Guarantee of remaining life time – Integrity of mechanical components and control of ageing phenomena

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Abstract

The life time of safety relevant systems, structures and components (SSC) of Nuclear Power Plants (NPP) is determined by two main principles. First of all the required quality has to be produced during the design and fabrication process. This means that quality has to be produced and can't be improved by excessive inspections (Basis Safety – quality through production principle). The second one is assigned to the initial quality which has to be maintained during operation. This concerns safe operation during the total life time (life time management), safety against ageing phenomena (AM - ageing management) as well as proof of integrity (e.g. break preclusion or avoidance of fracture for SSC with high safety relevance).

Initiated by the Fukushima Dai-ichi event in Japan in spring 2011 for German NPP's Long Term Operation (LTO) is out of question. In June 2011 legislation took decision to phase-out from nuclear by 2022. As a fact safe operation shall be guaranteed for the remaining life time. Within this technical framework the ageing management is a key element. Depending on the safety-relevance of the SSC under observation including preventive maintenance various tasks are required in particular to clarify the mechanisms which contribute system-specifically to the damage of the components and systems and to define their controlling parameters which have to be monitored and checked. Appropriate continuous or discontinuous measures are to be considered in this connection. The approach to ensure a high standard of quality in operation for the remaining life time and the management of the technical and organizational aspects are demonstrated and explained.

The basis for ageing management to be applied to NNPs is included in Nuclear Safety Standard 1403 which describes the ageing management procedures. For SSC with high safety relevance a verification analysis for rupture preclusion (proof of integrity, integrity concept) shall be performed (Nuclear Safety Standard 3206 under preparation),

This paper presents verification and related requirements to guarantee the remaining life time with main focus on integrity of mechanical components and ageing phenomena to be involved.

1 Introduction

In most countries it has been stipulated that the licensing of nuclear power plants (NPP) and their subsequent operation is based mainly on proof of the plant safety (e.g. strength analysis for operational conditions, postulated accidents, etc.). In Germany the atomic energy act requires that ''every necessary precaution has been taken in the light of existing scientific knowledge and technology to prevent damage resulting from construction and operation of the installation''. This has been realized in guidelines and in the nuclear standards [1], [2], [3] and [4], with their indications and requirements for plant safety. According to these documents it has to be ensured that:

- Safety with respect to the quality of the systems, structures and components (SSC) is provided by the design, the material and the manufacture.
- Quality of the SSC has to be guaranteed and documented throughout the lifetime (extensive quality assurance during design, manufacture and operation).
- Operational parameters relevant for the integrity of the SSC (i.e. relevant for damage mechanisms) are monitored.
- Operational experience is recorded continuously and safety-related information is evaluated.

Therefore, the guidelines and standards contain all the requirements for a safe and reliable operation throughout the life time (life time management), for the control of ageing phenomena (ageing management, AM) as well as for proof of integrity (e.g. with the aim to demonstrate break preclusion) for mechanical SSC, Fig. 1. In Germany the discussions on ageing of mechanical SSC to be included in a structured AM process for nuclear power plants started at the beginning of the 1990s [5], Fig. 2, and later on put into praxis by the nuclear safety standards KTA 1403 [6] for AM of NPP and KTA 3206 [7] for break preclusion, Fig. 3.

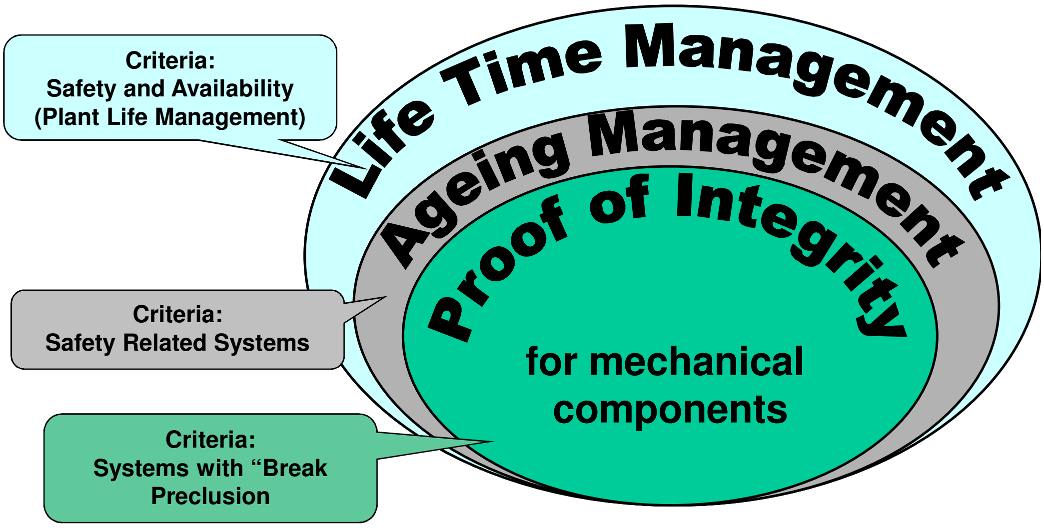
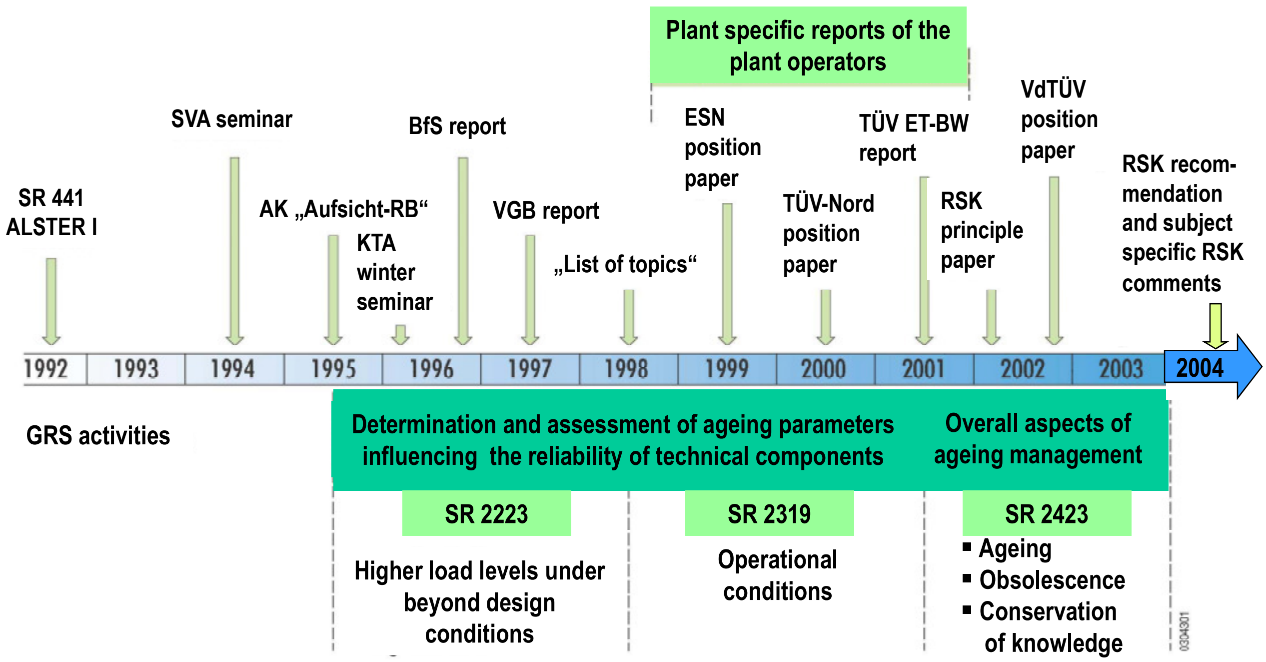


