APPLICATION OF LIFETIME MANAGEMENT FOR MECHANICAL SYSTEMS, STRUCTURES, AND COMPONENTS (SSC) IN NUCLEAR POWER PLANTS

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Abstract

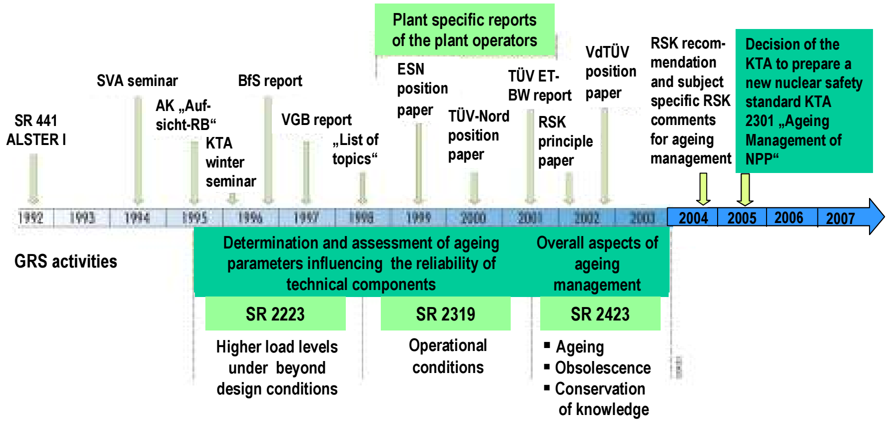
Guidelines, codes and standards contain regulations and requirements to guarantee a high quality of mechanical systems, structures and components (SSC) of nuclear power plants. These concern safe and reliable operation during the total lifetime (lifetime management), safety against ageing phenomena (ageing management) as well as proof of integrity (e.g. break exclusion or avoidance of fracture). Within this field 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 and the management of the technical and organisational aspects are demonstrated and explained.

1. INTRODUCTION

In most countries it has been stipulated that the licensing of nuclear power plants 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 [1] 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 realised in guidelines and in the nuclear standards [2][3][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;
- the quality of the SSC has to be guaranteed and documented throughout the lifetime (extensive quality assurance during design, manufacture and operation);
- the operational parameters (damage mechanisms) relevant for the integrity of the SSC are monitored and
- 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 lifetime (lifetime management), for the control of ageing phenomena (ageing management) as well as for proof of integrity (e.g. with the aim to demonstrate break exclusion) for mechanical SSC. In Germany the discussions on ageing of mechanical SSC to be included in a structured ageing management process for nuclear power plants started at the beginning of the 1990s [5][6], Fig. 1.



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. 1. Relevant ageing management activities in Germany – an overview.

2. DEFINITION AND METHODOLOGY

2.1. Lifetime management and classification of the components

Lifetime management, Fig. 2, stands for the integration of ageing management and economic planning for SCC in order to

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

Various engineering measures are required depending on the safety relevance of the SSC or for rea-sons of preventive maintenance [7][8][9]. Consequently, the SSC have to be divided into three groups, Fig. 2.

The first step within the scope of lifetime management of mechanical SSC is to select and arrange the SSC and to assign these to group 1, 2 or 3. The classification is according to the requirements of the nuclear codes and standards [3][4] 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.

- Group 1: Failure of the SSC shall be excluded to avoid subsequent damage, e.g. reactor pressure vessel (RPV) and main coolant lines (MCL). The required quality shall be guaranteed for the total lifetime. 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. 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).

