Methodology for lifetime characteristics assessment of mechanical equipment in nuclear power plants. Ageing management of NPP mechanical equipment

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Abstract. In the 20s of the twenty-first century many nuclear power plants around the world have reached the final years of their design lifetime. The technical aspects of Plant Life Extension (PLEX) activities involve tests, in addition to the routinely performed ones, of the materials and structures of reactor units, as well as the carrying out operability analyses. In relation to this, the absence of regulatory and methodological basis becomes apparent, in Bulgaria as well. In recent years, new approaches have been adopted for evaluation of lifetime characteristics of components. The algorithm implemented is based on the active mechanism of degradation of the mechanical properties of materials. This paper discusses PLEX stages and corresponding activities. A methodology has been developed to assess the lifetime characteristics of Nuclear Power Plant (NPP) components such as to suit the stages of plant life extension and long-term operation. The methodology consists of: 1) Equipment classification; 2) Identification of the major degradation mechanisms of the mechanical properties of materials; 3) Determining the degradation effects of the mechanical properties of materials; 4) Identification of methods to control degradation effects (ageing); 5) Development of methodologies for evaluation of the ageing effects.

1. Introduction

In the 21st century, the development of societies utilises a variety of energy resources, and in the energy mix the share of power generation from nuclear energy is essential. A nuclear power plant's operating life for a specified service-time period is justified by the required strength margin [1]. Normally, the operating design life of nuclear reactors is 30-40 years. Data of the International Atomic Energy Agency (IAEA) show that as at April 2022, 133 nuclear power units have been operated longer than 40 years, while 164 units have exceeded 30 years of operation, (https://www.iaea.org/pris**,** [2]). Often the owners of nuclear power plants (NPPs) make decisions to extend the plant life of the power units: these capacities are the source of various benefits for society such as affordable electricity, energy independence, jobs, knowledge and technological development. However, in the operation of nuclear power plants and particularly the older ones, the level of safety may not be decreased. In Japan, the following analogy is very popular: nuclear safety culture is represented as a person standing on the steps of a downward moving escalator. The escalator is a metaphor for all burdening factors of the equipment, the resulting ageing of materials and design obsolescence, human errors, i.e., all those contributors to the reducing of nuclear safety. In order to maintain one's position on the escalator, the person has to make constant efforts, while climbing upward requires even greater efforts.

The technical aspects of PLEX activities involve supplementary tests, in addition to the routinely performed ones, of the materials and structures of reactor units, as well as carrying out operability analyses. If the results of such analyses show that the parameters' changes due to the burdening factors during the operation of the structure in the following 20-30 years will not lead to degradation, extending the service life of the structure is the solution that normally ensues.

In relation to this, the absence of regulatory and methodological basis has become apparent, in our country as well. The Bulgarian nuclear power plant, Kozloduy NPP, operates Units 5 and 6 with WWER-1000 reactor type. Their lifetime has been extended and they are currently in their long-term operation period.

In the second half of 2021, the European Commission faced the issue of whether to include nuclear energy in the Renewable Energy Directive to deliver on the European Green Deal. Regardless of the understanding of the benefits from obtaining cheap electricity, the problem that surfaced again concerned the safety of nuclear power plants and if they should continue operation once their design life has expired. In December, 2022, the IAEA will be holding in Vienna the 5th annual conference dedicated to NPPs service life extension.

The topic of this paper is prompted by the problems associated with the operational life extension of nuclear power plants while ensuring the safe operation of the power units.

2. National approaches to the extension of NPP's operational life

The technological evolution level of the individual countries manifests in different approaches to the resolution of nuclear energy lifetime issues. Various national approached have emerged in this specific scientific area of lifetime extension of nuclear power units.

France is one of the pioneers to table the issue for extending the service period of nuclear power units. Plant Life Extension (PLEX) activities date back to the 80s of the 20th centuries. At present, France has 56 nuclear reactors in operation, and 14 ones have gone through final shutting-down for decommissioning. The French principal programme on ageing rules that the functions of all Structure, Systems and Components (SSCs) subject to ageing mechanisms shall remain within the design limits and safety criteria [3]. The ageing management programme covers SSCs that impact safety of an NPP and are affected by ageing; analyses are conducted to identify SSCs degradation while taking into account the possibilities to maintain a particular facility, the challenges faced in case of replacement, the risk of unavailable disposal technology.

Russia has 38 nuclear reactors in operation, and 9 of them have been decommissioned [2]. The Russian ageing management programme comprises the following requirements:

- the systems and components shall be maintained so as to satisfy the reliability levels as necessary.
- the maintenance processes shall be optimised;
- ageing shall be subject to detection, the residual lifetime shall be estimated, and the ageing trend kept under control.

At present, Bulgaria has two nuclear reactors with their operational life extended (beyond the design one), and four reactors that have been decommissioned. The Bulgarian approach to the ageing management processes consists of several stages. The initial stage is a continuation of the equipment modernisation programme on Units 5 and 6, involving a set of 212 engineering and organisational measures.