Fig. 1 : Application of life time management, ageing management and proof of integrity for mechanical components



SR ... - Research projects sponsored by Government
BfS - Federal office for radiation protection; GRS - Gesellschaft für Anlagen- und Reaktorsicherheit mbH, a scientific-technical expert and research organisation; KTA - Nuclear safety standards commission; RSK - Reactor safety commission; SVA – Swiss association for atomic energy; TÜV - Technical supervisory association; VGB – German federation of the owners of large boilers
Source: GRS (2003) Cologne

Fig. 2 : Retrospective view - Essential activities for ageing management in Germany

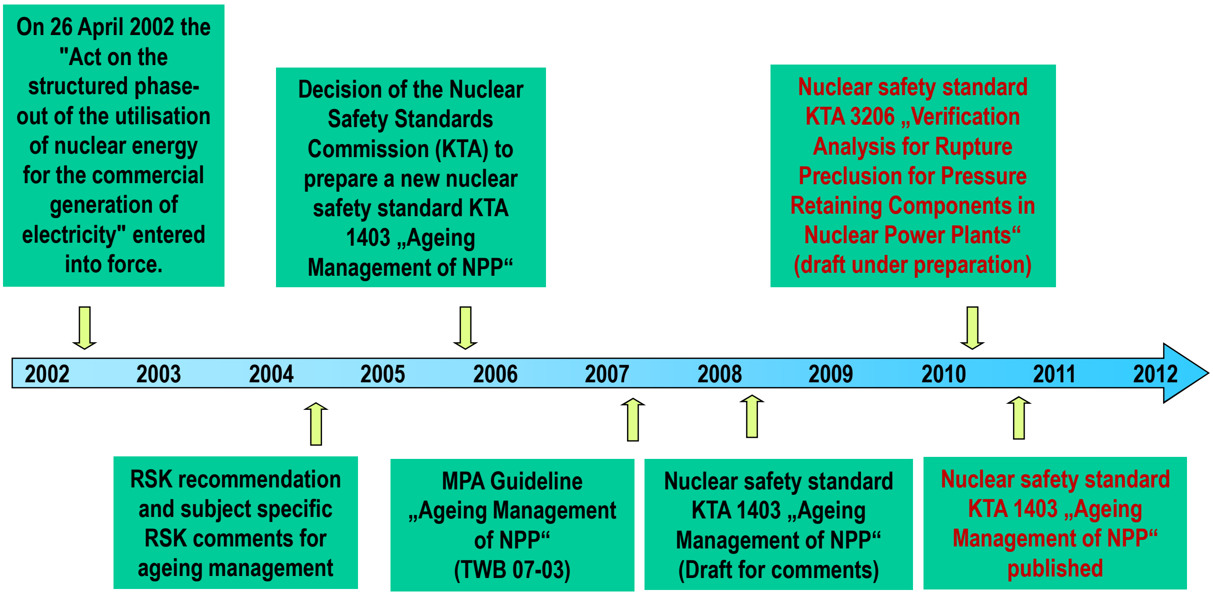


Fig. 3 : Retrospective view - Essential activities for ageing management in Germany

2 Regulatory requirements

On July 22, 2004 the German Reactor Safety Commission (RSK) published Comments and Recommendation on „Management of Ageing Processes at NPP“ including the following topics:

- An effective AM concept shall to be implemented for the SSC with regard to the safety-related relevance.
- The plant relevant ageing mechanisms shall to be identified and pursued.
- AM shall to be implemented as a permanent task on a high management level in connection with the management responsible for safety.
- An annual report on AM shall be submitted to the competent supervisory authority of the different German states.