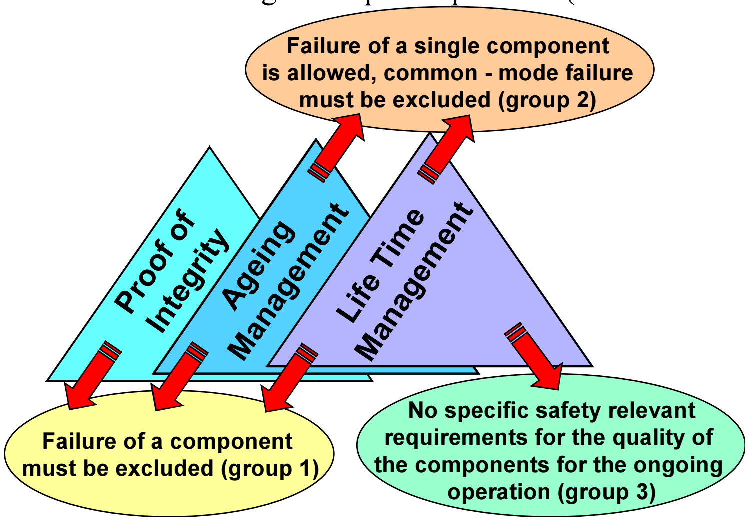


FIG. 2. Application of lifetime management, ageing management and proof of integrity for mechanical components of groups 1, 2 and 3

2.2. Aging phenomena and engineering measures

Ageing stands for the time-dependent gradual change of features and properties related to their func-tion, e.g. regarding

— the engineering (mechanical SSC, buildings, I&C),

— the systems and control devices relevant to the operation of the plant,

— the specifications and the documents,

— the plant operating staff.

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 may become obsolete compared to the state-of-the-art.

Ageing management covers all engineering and organisational actions for the plant operator to guarantee safe operation during the lifetime including control of the ageing phenomena.

Ageing management of mechanical SSC is the entirety of technical and organisational measures that guarantee the safe operation of the SSC for the lifetime 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.),

— 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, Fig. 3).

The terms technological and material-mechanical ageing are used as a synonym for all technical and organisational measures that guarantee the recording, monitoring and control of all possible in-service damage mechanisms. Causes and consequences of the in-service damage mechanisms are to be monitored or supervised. Furthermore follow-up actions have

to be carried out and any changes in current knowledge have to be recorded. These definitions and considerations are also in accordance with international procedures and methodologies, e.g. in [10].
Within the proof of integrity it has to be demonstrated that the load-bearing capacity is maintained for all relevant operational loads as well as accidental loads for the lifetime taking into account the specified or monitored number of load-cycles.
The proof of integrity for SSC assigned to *Group 1* is according to the fundamentals of the German basis safety concept (concept of break exclusion or avoidance of fracture resp. catastrophic failure) [11][12], Fig. 4. Consequently, "independent redundancies" will be effective since they are included in the basis safety concept to consider also any possible changes in operational conditions influencing the integrity of the SCC and to guarantee quality after manufacture, Fig. 5. A systematic procedure which is oriented on the basis safety concept, requires the following points to be considered to guarantee the integrity of components (for subsequent operation) such as, Fig. 6:

