENTIONAL FABRICATION AND VERIFIED BY MEANS OF • Low content of trace elements • Optimized chemical composition • Low content of steel accompanying elements • Optimized welding procedures • Specific heat treatment
HIGH PURITY AND HIGH TOUGHNESS AT INITIAL STATE TO IMPROVE THE LONG TERM BEHAVIOR UNDER • Temperature • Radiation • Corrosion
IMPROVEMENT OF EVALUATION OF THE COMPONENTS BY MEANS OF • Non-destructive examinations • Fracture mechanics analyses

Figure 3: Requirements of the "Basis Safety" for the material, [2] to [4]

2.3.1.4 Manufacturing

Only qualified manufacturers with reliable quality assurance programs shall be accepted for the manufacture of components, which comply with the BS. Manufacturer qualification must consider the manufacturer's staff, manufacture facilities, testing equipment and quality assurance. The requirements to be met in this context shall be those contained in the nuclear code or standard applied.

Component manufacturer, reactor vendor and authorized inspection agency shall assure that the flow of manufacture is supervised and documented in its entirety. Figure 4 comprises the description of the main features of manufacturing and quality assurance for application of BS.

It shall be demonstrated by suitable tests that there are sufficient ductility and strength properties over the entire wall thickness. All product forms intended for the pressure-retaining boundary shall be subjected to non-destructive examinations involving a sufficient detectability of degradations. The examinations shall include the ultrasonic (UT) examination of each volume element and a complete surface crack examination. The examination methods and sound scanning directions shall be selected in such a way that all safety-related discontinuities would be localized irrespective of their orientation. In this context, discontinuities whose orientation is vertical to the main stress directions (operational stresses) shall be considered by selecting particularly suited examination techniques and sound scanning directions. Prior to welding, a surface crack examination of the weld side faces must be carried out. In case of ferro-magnetic materials, the examination shall be carried out with magnetic particles methods (MT). After their last heat treatment, all welds must be subjected to an UT examination and one of the techniques of the surface crack examination providing a sufficient detectability of discontinuities. In case of components having an outer diameter of 100 mm and more, the welds shall be examined again after the pressure test.

BASIS SAFETY MANUFACTURING AND QUALITY ASSURANCE
MANUFACTURING • Qualified manufacturer and fabrication process • Enhanced requirements regarding the quality assurance system • Specific requirements for the design of welds a. Improved edge preparation b. Automatic welding processes c. Welding control and welding report d. One-side welds only in special cases e. Fillet welds shall be avoided wherever technically possible f. Weld surfaces shall be ground • Inductive (spool production) • Cold bending
QUALITY ASSURANCE • Well-defined requirements for preparation and implementation of tests • Enhanced requirements concerning testability of welds • Graded testing scope • Increased manufacturers responsibility for the tests

Figure 4: Requirements of the "Basis Safety" for the manufacturing and quality assurance, [2] to [4]

Basic measurements for recurrent tests shall be the non-destructive examinations carried out in the course of manufacture provided they are carried out with the same method that is intended for recurrent test, Figure 5. Recurrent tests for pipes shall be carried out with respect to representative pipe welds and points, which are subjected to special loads. These are e.g. connecting welds of bends, fittings that are subjected to special additional loads caused by forces and moments resulting from an impeded thermal expansion.

2.3.2 Independent Redundancies

Furthermore the **"Basis Safety Concept" (BSC)** requires the existence of redundancies to ensure that any possible deviation from optimization is sufficiently unimportant and unlikely for catastrophic failure. One redundancy of considerable importance relies on the verification and validation of calculation codes and fracture mechanics as well as the verification and qualification of non-destructive testing technologies and in-service monitoring. Therefore, now as before validation work is indispensable to provide the knowledge for the validation of codes and standards and a reliable in-service monitoring of operational parameters. The validation work was done mainly based on the results of uniquely large full scale quasi-static and dynamic testing of components without and with degraded sections to demonstrate their load bearing capacity and their failure behaviour under light water reactor (LWR) conditions, e.g. [7] to [12]. Furthermore for a safe operation and to prove and maintain high quality plant in-service monitoring and recurrent examinations are of indispensable importance. For the practical application of the BSC under operational conditions, the existence of the independent redundancies is demanded, but their application has to be balanced in a way case by case. This makes evident that BS ("quality through production" principle) exclusively cannot ensure the integrity of components for operation and the entire lifetime. Therefore the independent redundancies are demanded in a balanced way, Figure 1.

BASIS SAFETY CONCEPT
CONTINUOUS / RECURRENT MONTORING AND TESTING

CONTINUOUS IN-SERVICE MONTORING

- Standard instrumentation
- Control of water composition
- Leakage monitoring
  - Global methods, control of
    - Dew point temperature
    - Air temperature
    - Quantity of condensate
    - Level of flood basin
  - Localizing methods
    - Acoustic leakage monitoring system
    - Humidity leakage monitoring system
  - Locale methods, moister sensitive transmitter
- Sound conduct through solids monitoring system
- Vibration monitoring system
- Fatigue monitoring system
- Functional / operational tests
- Additional instrumentation

RECURRENT TESTING

- Preventive maintenance and servicing
- Functional/operational test of components and systems
- Hydrostatic pressure test
- Non-destructive examination

<u>Figure 5</u>: Requirements of the "Basis Safety Concept" for the operation, [2] to [4]

2.3.2.1 Multiple Parties Testing Principle

The first redundancy (Figure 1) refers to multi parties testing and demands a quality assurance through at least two independent instances. These instances are generally plant experts not subjected to directives, and independent inspectors of supervisory organizations.

2.3.2.2 Worst Case Principle

The second redundancy (Figure 1) referring to worst-cases, takes into consideration the possible human and technical influences, which may lead to serious reductions in quality during manufacturing and operation. The necessary assurance is provided by on-going research and development work also based on tests with components manufactured on lower bound quality to demonstrate the margins of high quality real components.