End of September 2005 a working group was installed to prepare a KTA safety standard for AM of NPP. The finalized safety standard KTA 1403 [6] was published in November 2010 with the main chapters for the application of AM to mechanical SSC, to buildings and structures, to electrical and I&C SSC and to operating supplies. Concerning the mechanical SSC the procedure included is mainly based and related to the German “Basis Safety Concept” (BSC), [9] and [10], and the enhanced “Integrity Concept” (IC or proof of integrity), e.g. [11], [12], [13], [14] and [15].

In parallel MPA University Stuttgart in co-operation with TÜV SÜD Energietechnik GmbH Baden-Württemberg commissioned by the Baden-Württemberg state ministry for environment published in 2007 their AM guideline for NPP [16]. At that time the guideline incorporates the national, e.g. [20], [18], [19] and [20], as well as the international, e.g. [21] and [22], state-of-the-art of AM.

Because until now there is no official document (safety standard) available in Germany for the application of break preclusion it was decided by KTA at the beginning of 2010 to develop a safety standard which governs the procedure and the methods to be used to proof break preclusion for safety relevant systems [7].

3 Life time cycle of mechanical components

The life time of mechanical SSC is governed by two main principles:

- The first one requires that quality has to be produced during the design and fabrication process.
- The second principle is denoted to the initial (i.e. required) quality which has to be maintained during operation up to end-of-life.

This concerns safe operation during the total life time (life time management), safety against ageing phenomena (ageing management) as well as proof of integrity (e.g. break preclusion or avoidance of fracture) for SSC with high safety relevance, Fig. 1. Especially for piping systems in power plants and specifically in NPPs this principle is very important because not all operational conditions can be specified during the design phase.

Life time management stands for the integration of ageing management and economic planning for SCC in order to

- optimize the operation, the maintenance and the life time of the plants,
- maintain an accepted level of safety and performance and
- maximize return on investment over the life time of the plant.

Ageing stands for the time-dependent and/or operational induced gradual change of features and properties related to their function. This also takes into consideration the development of the state-of-the-art (science and technology). Furthermore, it is possible that conceptual design and engineering methods as well as administration rules and requirements may become obsolete compared to the state-of-the-art, Fig. 4.

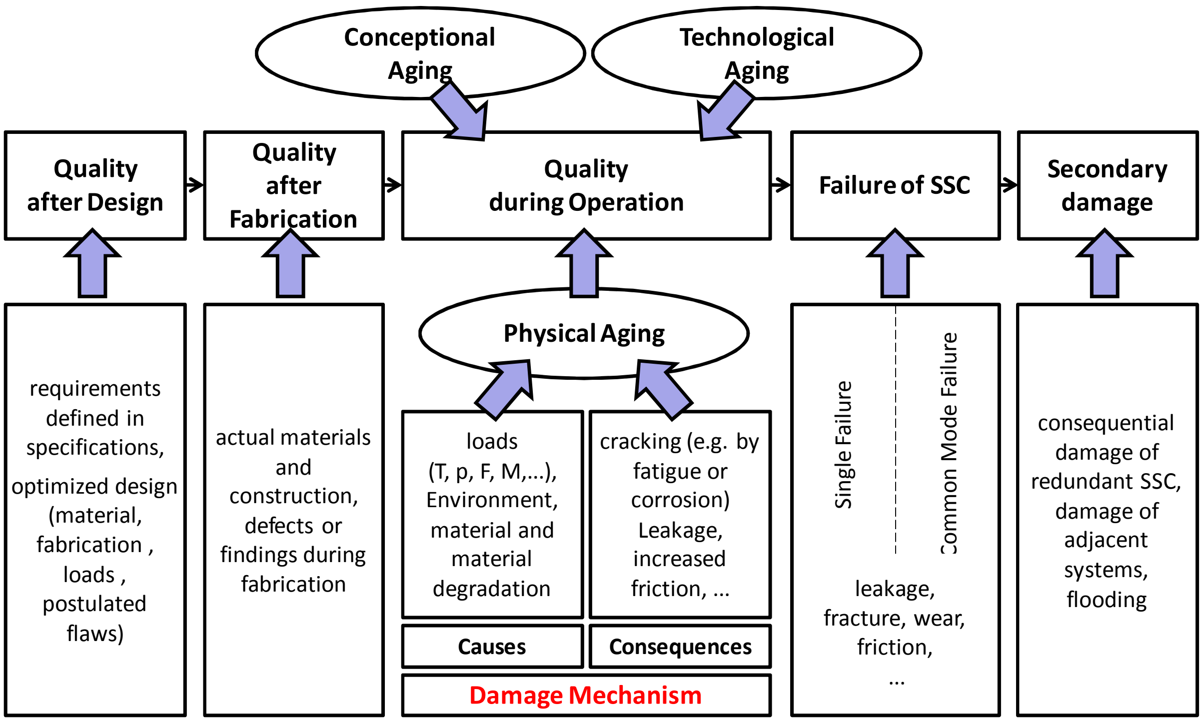


Fig. 4 : Life time cycle of SSC

AM covers all engineering and organizational actions for the plant operator to guarantee safe operation during the life time including control of the ageing phenomena. AM of mechanical SSC is the entirety of technical and organizational measures that guarantee the safe operation of the SSC for the life time by engineering measures and maintenance actions including ageing phenomena within acceptable limits. It has to be distinguished between

- conceptual aspects (modification of requirements, modification of safety philosophy),
- technological aspects (latest results on possible in-service damage mechanisms, on material properties of components, on test methods, on analysis methods, on assessment methods, etc.) and
- material-mechanical or physical aspects (in-service damage mechanisms caused by changes in material characteristics, by in-service loads and by in-service environmental conditions.