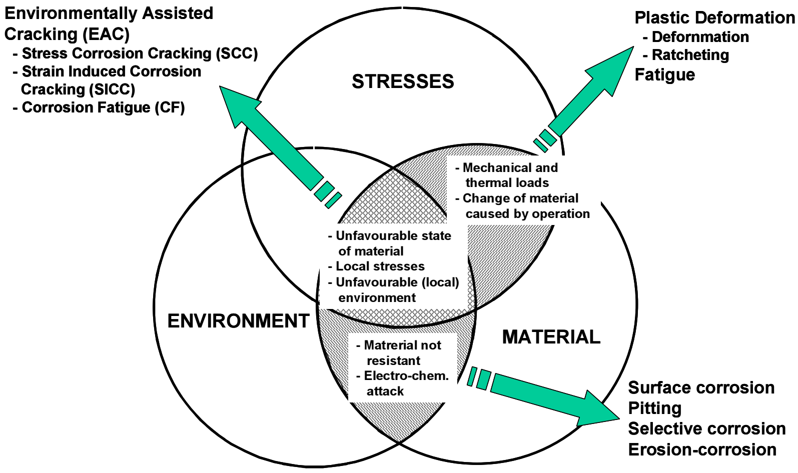


FIG. 3. Causes and consequences of damage mechanisms for mechanical components

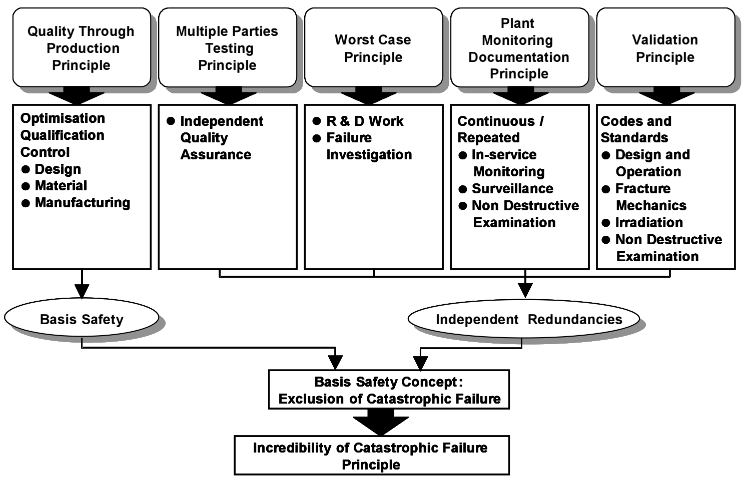


FIG. 4. German "Basis Safety Concept"

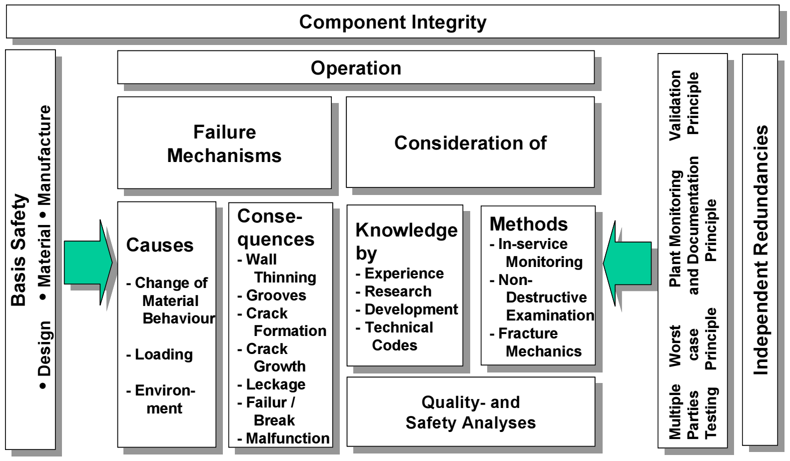


FIG. 5. Concept to proof the integrity of components

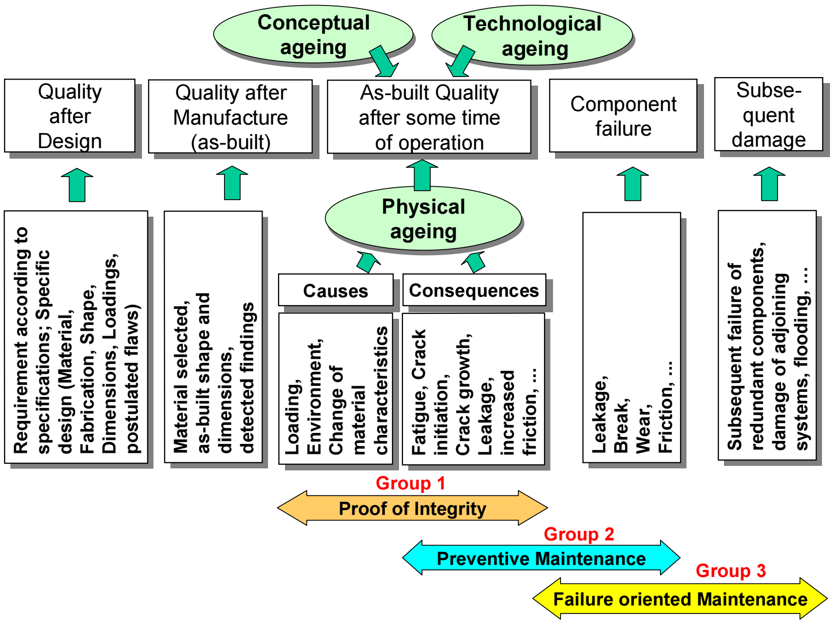


FIG. 6. Correlation between the state of quality as well as ageing and related to the groups 1 to 3

- The actual (as-built) state of quality (performance, design, loading) shall be in accordance with the particular requirements (guidelines, codes, standards). There has to be sufficient knowledge about the possible in-service damage mechanisms in the SSC, Table 1.
- This state of quality shall be guaranteed for subsequent operation by
  - in-service monitoring of the causes of possible in-service damage mechanisms and assessment of the data recorded (continuous measures),
  - in-service monitoring as well as periodic examinations (discontinuous measures) of the conesquences of possible in-service damage mechanisms and
  - follow-up of the state of present knowledge (reviewing the state of knowledge, consideration of research results and follow-up investigations of failure cases).