2.3.2.3 Plant Monitoring and Documentation Principle

The third redundancy (Figure 1) refers to continuous/recurrent in-service monitoring and documentation and allows a comparison by means of continuous in-service monitoring of actual operating parameters with the data presupposed during design (e.g. specified loading conditions). In addition the recurrent tests (e.g. non-destructive examinations, pressure test) and the on-line in-service monitoring are providing precaution against unexpected failure during operation, in particular by thinning of wall thickness (e.g. erosion/corrosion) and crack initiation as well as fatigue failure.

2.3.2.4 Validation Principle

The fourth redundancy (Figure 1) refers to the verification and validation of calculation codes, standards and mechanistic fracture mechanics as well as evaluation of non-destructive examination methods.

2.4 Integrity Concept

2.4.1 General Remarks

To apply break preclusion to mechanical components (piping and vessels) and to meet the concerns of operational terms and conditions for the total lifetime the **"Integrity Concept" (IC)** was developed. The IC emerged from the fundamentals of the BS, cf. chapter 2.3.1 (design, material, manufacture), considering plant specific terms and conditions. Consequently, the "independent redundancies" of the BSC, cf. chapter 2.3.2, will be effective to consider operational terms and conditions as well as the operational experience and results from R&D, Figure 6. As a premise for a systematically approach to ensure the integrity of components it is indispensable to show that the as-built status of quality (design, construction, material) is according to the required quality given in the guidelines, codes and standards, to show that sufficient knowledge of possible operational degradation mechanisms is available (e.g. no inadmissible cyclic and/or dynamic mechanical and/or thermal loading, no corrosion) and to show that the required quality can be guaranteed for the on-going operation. IC is a proactive approach to ensure the required quality for break preclusion during operation for the total lifetime , e.g. [13] and [14].

The following **"three steps"** shall be applied to guarantee the integrity of a component for the total lifetime such as in the following.

- **Evidence of the status of quality according to design conditions and manufacture before commissioning of the plant**
  It shall be in accordance with the particular requirements (guidelines, codes, standards, including layout and construction), especially the requirements of the BS.
- **Guarantee the required status of quality for the on-going operation**
  This shall be done by:
  i. In-service monitoring of the causes of possible operational degradation mechanisms and assessment of the data recorded.
  ii. In-service monitoring and recurrent examinations and testing of the consequences of possible operational degradation mechanisms.
  iii. Follow-up of the state of present knowledge (reviewing the state of knowledge, consideration of operational experience and research results as well as follow-up investigations of failure cases).
- **Verification of the present (as-built) status of quality**
  Layout, design, material and loading conditions of the component in operation. There shall be sufficient knowledge about the possible operational degradation mechanisms for the piping components.

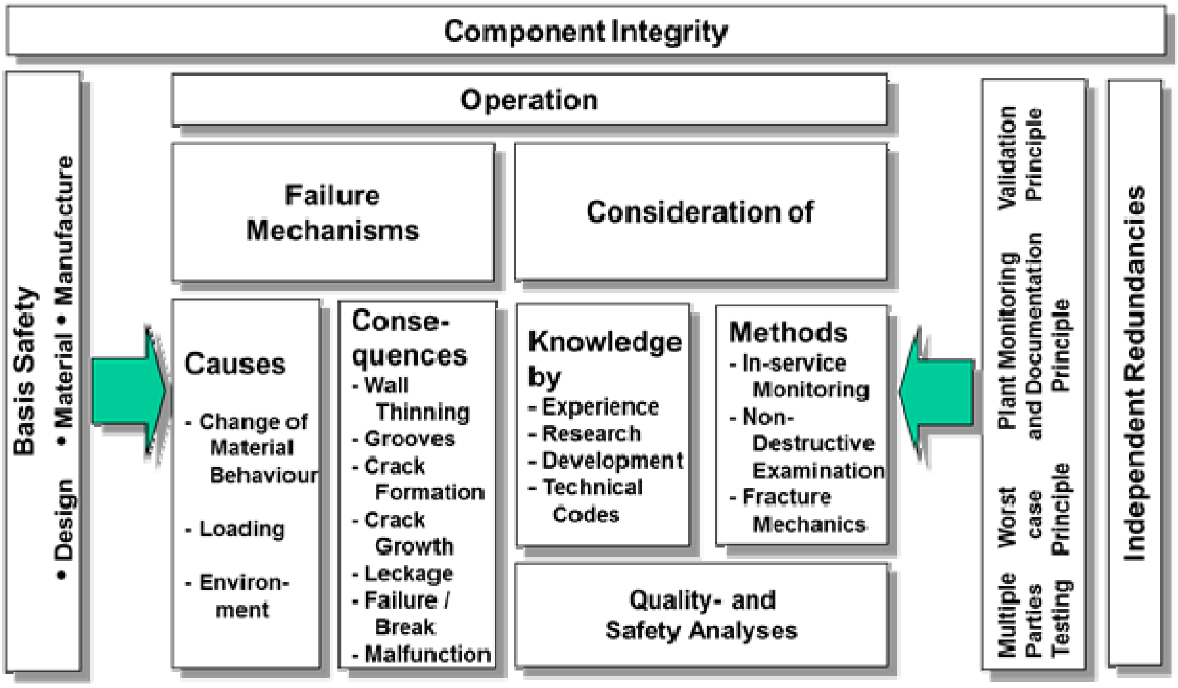

Figure 6: Concept to prove the integrity of components

In doing so, especially the following aspects are of importance.

- The control of the causes of possible operational degradation mechanisms by in-service monitoring of the method and mode of operation as well as of the operational parameters of the stressors relevant to the integrity of the component. The mechanical and thermal loads shall be kept to the limits. It must be shown that unallowable dynamic loads will not occur.
- As a redundant measure in-service monitoring of the consequences of possible operational degradation mechanisms due to recurrent examinations and testing (defining of detectable flaw sizes, test intervals and test areas) and the leakage monitoring system (detectable leakage flow rate and the pertaining leakage area).
- The fracture mechanics assessment of postulated part through and through wall flaw sizes (minimum detectable flaw size, determination of crack growth and critical through wall flaw sizes and load parameters) to demonstrate the leak-before-break (LBB) behaviour.
- The operational experience is recorded and evaluated safety related.
- Follow-up investigations of failure cases and updating of the state of knowledge.