4 Operational degradation mechanisms

Various engineering measures are required depending on the safety relevance of the SSC or for reasons of preventive maintenance. The first step within the scope of life time management is related to select and arrange the SSC and to assign the SSC to different groups (group 1, 2 and 3). This classification is according to the requirements of the nuclear codes and standards and if necessary according to plant-specific and safety-related factors. The plant operator is responsible for the classification and an expert has to check it on the basis of the current codes, standards and the state-of-the-art, Fig. 5.

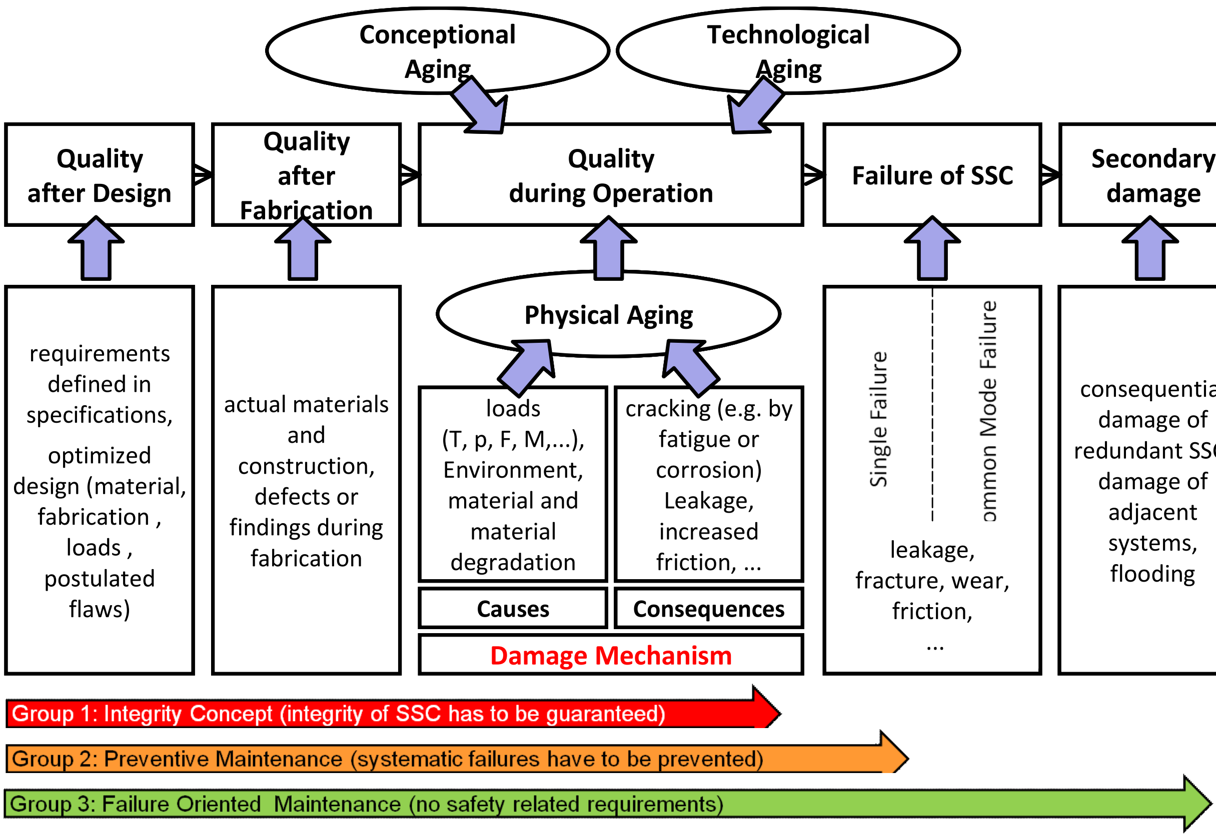


Fig. 5 : Application of lifetime management, ageing management and proof of in-tegrity for mechanical components of groups 1, 2 and 3

- *Group 1*:
  Failure of the SSC shall be excluded to avoid subsequent damage (comprises all components and component parts, whose failures are specified as being

impermissible). The required quality shall be guaranteed for the total life time. The causes of possible in-service damage mechanisms shall be monitored and controlled (proof of integrity). Implementing this "proactive approach" prevents damage.

- *Group 2*:
  Failure of the SSC is allowable from a safety relevant point of view (all safety-related mechanical components not assigned to group 1). However, common mode failure shall be excluded. In single cases the present quality may fall short of the required quality. For that the required quality shall be restored (preventive maintenance, time- or condition-oriented). The consequences of possible in-service damage mechanisms shall be monitored.
- *Group 3*: There are no defined standards for the quality of the SSC from a safety relevant point of view concerning subsequent operation (failure-oriented maintenance).

By life time management it shall be guaranteed by appropriate measures that all possible and relevant ageing phenomena are covered up to end-of-life. This concern to a large extend the material-mechanical or physical aspects (e.g. in-service damage mechanisms caused by in-service loads and/or by in-service environmental conditions not taken into account during design of the SSC). It is indispensable to show that sufficient knowledge of other possible operational damage mechanisms is available (e.g. no inadmissible cyclic and/or dynamic mechanical and/or thermal loading, no corrosion/environment, adequate material selection) and to show that the required quality can be guaranteed for the ongoing operation, Fig. 6.

It shall be kept in mind that the IC is a proactive approach to ensure the required quality for break preclusion during operation for the total life time.

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 layout, 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 recurrent inspection**
Wear		**Type and level of loading, state of material**	**Influence on functioning**	**Wall thickness measuring, operational in-service monitoring**

Fig. 6 : Causes, consequences and proof of operational damage mechanism

Mechanical and thermal loading conditions, Fig. 7, in conjunctions with the environment (primary hot water) are the cause for most relevant damage mechanisms. Thereby a key issue is to cope with the causes of active damage mechanisms. Related examination procedures are shown in Fig. 8.