Table 1. Causes, consequences and proof of damage mechanisms

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

SSC are to be assigned to *Group 2* if they are of safety-related importance, but may fail in single cases. In doing so it shall be ensured that measures have to be taken during operation to maintain the required quality and to exclude “common-mode” failure. Subsequent failures are of no effect from the safety-related point of view. To maintain the quality requires preventive maintenance (time-oriented or state-oriented), Fig. 6.
SSC are to be assigned to *Group 3* if failure cannot be definitely excluded and subsequent failures are considered negligible from the safety-related point of view. There are no defined demands on the qual-ity in service. It is sufficient to maintain measures against failures.
The safety-related important SSC shall be included in these groups as defined in chapter 1 “applica-tion range” of KTA Safety Standard 3201.2 [4] as well as in the General Specification “Basis Safety of Pressurized Components” [3].

3. Quality of components after design and manufacture

Requirements on material, design, calculation, construction and fabrication are included in guidelines, codes and standards and in the “General Specification Basis Safety of Pressurized Components” [3] as well as in specifications. It is the responsibility of the plant operator to

prevent damage resulting from construction and operation of the plant in accordance with the state-of-the-art.
The assessment of the actual design and construction is based on requirements included in the KTA safety standards and in the RSK-guidelines as well as the specifications to be considered which show the state of quality obtained within the scope of design and fabrication. For the definition of the component quality the following items are of concern.

- Materials:
  - As-built status corresponds to the requirements stated in the specifications.
  - The materials selected correspond to their applicability (the mechanical and thermal loads have to be considered; sufficiently resistant against the environmental conditions).
  - Mechanical-technological and fracture-mechanics properties (base material and weld metal).
  - Product form, low sensitivity against all manufacturing processes especially welding.
  - Type and extent of testing, test certificates (acceptance certificates).
- Construction and layout:
  - As built status corresponds to the requirements stated in the specifications (dimensions, shape/structuring, welds and weld shapes, supports, repair measures, etc.).
  - The construction shall be in conformity with suitability for the intended function, with suitability for strength, intended material, intended manufacture (suitability for testing/fabrication) and easy maintenance and inspection.
  - A clear piping layout including supports and dampers.
- Stress and strength behaviour:
  Determination of the relevant stresses on the basis of specified loads by stress analysis, fatigue analysis and fracture-mechanics analyses.
- Inspections performed (state of findings):
  Results of inspections, e.g. non-destructive testing (NDT), within the scope of manufacturing and special tests.

The SSC quality assessed after design and manufacture represents the state prior to commissioning. Consequently, the results cannot be transferred to the actual as-built state of the SSC. Deviations have to be balanced out depending on the requirements such as detailed proofs, extended in-service monitoring, recurrent tests and optimised mode of operation.

4. Change of component quality during operation by possible damage mechanisms

For the definition of the quality for SSC in operation the parameters of concern influenced by operational conditions shall be defined and supervised. Damage occurring in SSC may be caused by unfavourable interaction of the parameters, Fig. 3, like changes of the material characteristics during operation, changes of the applied loads (e.g. mechanical, thermal stresses) and changes of the environmental conditions.
These mechanisms are able to damage the SSC due to operation and shall be controlled by measures, which result in no inadmissible change of the material characteristics and no inadmissible loading conditions (operational loads are recorded and well-controlled, no inadmissible dynamic loads).

The loads are mainly recorded using in-service monitoring. On the one hand, this is by standard in-strumentation (recording of global and local parameters) such as monitoring of important operational parameters and data to record global loads. On the other hand, it is by measuring the chemical water composition and local strains. It has to be ensured that for the determination of the position to be instrumented, the measured variable, the extent of measuring and the measuring equipment, the operational parameters, the mode of operation and the functioning of active components (e.g. snub-bers, valves) are considered in the above mentioned sense. Because of these aspects, measures to monitor the causes of possible operational in-service damage mechanisms, which means checking the influencing parameters, is of the highest priority and is indispensable for the SCC assigned to group 1.