The approach for condition evaluation of NPP components made of structural steel (such as heat exchangers, mechanical equipment and connecting pipelines) involves firstly - assessing the physical condition of a component, and secondly - performing residual lifetime assessments.

Ukraine has 15 reactors in operation and four in a final decommissioned state. The Ukrainian methodology, MT-D.0.03.391-09 [4], specifies the principles of brittle fracture toughness assessment of reactor pressure vessels (RPV) in operation. The different types of assessments are implemented for postulated defects, or defects found through non-destructive examination; non-linear fracture mechanics is applied.

In Hungary, there are four WWER type of reactors (Paks Nuclear Power Station). Over the past 20 years, the units have been in long-term operation. A characteristic feature of the Hungarian approach is that a dedicated regulatory basis has been developed - Hungarian Guideline 4.14 [5], based on Russian and American standards. The Hungarian Guideline 4.14 document lists the NPP components (as a minimum) for which time-limited ageing analyses (TLAA) need to be in place. The objective of the analyses is that: 1) the analytical calculations can be extrapolated towards the end of the long-term operation; 2) the conservative methods used for the initial analyses can be replaced with less conservative ones. Special attention is dedicated to safety indicators (markers) the level of which may not be decreased.

Spain has seven nuclear reactors. The SSCs ageing management is a process that requires periodic re-evaluation and upgrade. A major source for streamlining the process is the feedback from operating experience. Many of the modifications in the Spanish NPP ageing management programmes concern the maintenance activities: 1) Preparing and verification of a new guideline for SSC maintenance activities with regard to the access conditions to the equipment; 2) Preparing and verification of a new guideline for inspection of cables and their condition assessment; 3) Enhancement of training for the conduct of walk-downs; 4) Improvement of the identification of structural components.

The Czech Republic operates six nuclear power reactors. The Czech methods and criteria for identifying SSCs within the scope of ageing management require that: 1) SSCs are listed and data on component ageing are summarised; 2) Assessments have been completed and potential degradation mechanisms have been documented regarding properties that could affects safety functions; 3) The policy in place requires work for enhancing the current understanding of all dominant ageing mechanisms; 4) The data necessary for ageing assessment inclusive of baseline data, maintenance and repair data, etc. have been subject to systematisation; 5) The efficiency of maintenance and repair programmes has been assessed in terms of ageing; 6) Criteria and indicators for safe operation in long-term operation (LTO) have been developed; 7) The physical condition of SSCs has been evaluated including the current safety indicators and any conditions that might limit the operating lifetime.

In Canada there are 19 operating reactors with the deuterium-uranium unit type (Canadian deuterium–uranium plants, CANDU**)**. The PLEX methodology has evolved and it is implemented to CANDU reactor installations. In the equipment screening process, two categories of components have been identified: critical components and less critical ones [6].

The types of critical non replaceable equipment identified for conduct of systematic assessments of the CANDU units are as follows: fuel channels, steam generators, reactor units, reactor building and civil buildings, pipelines, turbine generator, pumps and heat exchangers, electric motors, breakers and cable systems, pumps and buildings. The less critical components and equipment have been allocated in groups on account of some typical characteristic - commodity groups (pumps and tools). Each group undergoes specific operability analyses. These analyses shall remain valid for the LTO period, while specifying the component specific features that are more vulnerable to the operating lifetime. The PLEX activities comprise: 1) Review of the whole operating history of a component, its design and manufacturing in terms of the ageing characteristics; 2) Diagnosing the ageing stressors and degradation mechanisms of the properties in all operating modes; 3) Evaluation of the component maintenance in terms of ageing management effectiveness; 4) Developing a lifetime estimate

The USA have 96 reactors. The SSCs assessments for LTO vary within a wide range for the various NPPs and may be either limited only to the principal critical components, or represent a significant survey of all the SSCs in a plant. The components get classified based on their significance for reliable and efficient nuclear power plant operation.

The SSCs assessment is made on the grounds of NEI 95-10 [7] guideline and is, in fact, an integrated assessment of the power plant and a review of the time-limited ageing analyses for SSCs covered with the licence. This integrated assessment of NPP consists of:

- identification of the materials and their interaction with the environment for structures and components within the PLEX scope;
- determining the applicable ageing effects that might affect the loss of their intended;
- issuing a programme for ageing management as needed to maintain these functions.

The time-limited ageing analyses contain qualification of the environmental impacts, fatigue toughness and neutron embrittlement resistance analyses. The analyses are evaluated in order to demonstrate that these analyses shall remain valid to the end of the LTO period, they can be projected to the PLEX end, and that the ageing effect will be adequately managed for LTO.

An element of key importance for the continuous improvement of ageing management at US nuclear power plants is the use of feedback from operating experience together with incorporation of the lessons learned in the ageing management programmes. The document NEI 95-10 [7] that forms the basis for extended operation licence evaluation renewal in the US, identifies operating experience as one of the 10 key elements of each programme for plant life extension. Although ageing management activities are described in the regulatory norms, it is expected that operating experience should be continuously reviewed over the NPP lifetime in order to demonstrate the programmes' effectiveness. Nuclear operators in the US have an exhaustive operating experience programme on the grounds of the INPO 10-006 document [8]. Using this programme, information is collected from sources at various nuclear power plants, namely:

- event reports of NPPs licensed by the Nuclear Regulatory Commission (NRC);
- exchange of information (bulletins, letters, summary of recommendations of the regulatory body), etc.