Mechanical Loading				
Type of Loading	**Causes**	**Consequences**	**Monitoring**	**Validation**
Vibration (steady state, continuous)	Active component, unqualified support	Incipient cracking, crack growth, leakage, failure	Inspection during commissioning phase, operational on-line monitoring	Prevention of causes (change in operation mode, design)
Dynamic Loading Water hammer, pressure waves (dynamic, discontinuous)	Closing operation of active component, operation mode, design (valve, support)	Sliding groove, deformed supports, incipient cracking, crack growth, leakage, failure		
Static and quasistatic Loading (internal pressure, displacements, etc.)	Operation mode (internal pressure, temperature, forces and moments, displacements, residual stresses)	Global and local stresses, incipient cracking, crack growth, leakage, failure	Global operational on-line monitoring	Optimization of operation mode, determination of usage factor
Thermal Loading				
Type of Loading	**Causes**	**Consequences**	**Monitoring**	**Validation**
Change of Tempeature (thermal shock loading)	Operation mode, leaking valves, unscheduled switching operation	Local stressses, incipient cracking, crack growth	Adequate global operational on-line monitoring	Optimization of operation mode and design (components supports), determination of usage factor
Local Temperature Changes (longitudinal direction, cross section) • Thermal stratification • Thermal sloping position		Global and local stresses, incipient cracking, crack growth, leakage	Local operational on-line monitoring	

Fig. 7 : Mechanical and thermal loading

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

Fig. 8 : Selection of examination procedures

5 Concept to guarantee remaining life time

Depending upon the classification of the SSC to group 1, 2 or 3 different measures shall be applied to cover the ageing phenomena to guarantee the remaining life time.

To apply break preclusion, i.e SSC assigned to **group1**, and to meet the concerns of operational terms and conditions for the total life time the IC was developed. The IC emerged from the fundamentals of the “Basis Safety” (design, material, manufacture), considering plant specific terms and conditions. Consequently, the “independent redundancies” of the “Basis Safety Concept”, [9] and [10], will be effective to consider operational terms and conditions as well as the operational experience and results from R&D work. 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, material, manufacture) is according to the required quality given in the guidelines, codes and standards to show that sufficient knowledge of possible operational damage 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 ongoing operation. IC is a proactive approach to ensure the required quality for break preclusion during operation for the total lifetime.

The following three steps shall be applied to guarantee the integrity of a component for the total life time such as follows, Fig. 9.

- Evidence of the status of quality according to material, 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).
- Guarantee the required status of quality for the ongoing operation.
  This shall be done by
  i. in-service monitoring of the causes of possible operational damage mechanisms and assessment of the data recorded,
  ii. in-service monitoring and recurrent examinations and testing of the consequences of possible operational damage mechanisms, and
  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.
  This concerns layout, design, material and loading conditions of the component in operation. There shall be sufficient knowledge about the possible operational damage mechanisms for the piping components.

In doing so, especially the following aspects are of importance, Fig. 10.

- The control of the causes of possible operational damage 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 damage 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 behavior.
- The operational experience is recorded and evaluated safety related.
- Follow-up investigations of failure cases and updating of the state of knowledge.

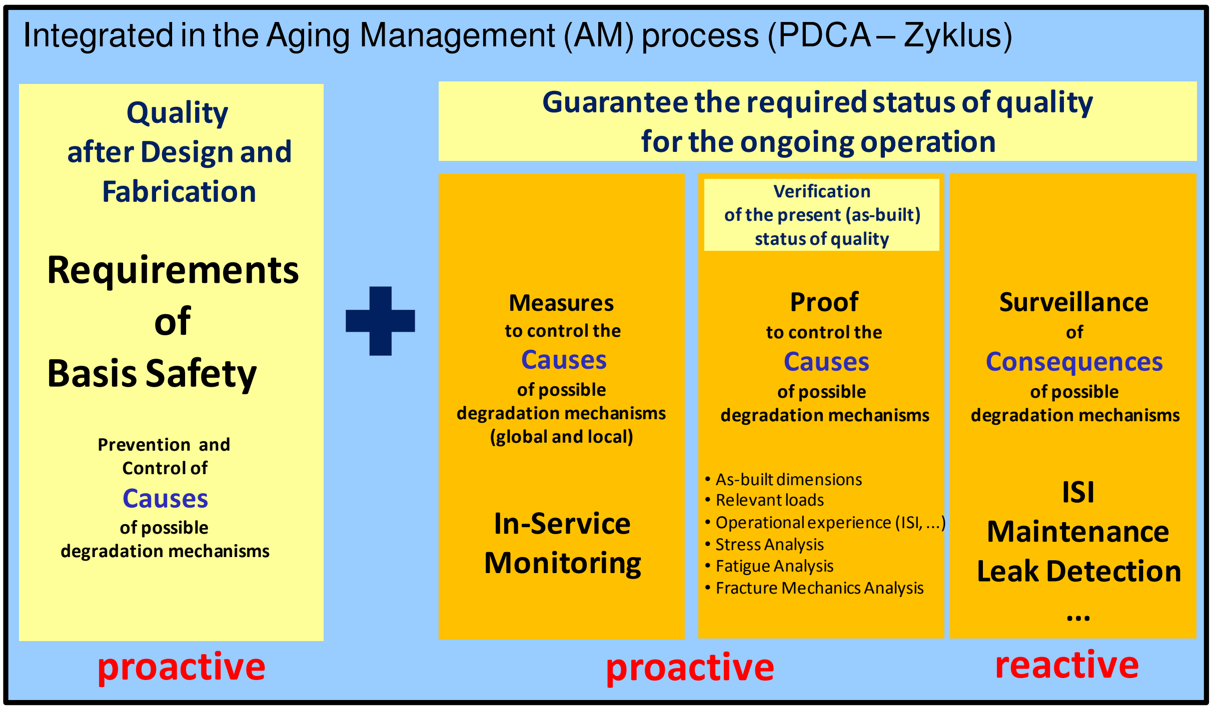


Fig. 9 : Concept to proof the integrity of group 1 SSC

Preventive maintenance of the state of quality for subsequent operation is to be kept and guaranteed for SSC assigned to **group 2**. Relevant failures have to be checked (monitoring of consequences of operational damage mechanisms). Consequential failures have no effect in view of the safety relevance. This means that the actual (as-built) state of quality has to be maintained for subsequent operation. To maintain the quality requires preventive maintenance (time or condition oriented), Fig. 11.