Concerning SSC assigned to group 2 the consequences of damage shall be monitored or checked using periodical testing and in-service monitoring to control operation. The consequences of damage can affect the quality and/or the functionality of an SSC and may lead to failure. Such consequences are, e.g. wall thinning, notch formation and crack initiation, crack growth, leakage, fracture, etc.. Methods are implemented depending on the possible in-service damage mechanisms, e.g. [13]. For SSC of group 1 this requires redundancy in representative areas.
The procedure concerning the monitoring of the causes and consequences of in-service damage mechanisms in SSC is established in KTA 3201.4 [4], Fig. 7.

5. PROCEDURE FOR APPLICATION TO MECHANICAL SSC

5.1. Proof of integrity for group 1 SSC

The integrity shall be proved within the scope of the lifetime or ageing management only for mechani-cal SSC assigned to group 1, Fig. 2 and Fig. 5 to 7. The causes of possible in-service damage mechanisms shall be controlled. Damage mechanisms whose causes are not specifiable (e.g. stress corrosion cracking, high cycle fatigue, water hammer) shall be exclude e.g. by measures during construction and design and verified during operation. The following points have to be dealt with [14]:

- *Documentation and assessment of the actual (as-built) state of quality according to the respective requirements.*
  The actual design is according to the requirements on the material and the construction (design and calculation, layout) including manufacture. These requirements are laid out in the KTA safety standards and the RSK-guidelines including the general specification basis safety and specifications to be considered. The relevant loads shall be determined and must be checked within the scope of the
  - Stress analysis (relevant stresses on the basis of recorded data for operational loads and specified loads for accidental conditions taking into account the actual design).
  - Fatigue analysis (equivalent stress range resulting from the relevant loads and limitation of the fatigue usage factor based on the number of load cycles; this is of importance for the determi-nation of the recurrent non-destructive inspection intervals).
  - Fracture-mechanics analyses shall be performed for the minimum flaw sizes detectable by recurrent non-destructive testing, for postulated flaw sizes and, if needed, for flaws caused by manufacture. Postulated flaw sizes have to be

assessed in relation to their critical size under in-service loads and specified accidental loads. In determining the crack growth for the time of the inspection intervals the relevant in-service loads should be assumed. In case of determining operationally related flaws the critical size under in-service loads, e.g. relevant loads from in-service monitoring, including the specified accidental loads are to be assessed and as a function of the damage mechanism crack initiation and crack growth are to be determined.

If any flaws are detected caused by in-service damage mechanisms the causes shall be indentifed and the assignment of the SSC to group 1 shall be reexamined.

It needs to be clarified whether in-service related damage mechanisms may occur. Therefore, possible damage mechanisms shall be excluded or shall be identified in view of operational experience and the NDT results, as well as the present state of knowledge. The parameters that cause corrosion as well as the state after manufacturing are to be compiled according to the present state of knowledge for austenitic and ferritic materials.