In the following the procedural method to apply the IC for break preclusion to the candidate mechanical component (vessel, piping) is demonstrated according the above shown “steps 1 to 3”.

2.4.2 Status of Quality According to Design and Manufacture

Before commissioning of the plant the evidence of the actual status of quality according to design conditions, the selected material and manufacture shall be given. The key elements of “step 1” (cf. chapter 2.4.1) are as follows.

- General design information.
- Documentation and assessment of the actual design, material and manufacture.
- Determination relevant loads and loading conditions.

- Elimination of possible operational degradation mechanisms.

Each of these elements is described in more detail in the subsequent chapters.

2.4.2.1 General Design Information

The following information for the candidate component shall be provided:

- Description of the layout in detail (e.g. design specifications) including the connections to the large components.
- Definition and description of the terminal ends.
- Description of the component with dimensions, locations of welds and connecting components and supports (values from drawings) as well as materials used (code minimum values).
- Detailed description of operational modes including possible malfunctions (from specifications).
- Codes and standards resp. specifications applied.

2.4.2.2 Actual Design, Material and Manufacture

Documentation and assessment according to the requirements on design (layout, construction and calculation), material and manufacture. These requirements are lay down in the RSK guidelines [1], including the General Specification Basis Safety and transferred to the KTA safety standards (KTA 3201.1, KTA 3201.2 and KTA 3201.3) [15].

The design shall be in conformity with the requirements according to BS, cf. chapter 2.3.1, for optimized design, Figure 2, for the material, Figure 3, and for manufacturing, Figure 4.

Possible operational degradation mechanism must be well known. Based on the (operational) experience and the state-of-the-art these degradation mechanisms must be identified and already considered for design (e.g. limitation of the applied stresses by stress analysis, calculation of the usage factor by fatigue analysis).

2.4.2.3 Relevant Loads and Loading Conditions

The relevant loads (mechanical, thermal) shall be determined based on specifications. They are to be evaluated within the scope of the following items.

i. Stress analysis
   Determination of relevant stresses for the component free of defects on the basis of specified operational loads and specified loads for emergency/faulted conditions based on design conditions. Limitation of the stress categories.

ii. Fatigue analysis
   Determination of the equivalent stress ranges/amplitudes resulting from the relevant operational loads based on design conditions. Calculation of the fatigue usage factor ($U<1$). If relevant, the environmental effect of the coolant medium shall be included. An analysis procedure shall be chosen so that a sufficiently realistic determination of the fatigue usage factor U can be guaranteed for the high stressed areas.

iii. Fracture mechanics analyses
   A fracture mechanics assessment (crack size and load level, crack growth, critical values) shall be performed for minimum flaw sizes detectable by recurrent non-destructive testing (postulated part-through flaw sizes) as well as for a through-wall flaw size.

Apart from the respective safety margin the results are of importance for the recurrent non-destructive testing to determine test intervals and testing areas (location).

The calculation and evaluation of leakage rate is within IC (no operational cracks, neglectable crack growth of the postulated part-through flaw sizes, monitoring of causes of possible operational degradation mechanism) not a mandatory requirement.

2.4.2.4 Operational Degradation Mechanisms

The fact has to be clarified whether operational degradation mechanisms may occur for the candidate components taking account of process engineering related boundary conditions and possible operating modes. Therefore, possible degradation mechanisms have to be excluded or have to be identified in view of the operational experience and the NDT results within the scope of manufacture as well as the present state of knowledge. The parameters to cause degradation as well as the status after manufacture are to be compiled according to the present state of knowledge for the different types of material in consideration.

2.4.3 Guarantee Required Status of Quality for On-going Operation

The proven quality of a component after manufacture is to be maintained for the on-going operation. Within “step 2” (cf. chapter 2.4.1) the guarantee of the required quality for break preclusion for the on-going operation shall be demonstrated. The key elements of step 2 are as follows.

- Requirements and measures of Nuclear Safety Standard KTA 3201.4.
- In-service monitoring of the causes of possible operational degradation mechanisms.
- In-service monitoring and recurrent examinations and testing of the consequences of possible operational degradation mechanisms.
- Follow-up of the operational experience and of the state of present knowledge.

2.4.3.1 Nuclear Safety Standard KTA 3201.4

On principle the requirements and measures of KTA 3201.4 (In-service Inspections and Operational Monitoring) shall be fulfilled and are the basis to guarantee the required quality for the on-going operation, Figure 7.

2.4.3.2 Monitoring of the Causes

The extent of the in-service monitoring of the causes of the possible operational degradation mechanisms, such as e.g. loads, environment (water chemistry) or material modifications, is to be defined on the basis of the assessment of the actual status of quality. The purpose of the in-service monitoring as well as of the recurrent examinations is to guarantee that the assumptions the component design is based on, especially for the loads (mechanical, thermal, corrosive), remain constant during the lifetime respectively to record possibly occurring changes.

The measures of in-service monitoring during plant operation are of highest importance with the first priority of monitoring causes (influencing parameters) of possible operational degradation mechanisms.

By in-service monitoring it shall be demonstrated, that dynamic loads can be excluded and that the relevant quasi-static loads are recorded completely. The data recorded shall be verified promptly. The mechanical, thermal and corrosive loads have to be kept on specified limits. Knowledge about the actual loads is of decisive importance because they are the basis for the stress analysis, the fatigue analysis and the fracture mechanics analyses. If the in-service monitoring indicates new operational loading conditions (not specified for design or up to now not known, operational experience) the consequences to stress analysis, fatigue analysis, fracture mechanics analyses and environmental effects shall be considered.