- Demonstration and assessment of the state of quality according to particular requirements:

  (i) Demonstration and assessment of the actual design according to the requirements of the KTA safety standards, the RSK-guidelines including the general specification basis safety as well as specifications and standards. This concerns the requirements on the material and construction (design and calculation) including manufacture.

  (ii) Results of tests performed (state of findings of manufacture, NDT, …).

  (iii) Operational experience (mode of operation, data records and results of operational in-service monitoring, failure investigations, NDT, maintenance measures, etc.).

  (iv) Determination of the damage mechanisms.

- Operational in-service monitoring and maintenance measures (time or condition oriented). The preventive maintenance can be organized as follows:

  (i) Maintenance (measures to keep the nominal condition).

  (ii) Inspection and measurement (measures and actions to determine and asses the actual as-built status).

  (iii) Repair work (measures to restore the required state of quality).

SSC assigned to **group 3** are allocated to failure-oriented maintenance and are concerned by engineering judgment, Fig. 12.

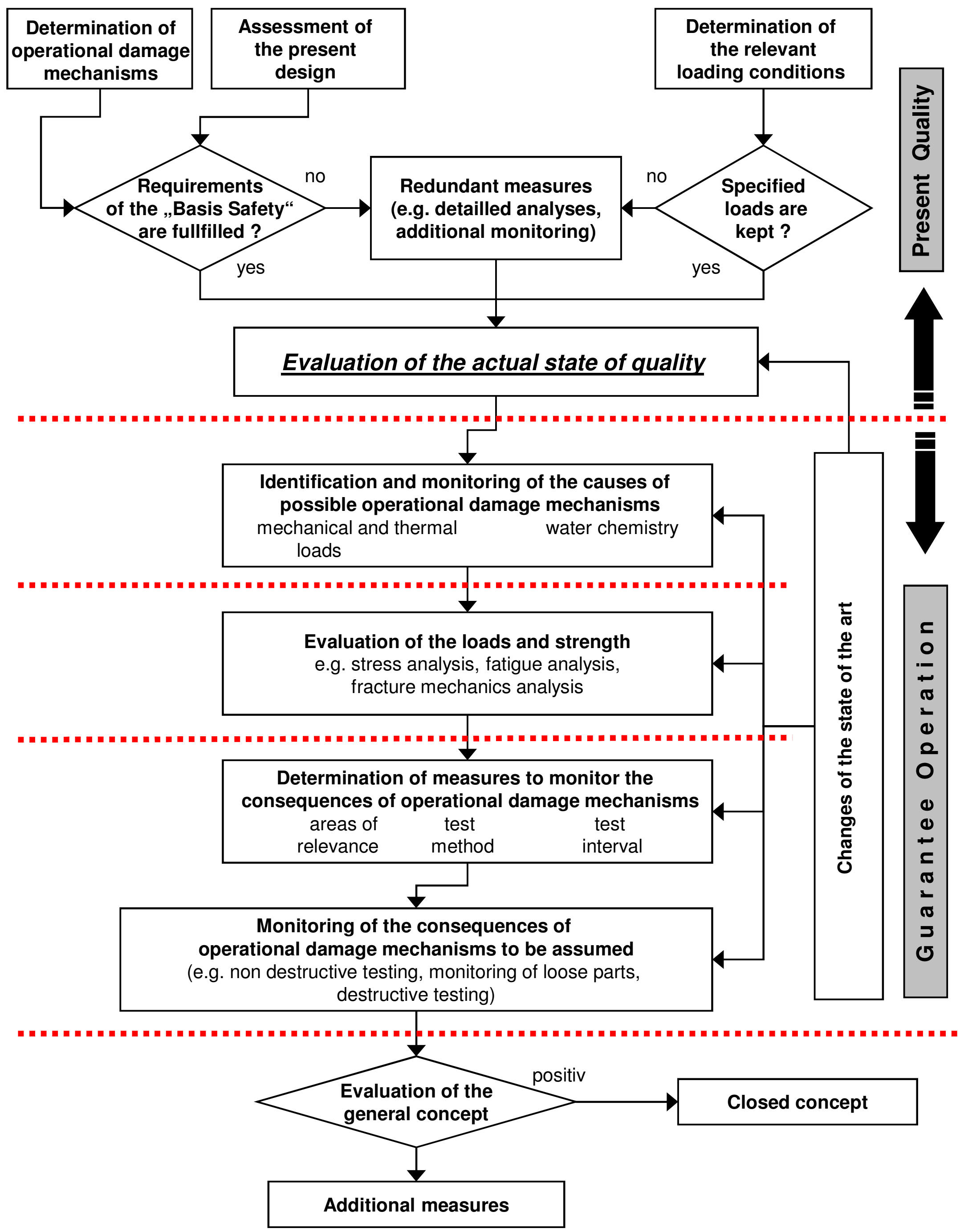


Fig. 10 : Integrity of components during operation

6 Technical and organizational measures

The engineering and organizational measures required within the scope of the ageing management and to guarantee remaining life time of mechanical SSC are oriented on the recommendations and guidelines, e.g. [8],[16] and [23], and are included in safety standard KTA 1403 [6]. A database embedded in a Deming-process (PDCA-cycle), e.g. [24] and [25], is the essential element containing all information relevant to ageing management, Fig. 13. Running through the PDCA cycle the appropriate organizational units have access to information in the data base which can be updated and if need be completed by necessary measures. This guarantees the availability of complete and updated information for all participants in the ageing management process. Additional information concerning operational damage mechanisms is included, e.g. in [22].