The process comprises activities such as:

- development of a database for defects/failures and data sharing with other databases (at other NPPs);
- performance assessment of the methods for monitoring, control and testing;
- performance assessment of the trend analysis methods;
- current state of energy industry (NPP operation, nuclear industry in general, studies);
- current technical legislation and regulations.

3. Summary of the measures for NPP lifetime extension

At a certain point in its life cycle, every NPP faces the issue of extending its service life or, respectively, decommissioning. With the growing number of years in operation, the number of failures/defects also goes up, as is shown in “Figure 1”. During the plant unit commissioning, failures on account of structures fitting in to one another are prevailing. Towards the end of the design lifetime, the number of failures/defects due to ageing of materials are predominant.

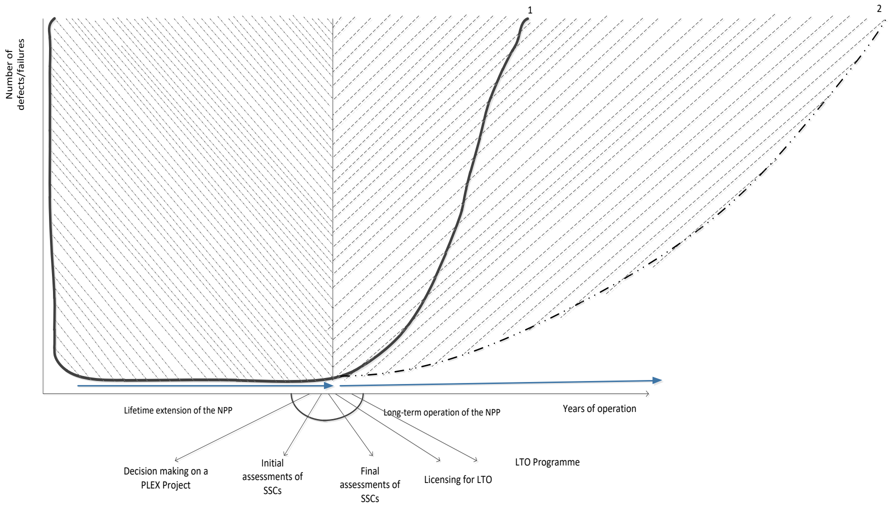

Figure 1. Variation in the number of failures/defects conditioned by the operational life of an NPP. Curve 1 - increase of failures/defects during the design lifetime of operation
Curve 2 - increase of failures/defects during operation in the lifetime extension period

A summary of the stages and activities for plant life extension is shown in “Figure 2”.