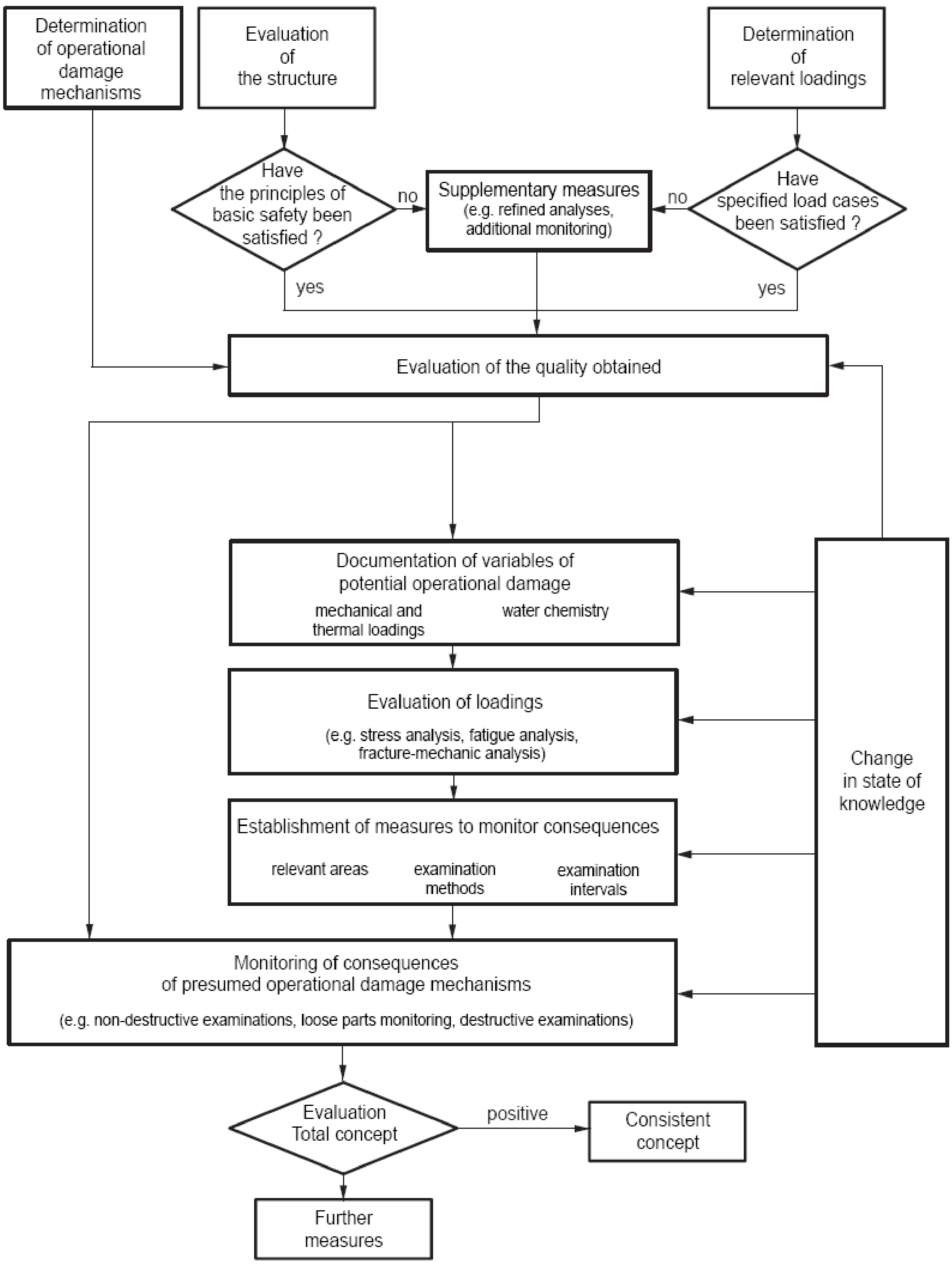

Figure 7: Concept to prove the integrity of components

2.4.3.3 Monitoring of the Consequences and Recurrent Examinations and Testing

The purpose of the recurrent examinations and testing as well as the in-service monitoring of the consequences of possible operational degradation mechanisms are within the IC a redundant measure to guarantee the required quality for the on-going operation.

2.4.3.4 Follow-up of the Status of Present Knowledge

The follow-up of the status of present knowledge (national and international) to guarantee the required quality for the application of break preclusion for the lifetime shall be done by (1) safety related evaluation of the operational experience, (2) review and consideration of operational experience from elsewhere, (3) evaluation and consideration of research results, (4) evaluation and consideration of follow-up investigations of failure cases and (5) evaluation of the influence of new hardware resp. software in monitoring the causes and consequences.

2.4.4 Verification of Present (As-Built) Status of Quality

Within “step 3” (cf. chapter 2.4.1) the verification of the present (as-built) status of quality shall be performed in a period fixed and in comparison with the requirements lay down in the RSK guidelines [1] including the General Specification Basis Safety and the requirements of the KTA safety standards and the relevant specifications. The key elements of step 3 are as follows:

- Description of the as-built system layout.
- Description of the relevant loads and loading conditions.
- Follow-up of the status of present knowledge.

2.4.4.1 As-Built System Layout

Documentation and assessment of the as-built system layout shall include the items as follows.

- Material:
  For the assessment of material characteristics the actual material properties, the heat treatments and the quality assurance during manufacture shall be documented.
    i. Actual material properties (base metal, weld metal) correspond to the requirements.
    ii. Selection of the material corresponds to the application (adequate for the acting mechanical and thermal load, environment).
    iii. Chemical composition corresponds to the requirements.
    iv. Welds the welding procedure, heat treatment, results from welding procedure qualification tests fulfil the requirements.
    v. Mode and scope of acceptance tests and certificates are fulfilled.
- Structural design:
  For the assessment of the structural design the as-built layout (e.g. radii, changes in wall thickness, supports, fixed points, location of weld and weld performance) and the as-built dimensions (e.g. wall thickness, diameter wall thinning) shall be documented.
    i. The as-built status (e.g. dimensions, shape, repair measures) corresponds to the requirements.
    ii. Conformity with the suitability for the intended function, the intended material, the applied strength, the intended manufacture (suitability for testing and manufacture) and with the suitability for an easy maintenance.
- Actual status of indications:
  For the assessment of the actual status of indications the following shall be documented.

i. Results of non-destructive examinations at manufacture (procedure and scope, findings).

ii. Results of recurrent NDT and of special examinations performed (procedure and scope. findings). If there are any findings, causes of the degradation mechanism and measures for prevention.

iii. Operational experience, repair actions and impact to the recurrent examinations.

iv. Size of the detectable flaw size by NDT.

v. As the case may be results from repaired and replaced components.

