AGEING MANAGEMENT EFFECTIVENESS FOR NUCLEAR POWER PLANTS

Ageing management

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INTRODUCTION

Atoms build up matter and are a source of a great deal of energy. Atomic energy today is used for electricity generation, medical and scientific research, or for exploring of submarine and cosmic worlds. There are over 450 nuclear reactors in operation worldwide. A 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 [2]. As at October 2016, of all the reactors in operation, 79 had been operated for over 40 years, while the service life of another 182 had exceeded 30 years (https://www.iaea.org/pris), Fig. 1.

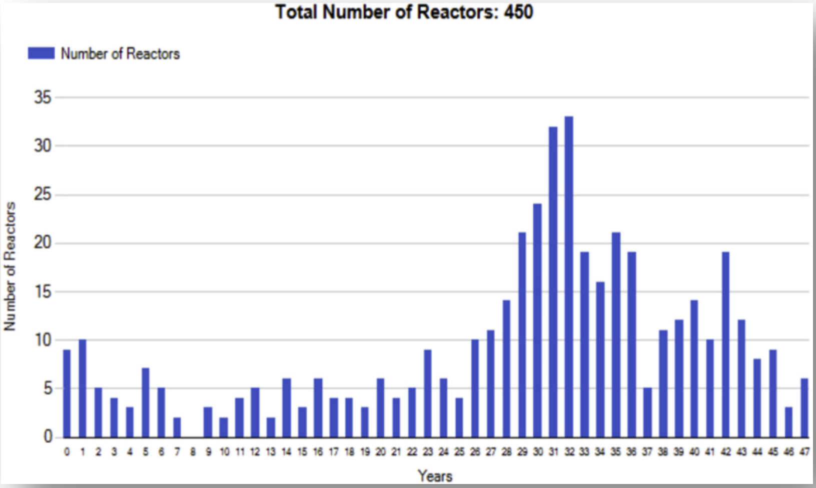


Fig. 1. Number of reactors/Years in operation

Often the owners of nuclear power plants (NPP) make decisions to extend the plant life of the power units: these capacities are the source of various benefits for society such as cheap 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 should 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 embodies all load 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. Continuous activities are needed to enhance safety culture. In the energy sector, the problem of ensuring the reliability of power equipment performance with each passing year is becoming more and more relevant, as the ageing of equipment significantly outstrips the pace of reconstruction and modernisation of the operating capacities. This problem is further complicated by the absence of a scientifically grounded concept of technical diagnostics and lifetime determination, as well as by the insufficient effectiveness of traditional non-destructive testing methods.

The opportunities for plant life extension (PLEX) of nuclear power plants are demonstrated through analyses, tests and adequate lifetime management for the expected long-term operation (LTO) [3]. Over the past decade, a growing number of countries have been putting the highest priority on the task of lifetime extension of nuclear power units. Technical disciplines have been emerging based on requirements for failure and defect prevention and ageing management of mechanical and electrical systems for plant life extension [4].

Failures and defects

Failures and defects of equipment and pipelines occur when a limit condition has been reached. Limit conditions are attained in the following circumstances:

- upon reaching of unacceptable residual changes of form due to plastic deformations, corrosion, mechanical or erosion wear;
- upon the emergence and growth of discontinuities;
- when service life characteristics have reached their ultimate limit values, for example the acceptable number of load cycles.

The natural process of mechanical properties degradation of the structural materials of the equipment components is expressed in terms of loss of their operability over time. The best visual presentation of this is the classical function for failure rate, λ (T), of a facility Fig. 2.

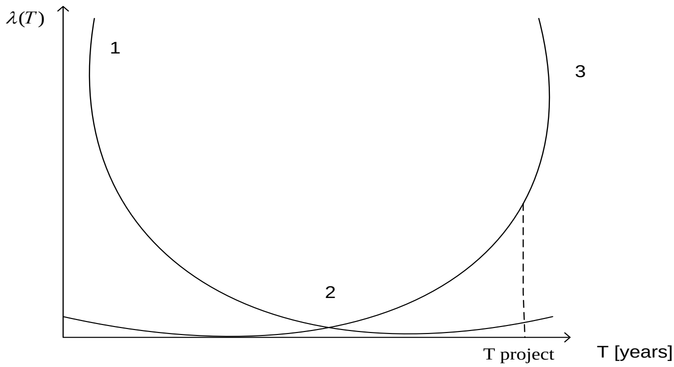


Fig. 2. Dependence of the failure rate function λ (T) on the operation time period T, 1 – failures due to equipment adjustments and installation; 2 – design operational life; 3 - failures resulting from degradation of the mechanical properties of metal