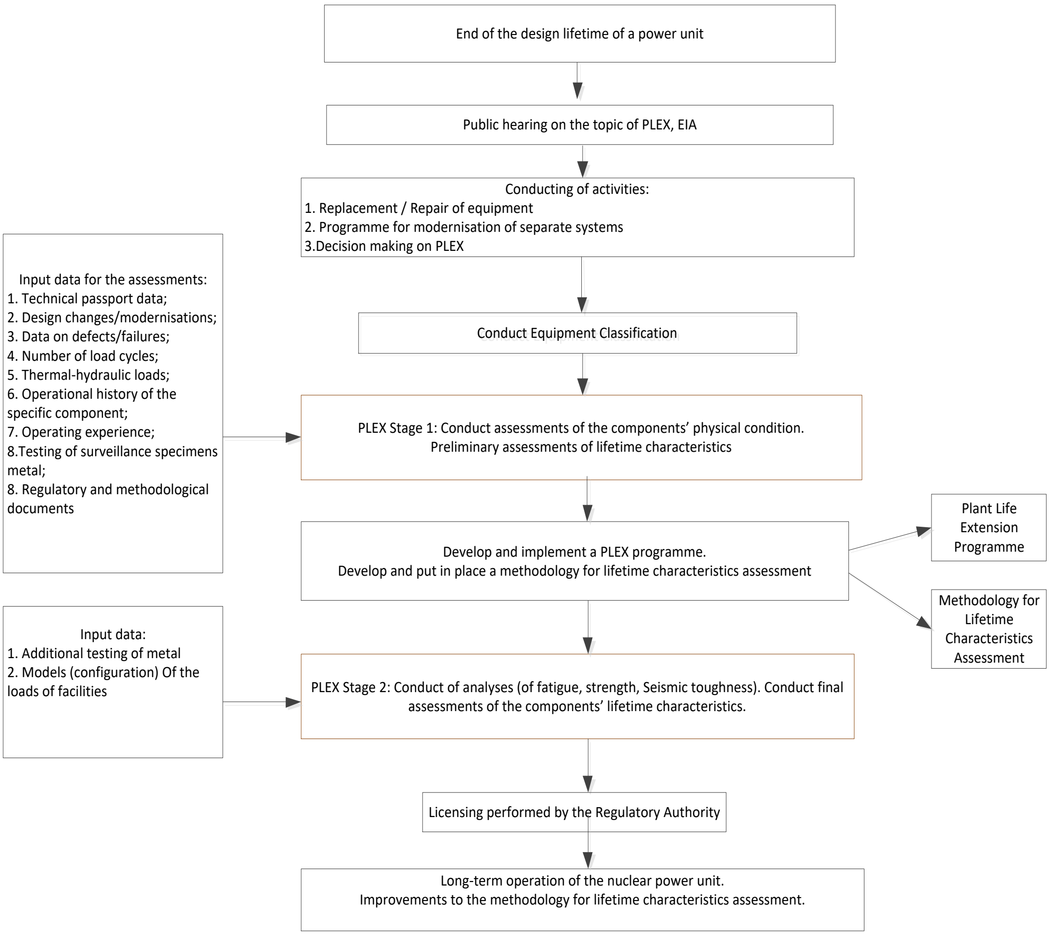

Figure 2. Stages and activities during a reactor installation lifetime extension

Prior to making a decision about plant life extension there has to be the understanding, that adequate lifetime margin is available to continue the particular unit's operation:

- the reactor unit has been operated according to the Technical Specifications requirements;
- assessment results confirming the good condition of the components. Thus, in the first stage of a plant life extension project, the actual physical condition of SSCs is assessed, while in the second stage analyses are made of the strength, fatigue, seismic toughness.

4. Ageing Management of equipment in an NPP - general principles

Experimental and operational studies for evaluation of the impact of mechanical properties degradation on the safe operation of the reactor unit are undertaken mainly on account of the NPP Technical Specifications requirements.

The standard (routine) testing (or maintenance and repair) will include:

- programme for in-service inspection of the base metal, built-up surfaces and welded joints of equipment and pipelines [9, 10];
- periodic monitoring of the corrosion status of components and systems;
- assessment of the metal of surveillance specimens from the RPV;
- strength analyses.

During operation of an NPP, the residual life is monitored by assessment of the lifetime characteristics that define the occurrence of a limiting condition. Limiting conditions occur in the following cases:

- upon reaching of unacceptable residual deformations due to ductile deformations, corrosion, mechanical or erosion wear, radiation exposure;
- upon the occurrence of any discontinuity on the surface or below the surface of a structure;
- when service life characteristics have reached their permitted limit values (such as limit number of load cycles / hours operating under load).

In general, the occurrence of a limit condition can be assessed through strength margin factors. Condition assessment uses regulatory documents that specify the final limit conditions of the components.

The conduct of routine in-service inspection (testing, measurement, monitoring) is followed by condition assessment, generally speaking. The aim of such assessment is to provide confidence that the tested facility (structure, assembly unit, etc.) can be safely operated for a future period of time.

The assessment of a facility can be described in two stages:

- performing periodic technical diagnostics;
- evaluation of the plant lifetime characteristics.

The input data for performing the technical diagnostics of a facility (such as the RPV, steam generator, pressuriser, main coolant pipeline) include (technical) passport data, data resulting from destructive and non-destructive examination methods, information about failures, number of work cycles worked in different operating states, regulatory requirements for strength, etc.

Next, there follows the application of a physical-statistical algorithm to process the available data.

The process of technical diagnostics issues the output data in the form of reports on condition assessment and reliability assessment.

The knowledge and theories accumulated over the past two decades show that the facilities technical diagnostics is performed in two consecutive stages of:

- assessing the degree of ageing of the equipment;
- evaluation of the change in the initial parameters of equipment as a function of ageing;
- on the grounds of the above reports, forecasts are made of any model of parameter failures.

The mechanisms of mechanical properties degradation and their impact on the operability of equipment tend to become evident only after some time has passed from the beginning of operation of the equipment. At the plant design and commissioning stages, these mechanisms and especially their combined action was not known; they get manifested after decades of operation. Thus, at the plant life extension stage (PLEX) it becomes clear that ageing effects need to be monitored not only as actual events, but also in terms of their prevention over the whole lifespan of the equipment. For the performance of technical diagnostics of NPP facilities and components, currently, there are neither standards in place, nor a generally accepted unified methodology or scientific support.

There are methodologies for assessing the residual life of individual components of the reactor units [11 ÷ 14]. There are IAEA documents that provide guidelines on ageing management of nuclear power plants equipment, such as: 1) IGALL, Ageing Management of Nuclear Power Plants [14], and 2) Unified Procedure for Lifetime Assessment of Components and Piping in WWER NPPs during Operation, Verlife [11]. In recent years, new approaches have been adopted for evaluation of residual lifetime characteristics. They implement an algorithm based on the active mechanism of mechanical properties degradation, as is shown in "Table 1".

Table 1. Measures for equipment ageing management.