2.4.4.2 Relevant Loads and Loading Conditions

Basis to determine the relevant strength are the actual operational loads and the specified accidental loads of the component design considering the as-built structural design within the scope of the stress analysis, fatigue analysis and fracture mechanics analysis.

Documentation and assessment of the relevant loads and loading conditions shall include:

i. Stress analysis
Limitation of the stress categories (equivalent stresses) for the actual operational loads with the allowable values specified in Safety Standard KTA 3201.2. Determination of highly stressed areas.

ii. Fatigue analysis
Determination of the equivalent stress ranges resulting from the actual operational loads. Calculation of the fatigue usage factor ($D<1$) based on the number of measured load cycles and allowable values according to Safety Standard KTA 3201.2. An analysis procedure shall be chosen so that a sufficiently realistic determination of the usage factor can be guaranteed for the highly stressed areas. If relevant the environmental effect shall be considered.

iii. Fracture mechanics analyses
It shall be demonstrated, that

   a. the calculated crack growth of the postulated part through flaw size detectable by NDT for actual operational load for the time of interval of the recurrent tests shall be assumed to be negligible and

   b. for the postulated through wall flaw sizes appropriate margin shall be assessed in relation to their critical crack size under actual operational loads superposed by the specified accidental loads.

2.4.4.3 Follow-up of the Status of Present Knowledge

It is the aim of the verification of the present status of quality to check the candidate components against possible operational degradation mechanisms. On the basis of the demonstrated situation and the results obtained the present status of quality of the candidate component shall be demonstrated under consideration of the actual state of knowledge (state-of-the-art). The assessment is based on the requirements contained in the BS.

- It shall be demonstrated, that under the as-built system layout and the actual loading conditions the causes of possible operational degradation mechanisms are controlled and no consequences must be expected.
- It shall be demonstrated, that under as-built system layout and the actual loading conditions the consequences of possible operational degradation mechanisms are controlled by stress analysis, fatigue analysis and fracture mechanics analysis.

2.4.5 Reporting

The results of chapter 2.4.2 and 2.4.3 shall be documented in full. In a periodic way the results of chapter 2.4.4 shall be reported. All reports and documents are part of the knowledge base of the ageing management, [16] and [17].

2.5 Areas of Application in German NPPs

The proof of integrity (break preclusion) shall be applied to systems which must not fail under maximum loading conditions (operational and accidental) or for which the sequential degradations of postulated Double Ended Guillotine Break (DEGB) cannot be controlled. In principle these are mechanical components allocated to group 1 according to Nuclear Safety Standard KTA 1403 [17].

For German Pressurized Water Reactors (PWR) plants the area of application is the following:

- Main coolant lines (MCL) of all PWRs:
  Piping with nominal diameter (ND) of ND700 to ND800 depending on plant concerns made of low-alloy fine-grained steel (22NiMoCr3-7 similar to A 508 Cl.2 or 20MnMoNi5-5 similar to A 533 Cl.2) with austenitic internal cladding.
- Pipes connected to the MCL within the pressure-retaining boundary with nominal diameter ND150 to ND350 made of ferritic and stabilized austenitic steels associated with the dissimilar welds included. This concerns in a plant specific way the surge line, the emergency core cooling system (ECCS) and the volume control system.
- Main steam and feed water lines with nominal diameter ND150 to ND700 made of low-alloy ferritic steel grades in a plant specific way especially in areas within the reactor containment.
- Selected systems within and outside the pressure-retaining boundary in a plant specific way. This concerns e.g. the spray and auxiliary spray pipes with nominal diameter ND50 to ND150 made of austenitic steel as well as steam generator blow-down pipes with nominal diameter ND80 to ND150 made of ferritic steel grades.

For German Boiling Water Reactors (BWR) plants the key areas of application of the integrity concept are main steam and feed water lines within the pressure-retaining boundary up to the first isolation valve outside and partly also within the reactor building. Furthermore selected systems within the pressure-retaining boundary in a plant specific way.

3 Degradation Mechanisms to be considered for Power Plant Pressure Boundaries

3.1 General Remarks Concerning LWR Plants

In order to guarantee safe operation of LWR plants, the possible degradation mechanisms, **Figure 8**, for mechanical components during operation have to be known and be controllable by appropriate measures with respect to the safety relevance of the respective components. For this purpose, it is necessary to analyze and consider the causes of the possible degradation mechanisms by on-line monitoring and recurrent inspections and maintenance measures.

For LWR components (vessels and piping), below the range where creep effects need not to be considered, the possible (most relevant) operational degradation mechanisms, which might not have been considered respectively have not been covered by the design conditions and are of importance for monitoring, are fatigue and stress corrosion cracking, e.g. [18] and [19]. The cause of cumulative fatigue degradation may be unanticipated vibrations or cyclic thermal loading stated as a thermal stratification and fluctuation or a thermal shock. **Figure 9** shows how the causes and consequences of mechanical and thermal loads can be controlled, **Figure 10** gives an overview of possible inspection and test methods that can be used. For cracking due to stress corrosion cracking the applied loads and the water chemistry are of importance (relevant stressors).

Damage Mechanisms	*Causes*	*Consequences*	*Analysis / Proof*
Plastic Deformation	**Overload (excess load) (unspecified or unknown loading conditions)**	**Plastic deformations, Collapse**	**Stress analysis, limitation of primary stresses $\sigma_{actual} < \sigma_{allowable}$, operational in-service monitoring**
Corrosion SCC SICC CF	**Type and level of loading, environmental conditions, state of material**	**Crack formation, crack growth**	**Stress analysis, operational in-service monitoring (load, medium), choice of material, limited crack growth (da/dN or da/dt neglectable), ISI and periodical inspection**
Erosion-Corrosion	**Environmental conditions, state of material, geometrical conditions, piping lay-out, mode of operation**	**Plane wall thinning (surface corrosion, local)**	**Wall thickness measuring, operational in-service monitoring**
Fatigue	**High mechanical and/ or thermal loads and corresponding number of load cycles**	**Crack formation**	**Fatigue analysis, usage factor D < 1, operational in-service monitoring, ISI and re-current inspection**
Wear	**Type and level of loading, state of material**	**Influence on functioning**	**Wall thickness measuring, operational in-service monitoring**