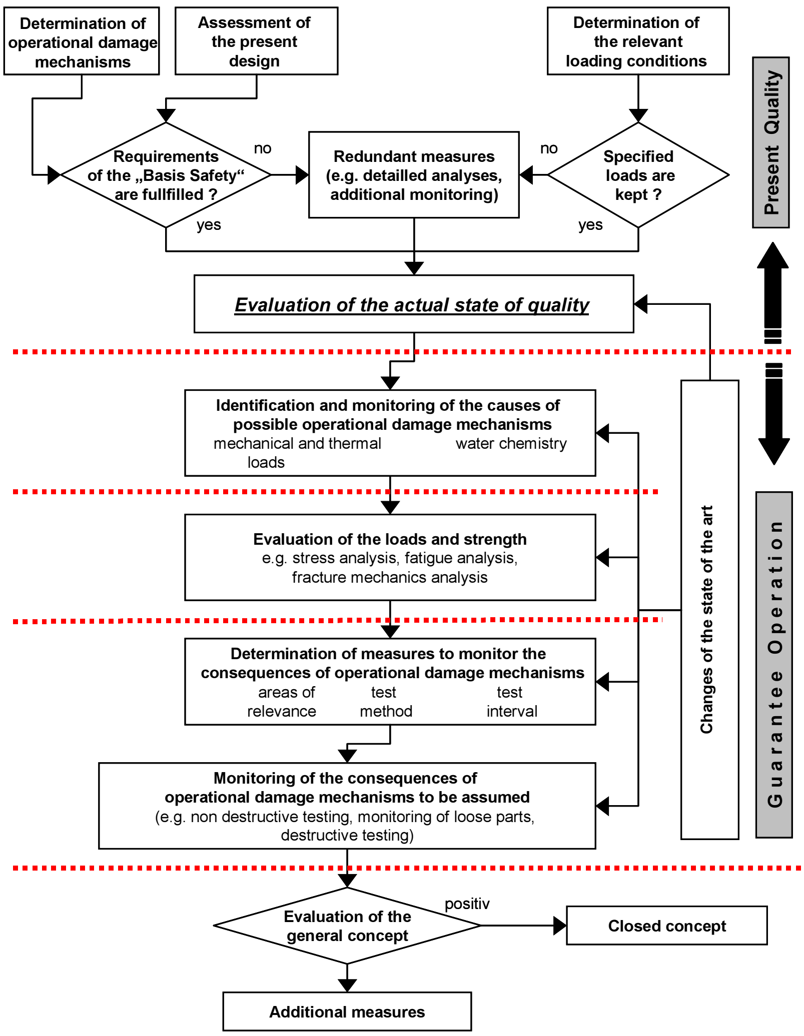


FIG. 7. Component integrity according to KTA 3201.4 [4]

— *The required quality shall be guaranteed for the total lifetime reflected by supervising and valuation of the influecing parameters*

  — Identification and monitoring of the causes of possible operational damage mechanisms. The proven quality of an SSC after manufacture or a certain time in operation shall be maintained during subsequent operation. The in-service monitoring of the plant is of greatest importance with the first priority to monitor

- the causes (influencing parameters) of possible in-service damage mechanisms (see Table 1). Knowledge about the actual loads is important because they are the basis for the stress analysis, fatigue analysis and fracture-mechanics analyses.
- Defining the influencing parameters for the causes of the damage mechanisms and their recording.
  The extent of in-service monitoring is to be defined on the basis of the assessment of the actual state of quality. The purpose of the standard instrumentation is to monitor the variables of state and data necessary for the integrity of the SSC. The purpose of the in-service monitoring and the recurrent in-spection is to guarantee the basic SSC design assumptions, especially loads (mechanical, thermal, corrosive) remain constant during operation and record probable changes. Furthermore, the in-service monitoring shall demonstrate that dynamic loads can be excluded and quasi-static global and local loads which are relevant to the integrity of the SSC can be recorded completely .
- Monitoring of the consequences of in-service damage mechanisms.
  The procedure is based on the requirements of the nuclear safety standard KTA 3201.4. The extent of the in-service monitoring is to be defined related to the possible damage mechanisms. This concerns the parameters important to integrity and data to guarantee subsequent operation (global and local measuring, leakage monitoring) as well as the extent of the periodic inspections (NDT and destructive testing). These inspections shall be applied to representative areas which result from assessment of the most critical stressed areas and shall monitor the consequences of possible damage mechanisms. The inspection methods and definition of the intervals is component-related depending on the component quality in relation to the damage mechanisms to be expected. The results of fracture-mechanics assessments for critical crack sizes and crack growth rates shall be considered. The investigation of removed parts is also part of the in-service monitoring. When changes, repairs and maintenance measures take place, consideration has to be made about the type of investigation performed on removed parts to extend knowledge and to optimise the assessment concept.

5.2. Preventive maintenance for group 2 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 rele-vance. This means that the actual (as-built) state of quality has to be maintained for subsequent op-eration. This takes place by preventive (time- or condition-oriented) maintenance.