Process of identifying adequate measures for ageing management of equipment		
Input data	Requirements	Output data
Requirements in the Technical Specifications for the NPP equipment. Data on the SSCs condition after implementing the methodologies for surveillance, monitoring and testing. Data from the equipment technical diagnostics. IAEA recommendations and documents [11, 15].	All the preceding activities shall be implemented via a unified document - an ageing management programme.	Ageing management programme, contains measures. The measures can be prescribing additional surveillance, monitoring and testing; replacement of the equipment; prescribing additional analyses. The programme shall be implemented in order to be acted upon at NPPs; it shall be a live document, subject of continued updating till the end of the PLEX period.

The currently effective regulations and standards do not have a methodology for evaluation of the lifetime characteristics of the equipment of a nuclear power plant unit – a methodology based on the approach in which assessments of the facilities are performed in accordance with the degradation mechanisms of the material's mechanical properties. In order for an evaluation methodology to be applicable to the hundreds of different commodity groups in an NPP, some practical issues need to be addressed such as performing equipment qualification.

5. Essence and application of the methodology for the assessment of lifetime characteristics

The methodology for assessing the operating life characteristics of equipment outlines the approach and common points to adhere to in the process of assessing components in NPPs.

The methodology consists of:

1) Equipment classification;
2) Identifying the main degradation mechanisms of the materials mechanical properties;
3) Identifying the effects of degradation on the material's mechanical properties;
4) Identifying methods to control the effects of degradation;
5) Development of methodologies for effects' assessment.

Each of the above activities comprising the methodology is detailed herein below. The methodology is suitable for application at the initial stage of PLEX preparation, as well as prior to the LTO period.

5.1. Equipment classification

The NPP equipment is allocated in technical systems, components and structural assemblies and is, in fact, a huge set of individual parts. As it is impossible to assess the condition of each component, systematisation per group is needed. Implementing equipment classification allows for commodity groups to be specified of equipment subject to assessment in terms of safe operation during the LTO period.

Firstly, the equipment is classified on the basis of the economic consequences from its replacement or repair [1]:

- category 1: Irreplaceable equipment reactor pressure vessel and reactor protection systems;
- category 2: Replaceable equipment the replacement of which is too expensive and the downtime period - too long (steam generator, separator - reheater, etc.);
- category 3: Equipment the main function of which is to ensure reliability and safety; it is highly sensitive to ageing, yet the replacement approaches are not so costly;
- category 4: Equipment not included in the preceding categories 1, 2 or 3.

The second type of equipment classification uses the criterion “equipment significance for ensuring the operational safety of an NPP”. The mechanical equipment is subdivided in:

- equipment of the safety systems;
- equipment of the systems important to safety;
- other equipment.

The third classification uses the criterion for current physical condition of the equipment. To identify the elements that are of critical significance regarding their impact on safety, summary information is prepared on failures and defects of NPP equipment elements. This is followed by analysis of the statistical data for failures due to metal degradation. Once the mechanical equipment has undergone these three types of classification it becomes clear which components and systems will be included in the scope for assessment of the lifetime characteristics. This screening process adheres to several typical considerations that may not be omitted:

- The groups of equipment for assessment include commodity groups (i.e., steam generator SG group; the physical condition is reviewed of all the steam generators in the SG group; however, the most detailed analyses (e.g., strength analyses) can cover only the steam generator with the worst physical condition within the group. The results from the assessment of this specific SG are regarded as applicable to all the remaining SGs in the group);
- The equipment at the borderline between systems needs to be carefully identified and also included in the scope for assessment. “Table 2” depicts the process of equipment classification.

Table 2. Equipment classification process.

Input data	Conducting SSCs classification	Output data
Technical Specifications of the NPP, technical passports and drawings of SSCs. Equipment of the safety systems, the systems important to safety, and other equipment. Economic analyses of the cost price of SSCs, inclusive of the power unit’s downtime. Data on failures and defects of the SSC metal. Equipment operated under similar environment conditions.	Conduct of several types of classification. Ranking of the pieces of equipment. Grouping of the pieces of equipment (e.g., the SG group).	SSCs classification per individual indicators. Listing of SSCs subject to lifetime characteristics assessment for the purpose of lifetime extension (the Bulgarian approach). Commodity groups subject to lifetime characteristics assessment (the approach of the NPPs in Central and Western Europe).

5.2. Main degradation mechanisms of the mechanical properties of metal of the Water-Water Energy Reactor (WWER) equipment on NPPs

To achieve effectiveness of the activity for assessment and lifetime management of the facilities it is important to firstly identify the contributors to the mechanical properties' degradation. In fact, during the operational life of a nuclear installation, data have been accumulated on metal inspection using destructive and non-destructive methods, also results from corrosion status monitoring, strength analyses, data from operating experience shared with other nuclear power plants. The process of collecting data on failures and defects of equipment elements on an NPP, implemented as part of surveys, naturally results in the need of setting up databases. For the purpose of follow-up analyses, a representative sample of the data is taken. Naturally, out of the numerous assemblies and elements of a reactor installation, the most important ones have to be selected, the residual lifetime of which should be tracked, i.e., classification shall be made.