Figure 8: Possible operational degradation mechanisms of mechanical SSC

<table>
<tr><th colspan="5">MECHANICAL LOADING</th></tr>
<tr><th>TYPE OF LOADING</th><th>CAUSES</th><th>CONSEQUENCES</th><th>MONITORING</th><th>VALIDATION</th></tr>
<tr><td>Vibration
(steady state, continuous)</td><td>Active component, unqualified support</td><td>Incipient cracking, crack growth, leakage, failure</td><td rowspan="2">Inspection during commissioning phase, operational on-line monitoring</td><td rowspan="2">Prevention of causes (change in operation mode, design)</td></tr>
<tr><td>Dynamic Loading
Water hammer, pressure waves (dynamic, discontinuous)</td><td>Closing operation of active component, operation mode, design (valve, support)</td><td>Sliding groove, deformed supports, incipient cracking, crack growth, leakage, failure</td></tr>
<tr><td>Static and quasistatic Loading
(internal pressure, displacements, etc.)</td><td>Operation mode (internal pressure, temperature, forces and moments, displacements, residual stresses)</td><td>Global and local stresses, incipient cracking, crack growth, leakage, failure</td><td>Global operational on-line monitoring</td><td>Optimization of operation mode, determination of usage factor</td></tr>
<tr><th colspan="5">THERMAL LOADING</th></tr>
<tr><th>TYPE OF LOADING</th><th>CAUSES</th><th>CONSEQUENCES</th><th>MONITORING</th><th>VALIDATION</th></tr>
<tr><td>Change of Tempeature
(thermal shock loading)</td><td rowspan="2">Operation mode, leaking valves, unscheduled switching operation</td><td>Local stressses, incipient cracking, crack growth</td><td>Adequate global operational on-line monitoring</td><td rowspan="2">Optimization of operation mode and design (components supports), determination of usage factor</td></tr>
<tr><td>Local Temperature Changes
(longitudinal direction, cross section)
• Thermal stratification
• Thermal sloping position</td><td>Global and local stresses, incipient cracking, crack growth, leakage</td><td>Local operational on-line monitoring</td></tr>
</table>

Figure 9: Control of the causes of degradation mechanism

Inspection of Wall Thickness Thinning				
Consequence	**Measured Variable**	**Test Method**	**Criteria**	**Influencing Factors**
Wall Thickness Thinning	Wall thickness	Ultrasonic examination (US), eddy-current examination (ET), radiographic examination (RT)	Accessibility, removing velocity, sensitivity, measuring point	Environment, material, system parameter
Inspection of Incipient Cracking and Crack Growth				
Consequence	**Measured Variable**	**Test Method**	**Criteria**	**Influencing Factors**
Incipient Cracking, Crack Growth	Crack size	Nondestructive: visual inspection, surface examination (OFR-FE, MP), US, DS, WS	Accessibility, detectability, crack growth, measuring point	loading, environment, component shape, material
		Destructive : Microsection surface, fracture surface	Possibilty for dismounting, radiation	NDT relevant indications, usage factor
	Crack growth	Potential drop, US	Accessibility, sensitivity, reproducibility, measuring point, crack growth, complexity	Temperature, material, component shape, damage mechanisms
	System performance	Vibration monitoring	Sensitivity, crack growth	Loading, environment, component shape
	Impact sound	Acoustic emission	Accessibility, detectability, measuring point, construction, crack growth	Loading, crack size
Monitoring of Leakage				
Consequence	**Measured Variable**	**Test Method**	**Criteria**	**Influencing Factors**
Leakage, Leak-before-Break	Environmental conditions	Global moisture recording	Subsequent damage, sensitivity, crack growth, leakage size, critical crack size	Loading, environment, system parameter, material
	Impact sound	Local impact sound examination	Accessibility, measuring point, crack growth	Loading, system parameter

Figure 10: Control of the consequences of degradation mechanism

Detailled information is issued within the report “Expert Panel Report on Proactive Materials Degradation Assessment” (NUREG/CR-6923) [19]. The main objective is the identification of materials and components in LWR plants which may be affected by degradation mechanisms in the future. The report includes, besides the evaluation and statement of an expert panel and the deduced conclusions, a sophisticated documentation of the relevant data and facts as well as additional information. The evolution of different degradation mechanism related to the type of material is included in **Figure 11** for BWR components.

Component and degradation mechanism	Type of material	Periode
Fuel cladding, irradiation assisted SCC	304	1960
Furnace sensitized safe ends, IGSCC	304,182,600	
Weld sensitized large diameter piping, IGSCC	304	
Weld sensitized large diameter piping, IGSCC	304	
Furnace sensitized weldments & safe ends, IGSCC	182/600	
Low alloy steel nozzles, thermally induced vibration	A508	1980
Crevice induced cracking	304L/316L	
Jet pump beams, IGSCC	X750	
Cold work induced IGSCC of "resistant" alloys	304L	
Low alloy steel pressure vessel, TGSCC	A533B/A508	
Irradiated core internals, IASCC	304, 316	
IGSCC/IASCC of low carbon and stabilized stainless steel	304L, 316L, 321,347	2000

Figure 11: Evolution of degradation mechanism for BWR [19]

The evaluation of the expert panel was concentrated on the analyses of the susceptibility of components for certain degradation mechanisms and on the respective state of knowledge, stated separately for PWR and BRW plants. Due to the evaluation of the documents available to the expert panel and the consequent assessment of possible degradation mechanisms, stress corrosion cracking and fatigue emerge as dominant degradation mechanisms for all systems and components treated in the report [19]. Systems and components to be considered are included for BWR in **Figure 12** and for PWR in **Figure 13**.