The results obtained from research, technical publications, as well as circular letters and important events and if needed findings from other accessible data bases have to be considered. The data are to be integrated into the power plant organization according to a PDAC-cycle, Fig. 13. This includes in particular the following aspects.

- “**Plan**” (coordination) – coordinating ageing management activities:
  - Documents the regulatory and the expert requirements and safety criteria.
  - Considers the development of the nuclear codes and standards, of the safety criteria and of guidelines as well as relevant activities.
  - Describes and up-dates the organizational and co-ordination mechanism.
  - Optimizes, if necessary, the ageing management program based on current state-of-the-art.
- “**Do**” (preventive measures) – managing ageing mechanism:
  - Operation according to the procedures and technical specifications.
  - In-service monitoring of the water chemistry and the environmental influences.
  - Documentation of the mode of operation (history) including transient records.
- ”**Check**” (monitoring, analysis, assessment) – detecting and assessing ageing effects:
  - Recording of the causes and consequences of damage mechanisms by online in-service monitoring and recurrent tests as well as data recording.
  - The as-built status is to be compared with the nominal condition and the changes to be expected due to ageing are to be assessed.

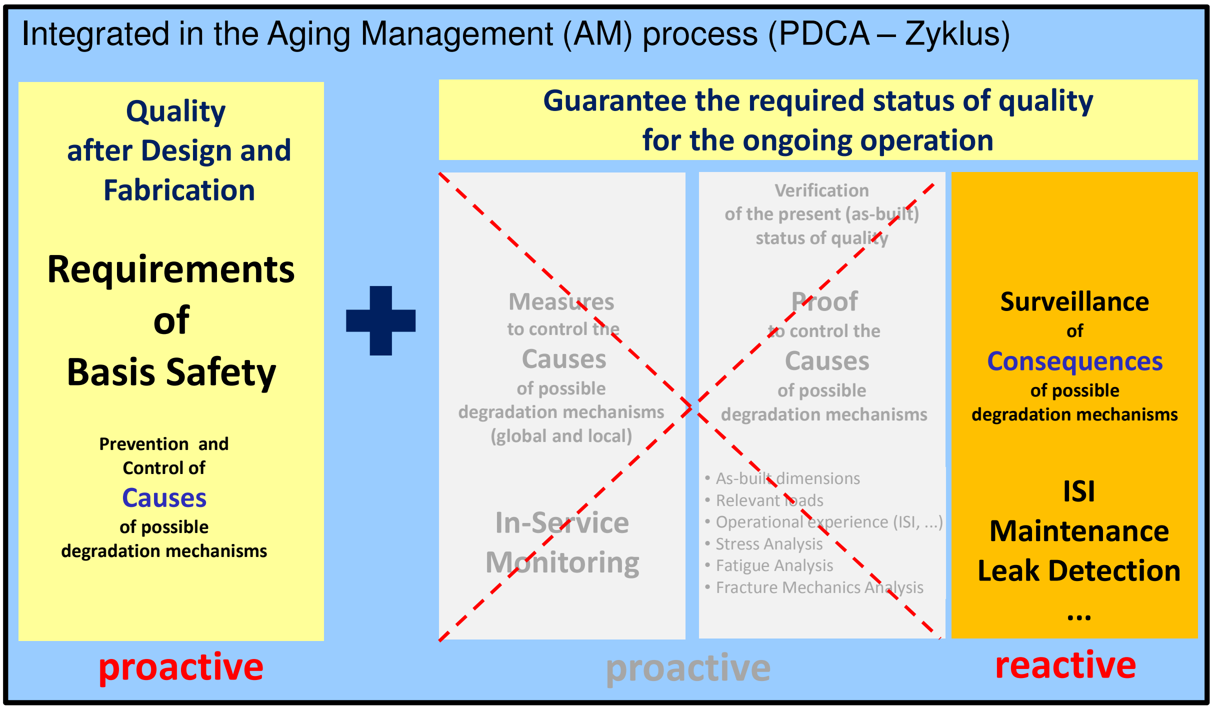


Fig. 11 : Preventive maintenance of group 2 SSC

- **"Act"** (correction measures) – managing ageing effects:
    - Preventive and corrective maintenance.
    - Replacement and maintenance history.