The degradation mechanisms applicable to the classified equipment shall be defined. This should be done on the basis of:

- Operating environment conditions;
- The results from metal inspection through destructive and non-destructive methods, data from surveillance for corrosion, strength analyses, etc.

The typical degradation mechanisms affecting the mechanical properties of metal are contingent on the loading and the work environment that characterise that normally characterise the various reactor installation types [14, 15, 16].

Regarding WWER-type of plants, the mechanical degradation mechanisms include metal fatigue, corrosion (pitting corrosion, stress corrosion, corrosion fatigue, radiation-assisted corrosion), corrosion-erosion, growth of fatigue cracks as a result of cyclic loading, embrittlement and hardening due to the neutron flux, thermal embrittlement, radiation-induced size changes, phase transformations and wear. "Table 3" contains input and output data for identification of the mechanical degradation mechanisms of equipment.

The effects of the degradation mechanisms thus identified have been studied separately from one another, in laboratory conditions, while the effects of their combined action can be traced only in actual working conditions. This imposes the need of setting a data base of failures and defects.

Table 3. Process for identification of the mechanical degradation mechanisms of equipment.

Process for identifying the degradation mechanisms of the material's mechanical properties		
Input data	Knowledge	Output data
Results from metal inspection using destructive and non-destructive methods, results from corrosion status inspection, strength analyses. Metallographic data of the metal condition. Failures and defects data. Data from operational experience shared with other NPPs regarding equipment failures and defects. Typical mechanical degradation mechanisms of metals - research knowledge accrued. Working conditions of the facility. Operational history incl. number of operational load cycles.	Physical-statistical models of degradation.	Degradation mechanisms specified for each classified facility. Both the actually manifested mechanisms and the potential ones (that may occur in the future) shall be identified. Ranking of the identified mechanisms according to their degree of importance (severity). Database of failures and defects.

5.3. Mechanical degradation effects of metal of the equipment

The final degradation effects of the mechanical properties of metal of the equipment (ageing effects) are manifested in terms of loss of operability of the components and systems, as is shown in “Table 4”.

Table 4. Degradation mechanisms and further degradation effects that characterise NPP equipment.

Mechanism of mechanical properties degradation	Degradation effects
General corrosion.	Degradation of the surfaces affected.
Corrosion on the inner surfaces of vessels and systems	Emergence and growth of discontinuities.
Stress corrosion.	Accelerated growth of discontinuities posing a danger of brittle fracture.
Corrosion of pipes and piping systems.	Emergence and growth of discontinuities.
Corrosion wear.	Reduced wall thickness of pipes/elbows/T-pipes
Erosion.	Emergence and growth of discontinuities.
Flow-accelerated corrosion.	Flow-accelerated corrosion on the inner surfaces of vessels and pipes. Reduced wall thickness of pipes/elbows/T-pipes, etc.
Neutron embrittlement.	Increased temperature of the metal cold brittleness, danger of brittle fracture. Emergence and growth of discontinuities. Discontinuities grow quickly, thus posing a danger of brittle fracture. Form changes (deformations). Changes in metallographic phase structures.
Thermal embrittlement	Material embrittlement. Especially significant following a operational period of considerable length (100,000 hrs or 200,000 hrs).
Fatigue	Metal fatigue degradation. Emergence and growth of discontinuities. Growth of discontinuities posing a danger of brittle fracture.
Wear	Degradation of the surfaces affected (sealing surfaces, in most cases). Emergence and growth of discontinuities. Growth of discontinuities upon further operation.

Metal degradation effects are identified through methods for surveillance, monitoring and testing of metal. The ageing effects occurring get measured through ageing indicators. The methods support the trending of ageing indicators. These methods form part of the maintenance and repair measures taken by each power plant in operation, while for the purposes of plant life extension additional metal inspections (complementing the standard ones) are implemented [16, 17, 18]. “Table 5” contains input and output data for identification of the mechanical degradation effects of equipment.

Table 5. Input and output data for identification of the mechanical degradation effects of equipment.

Process for identifying the degradation effects of the material’s mechanical properties		
Input data	Knowledge	Output data
Results from metal inspection using destructive and non-destructive methods, results from corrosion status inspection, strength analyses. Metallographic data of the metal condition. Results from condition monitoring	Understanding the models of degradation and deformation	Specified degradation effects ensuing from the facility inherent degradation mechanisms. Ranking of the effects according to their importance for the structural

including of (automated) computerised systems. Failures and defects data. Identified mechanical properties' degradation mechanisms. Requirements of the normative, regulatory and reference technical documentation. Operational experience shared with other NPPs regarding equipment failures and defects.	integrity and operability of the facility. Degradation effects database.

5.4. Inspection methods for the mechanical degradation effects of metal of NPP mechanical equipment

5.4.1. Deterministic methods. The components' strength and lifetime in WWER reactor installations are justified via deterministic methods using strength margin coefficients [19]. The limit condition of NPP equipment and piping is determined per strength criteria, taking into account the operating environment and the condition of the structure.