General System/Function	**System/Component**
Reactor Coolant System (RCS)	Reactor Pressure Vessel (RPV)
	Reactor Vessel Internals (RVI)
	Reactor Recirculation System (RR)
	Recirculation Pump (RP)
Engineered Safety Feature (ESF) Systems	Residual Heat Removal System (RHR)
	Emergency Core Cooling System (ECCS)—Low Pressure Core Spray (LPCS), High Pressure Core Spray (HPCS)
	Condensate Storage Tank (CST)
Steam and Power Conversion Systems	Main Steam System(MS) Automatic Depressurization System (ADS)
	Condensate System
	Feedwater System (FW)
Support Systems	Reactor Water Cleanup (RWC)
Auxiliary Systems	Reactor Core Isolation Cooling (RCIC)
	Control Rod Drive (CRD)

Figure 12: Systems/components to be considered for BWR [19]

General System/Function	System/Component
Reactor Coolant System (RCS)	Reactor Pressure Vessel (RPV)
	Reactor Vessel Internals (RVI)
	Reactor Coolant Pressure Boundary (RCPB)
	Reactor Coolant Pump (RCP)
	Pressurizer, Power Operated Relief Valves (PORVs), Safety Relief Valves (SRVs)
	Steam Generator
Engineered Safety Feature (ESF) Systems	Emergency Core Cooling System (ECCS)—High Head Injection (Charging Mode of Chemical and Volume Control System, CVCS)
	ECCS--Intermediate Head Injection (Accumulators, Safety Injection, SI)
	ECCS—Low Head Injection (Residual Heat Removal System, RHR)
	Refueling Water Storage Tank (RWST)
	Containment Penetrations
Steam and Power Conversion Systems	Main Steam System(MS)
	Feedwater System (FW)
	Auxiliary Feedwater System (AFW)
	Steam Generator Blowdown (SGBD)
Support Systems	Chemical and Volume Control System (CVCS)
	Component Cooling Water (CCW)
	Reactor Coolant Pump Seal Cooling
	Service Water (SW)
	Spent Fuel Pool Cooling and Cleanup
Auxiliary Systems	Spent Fuel Pool and Storage

Figure 13: Systems/components to be considered for PWR [19]

3.2 Integrity Assessment in Pressurized High Temperature Components

At LWR operating temperatures no time dependent materials behaviour (creep and/or creep –fatigue) has to be considered. In advanced HTR-technology the components of the PCU will operate at temperatures where creep processes take place. This means that compared to LWRs additional damage mechanisms shall have to be taken into account.

For fossil fired power plants regulations of the European Pressure Equipment Directive (PED) and subsequent standards e.g. DIN EN 13445 or DIN EN 12952 as well as other regulations, e.g. “AD Merkblätter” are used for design and lifetime assessments. In the framework of the development of CO_2-reduction technologies a demand for high efficiency fossil fired power plants was identified in recent years and development programs for high efficiency plants operating at temperatures as high as 700°C or 750°C have been established. Within the Cooretec initiative of the German Federal Ministry for Economy and Technology (BMWi) and European projects (Thermie AD700, COMTES700) research on advanced ultra super critical plants was put forward. To reach the high efficiency goals, high steam parameters (700°C and 350 bars) are used and the qualification and development of new materials such as Nickel based alloys are needed.

In this developments the following issues are considered in detail:

- materials qualification procedures taking into account time dependent material behaviour
- manufacturing procedures for heavy section components
- consideration of material behaviour under multiaxial loading conditions

- derivation of design procedures including advanced design by analysis (DBA)-methods using inelastic constitutive equations allowing for simulation of time dependent service conditions (incremental creep laws and compex formulations of cyclic viscoplasticity)
- verification procedures of new design and lifetime assessment methods
- inclusion of time dependent changes in the microstructure by electronmicroscopical investigations

A detailed description of the assessment methods including ne multi-scale approaches developed in non-nuclear technology as a basis to extend the IC to HTR-components operating in the creep-regime will be given in a separate deliverable (D25.13).

3.3 Experience from Licensing Processes

One of the issues to be addressed for the application of IC respectively of the BSC to HTR plants is the consideration of possible operational degradation mechanisms, i.e. the consideration of the operating medium (helium environment). The object in view shall be to exclude any possible operational degradation mechanisms.

Based on the information of deliverable D25.11 (Loading and Boundary Conditions for HTR Primary Pressure Boundaries, Experience from Licensing Processes) [20] of the ARCHER project the following two major degradation mechanisms shall be considered: (1) Irradiation with Fast Neutrons and (2) Corrosion.

- Irradiation with Fast Neutrons
  For RPV and RPV internals irradiation and irradiation-assisted stress corrosion cracking (IASCC) shall be considered as major degradation mechanisms, e.g. [18] and [19].
  Irradiation and IASCC shall be considered as potential long term degradation mechanisms during normal operation.

- Corrosion
  In HTR plants Helium gas (He) is used as coolant (environment) for the RPV and as energy transfer medium from the RPV to the power turbine and to the pressure compressors.
  Depending on the different HTR concepts and the location inside the primary pressure boundary (PPB) He gas may be in direct contact with the component inside surface.
  In context with the requirements of IC the influence of the He coolant (helium environment with high purity, or with different amount of impurities) on the pipe material behaviour (He environment as a possible corrosive operational damage mechanisms) is of decisive importance. .
  The corrosion behaviour of metallic materials under He environment has been studied intensively mainly in the frame of the different national as well as international projects for the development of HTGR such as DRAGON, Peach Bottom, AVR, PNP and HHT. A wide range of materials was investigated, comprising commercial available alloys as well as new developments aiming at a better performance under the special conditions in HTR He environment. The alloys of interest were:

    - low alloy ferritic steels
    - ferritic 2.25 to 9 % Cr-steels
    - austenitic steels
    - Fe- and Ni-based high temperature alloys

  The impurities of the PPB He gas have important implications for the metallic components operating at high temperatures. The main characteristics of HTR He giving rise to special corrosion effects derive in the first place as a consequence of the virtual absence of free oxygen, the oxydation potential then being dominated by the H_2/H_2O ratio. At the expected ratios important alloy elements in high temperature alloys like iron, nickel, cobalt molybdenum, and tungsten will not oxidize. Only chromium as a major alloying element is expected to oxidise. In principle the HTR He environment can lead to:

    - Oxidation

- o Carburisation
- o decarburisation
- o loss of section due to internal oxidation and development of subsurface precipitation free zones
- o spalling of surface scales

of metallic materials [21]. The actual reaction depends on the specific alloy system, the temperature, the oxygen partial pressure and the carbon activity of the HTR helium.
It must be pointed out, that corrosion effects depend not only on alloy and gas composition but also on factors that influence the kinetics of the reactions, such as gas velocity, gas pressure and the surface conditions of the specimens. At low water levels (about 0.5 μbar) and low gas velocities (about 1cm*s-1), carburisation is the dominant effect whereas at water levels of about 1 μbar and high gas velocities decarburisation has been observed [22].