In the course of the power unit initial start-up and adjustments lasting for about 1-1,5 years, the main body of failures, defects and damages occur on account of design errors, or errors made during the manufacturing of facilities and welding of joints [5]. Once they have been remedied, the power unit enters a normal operation mode that should last over its design life of operation of 30-40 years. The fast increase of the failure rate, λ (T), following the moment T_{proekt} is mainly related to the intensive degradation processes of the mechanical properties of the NPP equipment structural materials.

Deformation of crystal solid bodies

All the metals in the form in which they are implemented by machine building have a polycrystalline structure, i.e. they consist of a number of small crystals (crystal grains) [5]. These crystal grains contain a number of tiny crystals, chaotically positioned within the body volume. In the interior of a crystal, the metal atoms are arranged in a particular order, forming a regular spatial lattice. Interaction forces exist among the atoms of a crystal lattice. At great distances there are forces of mutual attraction between two atoms, and at short distances - forces of repulsion. Under the impact of external forces, the lattice atoms shift in respect to one another and the interaction forces between them change. The dependence of the interaction forces on the displacements is complex in nature (strain-stress diagram). However, within the range of small displacements, this dependence may be regarded as linear. Crystal lattice shifts occurring in different directions for the multitude of chaotically positioned crystals integrally generates a proportional relationship between a displacement of solid body points and external forces, which is expressed in Hooke's law.

In elastic deformations: $\sigma = E.\ \varepsilon$ (for normal stresses), Fig. 3

$\tau = \mu\ .\ \gamma$ (for flexural stresses)

σ – linear stress;

τ – shear (angular) stress

ε – linear deformation (normal strain);

γ – shear strain (deformation)

E – elasticity modulus (Young's modulus);

μ - modulus of slip elasticity.

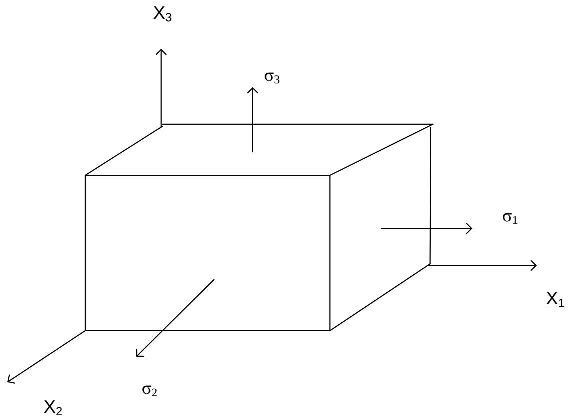


Fig. 3. Forces acting along the three main planes of the stress tensor

The elasticity of bodies is explained by the fact that when the impact of external forces is withdrawn, the atoms in the crystal lattice regain their strictly defined positions and the geometrical dimensions of the bodies are completely restored.

Experiments have found that plastic deformations occur in connection with shifts (slips) in the crystal lattice. Within the boundaries of a crystal, plastic deformations result from the movement of parts of the crystal along some crystallographic plane of a whole number of elements (atoms) from the lattice. The smallest plastic deformation corresponds to the shift of one element (atom). This is a sort of a quantum of plastic deformation. As a result of this shift, each preceding atom occupies the position of the next one and, in general, all atoms find themselves in places characteristic of the particular crystal structure. Therefore, the crystal retains its properties while changing only its external configuration.

In metals, the formation of plastic deformations is initiated even at relatively small loads. Among the multitude of chaotically oriented crystal grains, there are always some unfavourably positioned grains, or even such ones with internal defects, which can cause residual alterations in the structure even at relatively small load forces within the elasticity zone. The number of these crystals, however, is not large and so localised plastic deformations do not exercise any perceptible effect on the overall linear relationship between the load force and the displacement of the atoms (of a sample).

In case of sufficiently strong load forces, the plastic deformations of the sample will prevail. In the majority of crystals, irreversible displacements occur along their weakest planes, especially if the latter are oriented close to the planes of maximum tangent stresses in the sample [6, 11]. Thus, slip planes form, Fig. 4.