The practically implemented deterministic methods are:

- Non-destructive and destructive testing of metal to check for any discontinuity and its type, size and location;
- Metallographic methods of non-destructive and destructive testing of metal to measure the values of its mechanical characteristics, metallographic structures, intergranular corrosion, structural defects, etc.;
- Analyses of strength and fatigue aspects, vibration state analyses.

The degradation mechanisms are manifested via the degradation effects, and the latter can be identified by inspection methods, such as, [9, 20, 21, 22, 23, 24, 25]:

- Corrosion, erosion: Visual testing (VT), penetrant testing (PT), magnetic particle method (MT), eddy-current testing (ET), ultrasonic testing (UT), radiographic testing (RT), metallography;
- Wear; VT, ET, UT, metallography;
- Fatigue: VT, UT, PT, metallography;
- Thermal ageing: VT, PT, UT, metallography;
- Radiation embrittlement: Mechanical testing, metallography.

"Table 6" shows the process of implementing adequate inspection methods.

Table 6. Process of identifying suitable methods for equipment inspection.

Process of identifying suitable deterministic methods for equipment inspection		
Input data	Knowledge	Output data
Inspection methods specified as per the NPP technical specifications. Inspection, testing and monitoring methods applicable in an NPP and ensuing from the current level of advancement of science and technologies. Equipment failures and defects database. Degradation effects database.	Understanding of the degradation process and knowledge of the material degradation models. Understanding of the manner of interaction between the field, the signal (inspection method) and the facility. Knowledge of the significance of the non-conformances and defects found through inspection.	A list of the applicable inspection methods for each facility within the plant life extension scope. Specified features of the method, such as resolution capability, sensitivity, confidence level, etc. Specified documents (standard, internal procedure) for each method of inspection. Compliance assessment document for the results obtained.

5.4.2. Probabilistic testing methods. Probabilistic methods of equipment lifetime assessment have not been developed or employed so far. It is not possible to make explicit preliminary predictions on the failure-free operation of facilities. The NPP Technical Specifications document does not provide for implementing of the probabilistic methods; neither have they been specified in any other regulatory technical documentation. Therefore, it is only logical to ask about the extent to which these probabilistic methods are effective, and if they can be used to predict lifetime characteristics. Nevertheless, on numerous NPPs in the US, lifetime extension of the power units is implemented on the grounds of the lifetime assessment conclusions made through probabilistic methods applied to the equipment functionality, system redundancy, etc. (e.g., the probability is assessed of a system failure due to a safety valve failure, etc.)

The Weibull probabilistic distribution is suitable for evaluation of metal lifetime. This distribution regards continuous structures, made up of many threads, and the subject of assessment is the probability of any of these threads breaking. If metal is considered as a structure of continuous atomic crystal lattices, then the distribution reviews the probability that one of the threads should break, (i.e., causing a discontinuity in the atomic structure), or that a defect will occur in the metal [26].

The process of identifying suitable probabilistic methods for assessment of the lifetime characteristics of equipment is shown in “Table 7”.

Table 7. Process of identifying suitable probabilistic methods for equipment surveillance.

Process of identifying suitable probabilistic methods for lifetime characteristics assessment		
Input data	Knowledge	Output data
Data on failures and defects of the equipment or materials.	Understanding of the degradation process and knowledge of the material degradation models. Knowledge of probabilistic models. Applying suitable models.	Probabilistic assessment of the components’ lifetime characteristics.

In particular, probabilistic methods based on metal defect data can be argued to be effective when the methods have incorporated sufficient data to support an understanding of the nature of degradation. The methodological part shall contain data on the loads and work environment, the actual facility defect shall be clearly defined, also the change in the mechanical properties during operation, and the degradation model.

In order to satisfy the NPP Technical Specifications, the probabilistic methods have to be applied in combination with the deterministic ones in the process of lifetime characteristics evaluation.

5.5. Methodology for assessment of the lifetime characteristics of facilities

The methodology is targeted at assessing the lifetime characteristics inherent to the specific components/assemblies/systems (herein below “facilities”).

5.5.1. Facility for assessment. This section shall include a description of the component, assembly or systems, technical passport data and mechanical properties of materials, drawings, work environment conditions, available strength analyses, design changes, etc. Further, the section shall describe the facility’s functioning, the operating modes (states) implemented, etc. The operational history of the facility shall also be attached clarifying the year of commissioning the facility, what modernisations of design modifications it has undergone, any specificities, etc. All the statistical data of the facility as needed for the assessment shall be input in this section, namely:

1) Number of operational modes (states) implemented, number of cycles (in hours);
2) Number and nature of past failures;
3) Metal defects and their parameters (location, type, size);
4) Maintenance and repair actions, i.e., the methods implemented to track lifetime characteristics, applicable programmes, procedures, etc.

5.5.2. Place of assessment performance. This section shall describe the place (places), arrangements for and conduct of the assessments.

5.5.3. Assessment performance period. This section shall state the time period over which statistical data of the assessed facility were collected (years from … to…, or the first *n* number of years following the commissioning, etc.). These data are of importance for trending the processes.