- Demonstration and assessment of the state of quality according to particular requirements
  - 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.
  - Results of tests performed (state of findings of manufacture, NDT, …)

  - Operational experience (mode of operation, data records and results of operational in-service monitoring, failure investigations, NDT, maintenance measures, etc.).
  - Determination of the damage mechanisms
- Operational in-service monitoring and maintenance measures (time or condition oriented). The preventive maintenance can be organised in the following areas:
  - Maintenance (measures to keep the nominal condition)
  - Inspection and measurement (measures and actions to determine and asses the actual as-built status)
  - Repair work (measures to restore the required state of quality)

5.3. Failure-oriented maintenance for group 3 SSC

SSC assigned to group 3 are allocated to failure-oriented maintenance and are not to be considered within the scope of ageing management.

6. TECHNICAL AND ORAGNIZATIONAL MEASURES

The engineering and organisational measures required within the scope of the ageing management of mechanical SSC are oriented essentially on the recommendations by RSK and the criteria compiled by the BMU project SR2319 [15]. A database embedded in a Deming-process (PDCA-cycle) [16][17] is the essential element containing all information relevant to ageing management, Fig. 8. Running through the PDCA cycle the appropriate organisational 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 proc-ess. Additional information concerning operational damage mechanisms is included e.g. in [18].
The results obtained from research, technical publications, as well as circular letters and notifiable events and if needed findings from other accessible data bases have to be considered. The data are to be integrated into the power plant organisation according to a PDAC-cycle, Fig. 8. This includes in particular the following aspects:

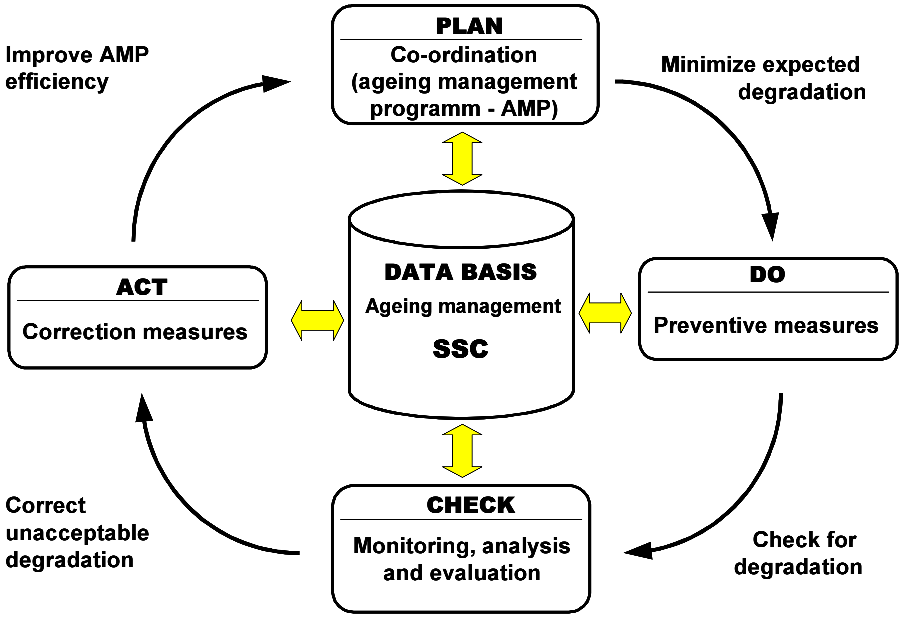


FIG. 8. Ageing management procedure (PDCA-cycle) [16][17]

- "Plan" (coordination) – co-ordinating 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 organisational and co-ordination mechanism.
  - Optimises, if necessary, the ageing management programme 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.
- "Act" (correction measures) – managing ageing effects
  - Preventive and corrective maintenance.
  - Replacement and maintenance history.

7. CONCLUDING REMARKS

Guidelines, codes and standards contain regulations and requirements to guarantee a high quality of mechanical SSC of nuclear power plants. This concerns safe and reliable operation during the total lifetime (life-time management), safety against ageing phenomena (ageing management) and proof of integrity (e.g. break exclusion). Within this, ageing management is a key element. Depending on the safety-relevance of the SSC under observation, including preventive maintenance, various engineering measures are required. In particular to be considered in this connection are the mechanisms which contribute system-specifically to the damage of the components and systems and define their control-ling parameters which have to be monitored and supervised by appropriate continuous or discontinu-ous measures. The approach to assure the high standard of quality in operation and the processing of the technical and organisational aspects are demonstrated and explained.

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