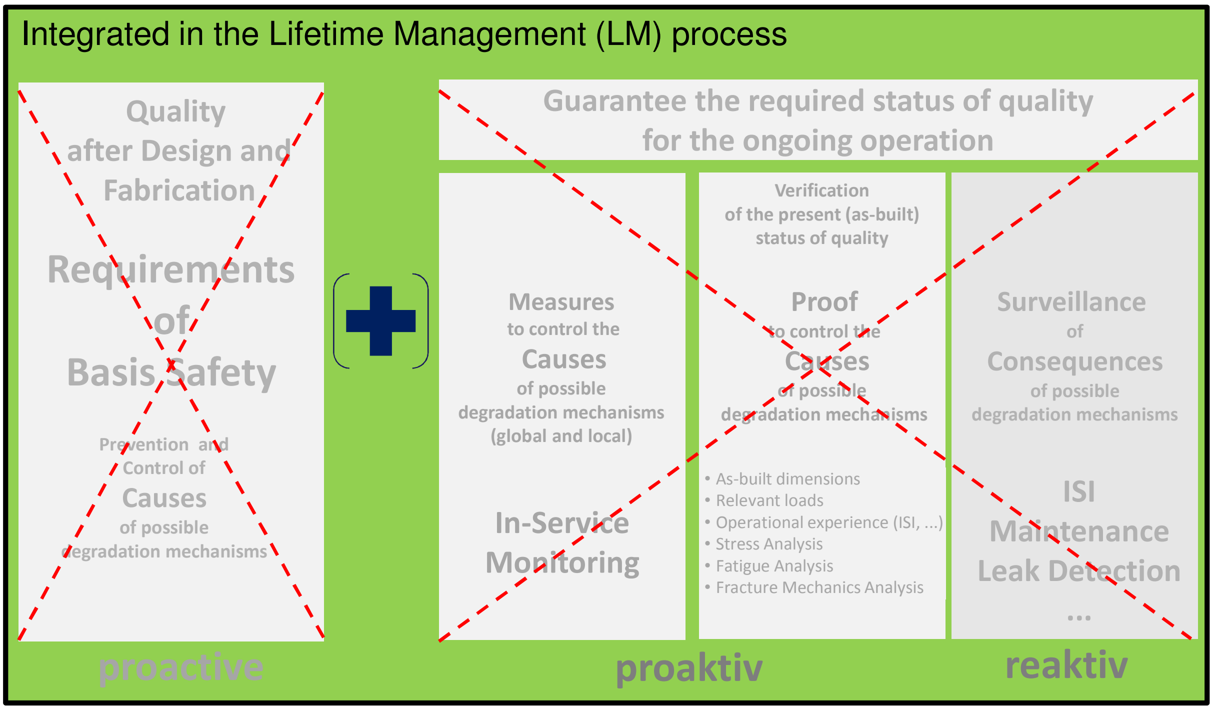


Fig. 12: Failure-oriented maintenance of group 3 SSC

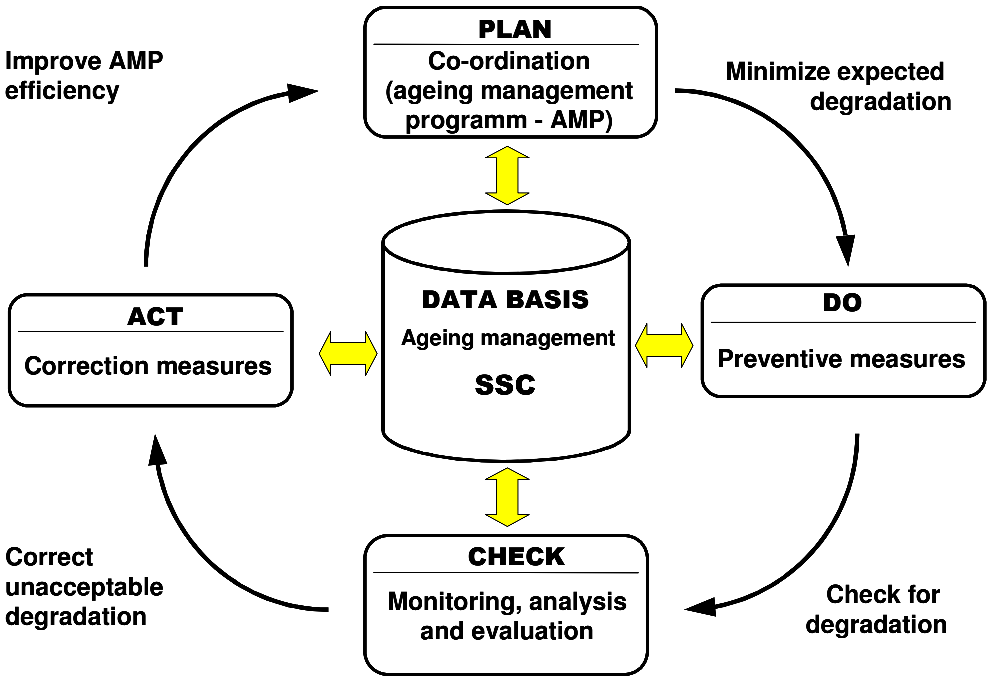


Fig. 13: Ageing management procedure (PDCA-cycle), [24] and [25]

7 Conclusion

- According to the technical safety concept (defense–in-depth concept) to be applied to NPPs the safety concept is designed to be preventive. For level of defense 1 and 2 measures and installations shall be applied to prevent the onset of anticipated operational occurrences and accidents as well as to prevent events with multiple failure of safety installations. Within this context for SSC possible operational damage mechanisms shall be controlled (monitoring of causes of possible operational damage mechanisms).

- For level of defense 3 (accidents) postulated accidents shall be controlled.

- Consequences of postulated accidents are controlled in a proactive way based on the Integrity Concept.

- A classification according to the required quality during operation:

  (i) Failure of the SSC shall be excluded to avoid subsequent damage (Integrity Concept - proactive measures).
  (ii) Failure of the SSC is allowable in single cases (preventive maintenance - reactive measures).
  (iii) Failure of the SSC is allowable (failure-oriented maintenance - reactive measures).

- Life time under operational conditions is dominated by the present (as-built) quality and the occurrence of ageing phenomena (of decisive relevance for the whole life time).

- By proactive measures (Integrity Concept) ageing phenomena are detected and controlled by appropriate measures. The quality is determined quantitatively in a fixed time interval. Failure of a SCC shall not be presumed.

- It is not possible to control the required quality just by monitoring the consequences of operational damage mechanisms (preventive maintenance). Thereby the required quality in operation cannot be quantified.

- The remaining life time of SSC may be evaluated by the Integrity Concept.

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