4 Gaps in Application of the Integrity Concept to HTR Primary Pressure Boundaries

4.1 Gaps Identified

4.1.1 Design, construction, material, manufacturing

The reflections of the layout (design, construction, material, manufacturing) and the operational conditions (e.g. plant monitoring, recurrent testing) of the PPB of HTR plants on the features of the German "Integrity Concept" (IC) may be concluded as follows:

- All PPB components working at temperatures below the creep range can be treated in the same way as LWR components. These components can be regarded as "cold" pressure boundary.
- As in the LWR IC no creep and/or creep fatigue effects are considered, these effects must additionally taken into account for "warm" pressure boundary, i. e. if the component operates at higher temperatures in the creep range. Details are given in D25.31.
- For the application of IC to the PPB pipes a comparison of the demands and requirements of codes and standards used with the demands and requirements of the IC (as pointed out in the RSK guidelines and the KTA safety standards, see chapter 2.3 and 2.4) and a subsequent evaluation is required. As a result IC requirements may be imposed in addition to the codes and standards selected for the PPB design and manufacture.
- Pipe specific evaluations are necessary. Utmost attention shall be given to longitudinally welded pipes and to welded pipe fittings (T-pipes).
- A HTR specific program/concept which covers the on-line monitoring (methods, areas, intervals) and the recurrent testing (non-destructive examinations: methods, intervals, extent) of the PPB pipes with the aim to detect the causes of possible operational degradation mechanisms and as a redundant measure the consequences of possible operational degradation mechanisms is required.

4.1.2 Degradation mechanisms in HTR He environment

- The possible influence of impure HTR-helium must be considered.

- Only few investigations of the He-influence on low all alloy ferritic and ferritic chromium steels were performed, whereas more investigations exist on austenitic steels, Alloy 800 type and Ni-based alloys.
- The behaviour of various materials in HTR helium environment not only depends on the composition but also on factors that influence the kinetic of the corrosion reactions like gas velocity, gas pressure and surface condition.
- At temperature of 370°C no oxidation of low alloyed ferritic steel was found in HTR He environment.
- In the temperature range 400 to 600°C decarburisation of low alloyed steel was observed, the rate increasing with temperature [22].
- There is a need for more investigations in the field on He-influence [23]. This is in particular true for modern alloy developements, that have not been investigated in the former HTR-projects.

4.2 Experimental Verification to Prove the Integrity

Based on plant specific operating conditions the following major items my be required:

- It shall be demonstrated by experimental and numerical investigations that local hot spots at the PPB pipes (temperature > 350 ^{o}C up to the operating temperature) can not affect the integrity of the pipe or that by any other measures local hot spots (temperature > 350 ^{o}C) are avoided and are not possible.
- Seamless pipes shall be used wherever possible for the straight legs of the pipes. If longitudinal welds cannot be avoided additional measures are necessary. Seamless pipe bends should be used wherever possible. Pipe bends shall be designed to have straight pipe ends (weldments must be positioned to be remote from critical locations with respect to mechanical and thermal loading).
- The load bearing capacity of longitudinal and circumferential welded straight pipe sections and pipe bends shall be demonstrated by experimental and numerical investigations. This applies also to pipes with degraded sections, i.e. determination of critical crack sizes and critical loading conditions and demonstration of the leak-before break behaviour.
- The load bearing capacity of welded fittings, i.e. T-pipe sections, shall be demonstrated under operational and emergency conditions by experimental and numerical investigation.
- The corrosion behaviour of the materials used should be investigated in a representative He coolant environment. Test temperatures shall cover the operating temperatures up to an exposure time of 10^{4} h to determine the corrosion effects like oxidation, carburisation and decarburisation.
- Based on the results of this corrosion tests an eventual degradation in the material properties relevant to the LBB-behaviour (e.g. crack initiation values, crack growth rates or even times to rupture) must be quantified and considered for the leak-before-break analysis.

5 Conclusions

In this report as a first step the LWR Integrity Concept is described emphasizing the importance of redundant measures covering quality assurance, design and manufacturing as well as monitoring and surveillance issues as given in the Basis Safety Concept (BSC). Based on this information and input from Deliverable 25.11 a gap analysis was elaborated, which identifies the additional steps that are necessary for the application of the existing LWR-BSC to HTR pressure boundaries. The description of the different HTR concepts given in D25.11 reveals that there will be a so called

"cold" pressure boundary (operational temperatures as LWR or lower, low alloy ferritic fine-grained steel as 20 MnMoNi 5 5 or similar; HTR-Modul, HTR-PM, PBMR) and a "warm" pressure boundary (operational temperatures at or in the creep range, e.g. high alloy creep resistant martensitic steel as Mod 9Cr 1 Mo; NGNP designs by AREVA and GA, also cross-cutting to GFR).
For those components that operate at temperatures below the creep range the LWR IC can be used taking additionally into account the HTR-specific damage mechanisms irradiation (RPV only) and corrosion in HTR-helium.
For components operating at higher temperatures where time dependent effects must be taken into account the LWR IC must be extended to assure that the causes of possible operational damage mechanisms (creep and/or creep-fatigue processes) do not impact the component integrity. Due to the complexity of ongoing and competing damage mechanisms advanced simulation methods and appropriate material data must be used to assure the safe operation. Such approaches developed for conventional modern 600°C plants and future 700°C plants can be used for the assessment of HTR components. A detailed description will be given in D25.31.
Finally it must be stressed that the application of the IC is based on a reliable and sufficient materials data base.

6 References

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