5.5.4. Methodological parts (calculations, graphs, statistics, etc.). This section shall describe the specific methodological parts such as the physical-mathematical model of testing/measuring, the method of testing/measuring, the instruments and manner of testing/measuring, input data and the periodicity of their collecting, assessment using either the deterministic or the probabilistic method, the manner of data systematisation, the type of statistical processing implemented, location and manner of storing the raw and the systematised data, the departments that own each of the processes, etc. The methodological part focuses on the specific mechanical degradation mechanism of the materials, explains the ageing effect and points out the method of measuring/testing that captured this effect, i.e., the method for measuring the ageing effect. The lifetime characteristics assessment may use either a deterministic, or a probabilistic method (see example in "Table 8"). Also, reference has to be made to the regulatory documents for compliance assessment as applicable to the specific indicator.

Table 8. Example of lifetime characteristics assessment in the presence of corrosion-erosion impact.

Degradation mechanism	Ageing effect	Effect indicator	Method of indicator measurement	Lifetime characteristics assessment using a deterministic method	Lifetime characteristics assessment using a probabilistic method
Corrosion-erosion of the metal on the inner surface of pipes/elbows/ T-pipes.	Corrosion-erosion wear of the metal on the inner surface of pipes/elbows/ T-pipes.	Decrease of wall thickness of pipe/ elbow/ T-pipe.	Ultrasonic one-sided thickness measurement of the wall of a pipe/elbow/ T-pipe (UT method).	Comparing the measured thickness values against the minimum permitted as per the passport of the pipe, or using some internal methodology.	Estimate of the time when a limit condition will occur. The pipe/elbow/T-pipe wall thickness decrease will reach a value that is below the permitted limit as per the passport data or the internal methodology adopted.

5.5.5. Results. This section shall contain the results from the implemented methodology parts for assessment of the lifetime characteristics of the facility.

5.5.6. Recommendations of the methodology. The recommendations (conclusions) are made in terms of the significance of the results from the lifetime assessments for the future safe operation of the assessed facility (structure, component). The conclusions should always refer to the requirements - normative, regulatory and technical, and design ones for operation, maintenance and repair of the facility. It is particularly important to provide recommendations for the further operation of the facility. The conclusions drawn from the lifetime characteristics assessments form the basis of ageing management of the NPP equipment. “Table 9” shows the process of preparing methodologies for lifetime characteristics assessments.

Table 9. Process of preparing methodologies for lifetime characteristics assessment.

Process of preparing methodologies for lifetime characteristics assessment		
Input data	Knowledge	Output data
The methodology specifies the input values relevant to the degradation process, e.g. The history of thermal-hydraulic loads and number of operating cycles worked, parameters of the working environment, etc., any available analyses of strength characteristics, design changes, etc. Requirements of the Technical Specifications. Description of the physical-mathematical method of measurement. Data resulting from the method of measurement - a representative sample, identified for each method. Periodicity of sample data collection / updating. Data on the work environment loads. Data of the actual defectiveness of the facility, mechanical properties changes during its operation. Information on the degradation model.	Understanding of the physical-chemical processes that occur between the object and the penetrating body, fluid or signal/field depending on the method for inspection, testing, measuring or monitoring.	The methodological part for performing of inspection/testing/measurement/monitoring for each method and inspection. The document shall specify the instruments, period for performing, responsibilities, manner of obtaining the data. Within the methodology, or in a separate document, the manner of data verification shall be specified, as well as of making inferences and drawing conclusions. Methodological part of the lifetime characteristics assessment - for each assessment method.

6. Conclusions

Nuclear facilities lifetime extension is a topical issue for many nuclear power plants in Europe, Asia, USA and Canada. At the start of the plant life extension process each power plant needs guidelines as to the nature of the upcoming process, the need of additional metal studies and analyses. This is where, publications on the subject come handy and serve as guidelines.

The methodology for assessing the lifetime characteristics of nuclear power plant equipment defines a new approach for technical diagnostics and assessment, based on identifying the effective metal degradation mechanisms of equipment.

The mechanical characteristics degradation effects can be measured (monitored, tested) using deterministic and probabilistic methods, as well as by a combination of them. The deterministic methods have been specified in the regulatory documents, while there is no such regulatory basis for the probabilistic methods.

The methodology for assessment of lifetime characteristics summarises the stages and activities in the plant life extension period and the long-term operation period. It has to be pointed out that there exist significant differences between NPPs in terms of their standard testing, measurements and monitoring activities. For instance, some NPPs perform reactor pressure vessel metal inspection within 8-year periods, while others implement it within 4-year periods.

The methodology for assessment of the plant lifetime characteristics is an internal document for the PLEX and LTO stages. Each NPP develops it in a way so as to fit the level of its own operational, maintenance and repair activities.

An NPP will develop and implement its methodology for assessment of the plant lifetime characteristics at the PLEX preparatory stage, but will use it throughout the whole LTO period.

Sharing operational experience with other countries is important for proving the effectiveness of the ageing management activities.

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