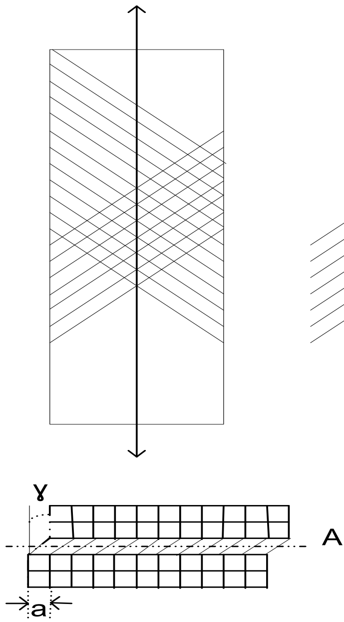


Fig. 4. Slip plane (A), the smallest plastic deformation corresponding to the slip of one element (a)

Upon stretching (tensile test) of the sample, the adjacent crystals interact with one another, and the emergence of a plastic shift within one crystal cannot grow indefinitely, as it is blocked by neighbouring, more appropriately oriented crystals. When the sample is subjected to stretching the number of dislocations does not diminish. On the contrary - each crystal grain interacts with adjacent ones and new dislocations form. Some types of dislocations are capable of propagation. If a dislocation cannot find an outlet and touches upon the adjoining crystal, more and more dislocations will form at the point of blockage. However, several closely spaced dislocations already form a micro crack which, upon increasing of the stretching strain, is able to "pave its way", i.e. it may begin to expand, Fig. 5. In the structure of the material, micro cracks may be inherent, forming under crystallisation conditions.

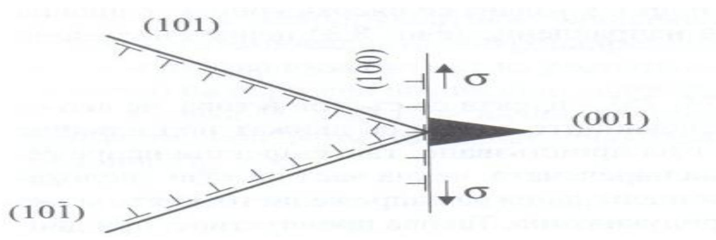


Fig. 5. The Cottrell model of crack formation; 101 - slip planes of dislocations; 100 - plane of forming of new dislocations; 001 - plane of crack formation

The Cottrell model suggests that in metal with a body-centered crystal lattice at the intersection of two slip-planes (101) along which dislocations move, new dislocations can be formed in plane 100. These dislocations pile up and create high stresses under the impact of which a crack is formed (plane 001). This pattern does not require any special barriers - in this case a barrier forms as a result of plastic deformation as the planes intersect.

At the basis of the fracture (destruction) process there are two mutually conditioned and mutually competing mechanisms, struggling for their "right" to destroy the sample. The first mechanism is the formation of plastic deformations along the path a deformation moves in specific crystallographic planes. The second mechanism is the formation and growth of cracks followed by cleavage. Sometimes the dominant mechanism is the first one, sometimes it is the second one.

The fracture process of facilities can be generally subdivided in two stages: the stage of crack formation and the stage of crack growth; the second one may progress over a significant part of the design life of the product. Degradation of facilities depends on the ageing processes.

Ageing of NPP materials and degradation of their mechanical properties

Ageing of materials stands for the change in their mechanical, physical and chemical properties, due to thermodynamic imbalance of the initial condition, and gradually bringing the structure to equilibrium in the presence of sufficient diffusive mobility of the atoms. Investigation of the ageing processes during NPP operation comprises activities such as:

- development of methodologies and instruments to diagnose the parameters of NPP in-service equipment;
- assessment of the ageing effects on the operability of equipment in view of making corrections to the scope and periodicity of outages, maintenance, tests and inspections;
- development of methodologies for express analysis of failures, damages and defects of components of equipment, and introducing those methodologies in the operational practice;
- establishing an NPP information system (a database of knowledge and expert systems) per types and groups of equipment; the system will store data on the results of calculations and measurements of the

parameters of the bearing capacity and effective loads during design, manufacturing, installation and operation.

DEGRADATION MECHANISMS OF EQUIPMENT AT NUCLEAR POWER PLANTS

Corrosion

Corrosion is the process of metal failure as a result of chemical or electrochemical interactions of metal with the surrounding environment [5]. The cause of corrosion is the thermo-dynamic instability of the system composed of the metal and components of the environment. The capability of metals and alloys to resist corrosion impact of the environment is contingent on the rate of corrosion under the given conditions. The following serve as quantitative indicators of the rate of corrosion, $\frac{dy}{dt}$:

the time t until the occurrence of corrosion outbreaks;
the number of corrosion outbreaks for a given time period;
the metal thickness decrease per time unit;
the change of metal mass per surface unit and time unit;
the change (in per cents) of any indicator of mechanical properties such as strength, plasticity, electrical resistance, etc.

In the absence of a compact oxide layer in metal, the corrosion rate is:

$$\frac{dy}{dt} = C_0.\gamma.e^{\alpha.T}.t^{\gamma-1}$$

or

$$\frac{dy}{dt} = C_0.A.e^{-B/T} \approx C_0.k_p.e^{\alpha'.T},$$

where

k_p - constant of the chemical reaction speed;

C_0 – reagent concentration on the external surface, at the boundary with the gaseous phase;

a, α'' – temperature coefficients;

γ - constant value, t – the operating lifetime considered, T - the temperature.

The presence of humidity on the metal surface may accelerate the reaction speed from 2 to 12 times.

In the presence of a compact oxide layer in metal, the corrosion rate is expressed as:

$$\frac{dy}{dt} = \frac{D(T^0).k_p}{D(T^0) + k_p{}^y} \cdot C_0$$

where $D(T^0)$ is the diffusion coefficient.

If the metal has a protective coating with a thickness of $h = const$, then the corrosion rate is:

$$\frac{dy}{dt} = \frac{D(T^0)}{D(T^0) + h_0 \cdot k_p} \cdot C_0 = \frac{k_p \cdot C_0}{1 + h_0 \cdot k_p / D(T^0)} = k_p{}' \cdot C_0$$

The better the coating, ($D(T^0)$ is lower, while h_0 is greater), the lower the k_p. The corrosion products accumulate on the walls of the structural materials of the NPP primary circuit due to the diffusion properties of materials and the chemical reactions. The corrosion products quantity can be characterised by their accumulation factor:

$$K(x,t,\delta) = \frac{M_a(h,t) + M_\partial(x,t)}{M_\partial(x,t) - M_\delta(x,t)}$$

where

M – the quantity of products deposited on the walls and made up of

M_a and M_d – deposits from adsorption and diffusion, respectively;

δ – thickness of the accumulated deposits layer;

x – location of the area considered.

An experiment with gas-cooled nuclear reactors examined the impact of various factors on the corrosion products accumulation coefficient. It turned out that $K(x,t,\delta)$ was most significantly affected by, as follows: the coolant flow rate, wall temperature, compatibility of various materials, quality of the surface of materials, gas composition, diffusion parameters, the time duration of the process progress, etc. The corrosion products of different stainless steel types located in high-temperature water are most intensely influenced by gamma-radiation. It has been established through experiments that gamma radiation increases the rate of release of insoluble corrosion products in the coolant, but does not increase the soluble substances release rate. These corrosion products form in the common water volume through oxidation of Fe ions with oxygen or with radiolysis products.

The Fe release level in the form of insoluble corrosion products from carbon steels under the influence of gamma radiation and in the presence of $0{,}02 mg/kg$ oxygen at $250^0 C$ will increase 10 times, for instance, as compared to a sample specimen that has not been subjected to gamma radiation. Gamma radiation exercises practically no influence on the level of Fe release in the form of ions. The release of cobalt, Co, from austenitic steels is similar to the release of Fe. The addition of $1mg/kg$ ammonia to the circulating water in the circuit noticeably decreases the level of Fe release in ion form, but does not affect the Fe release in the form of corrosion products. The corrosion product is mainly haematite, while on the metal surface magnetite and ferrite occur. One of the methods for retarding the general corrosion process and reducing the level of corrosion products transfer to the nuclear reactor plants, is the dispensing of oxygen in high purity water.
Corrosion of structural materials operating in water medium is electrochemical in nature. In the event of such a corrosion, electrical current is generated between metal and water, the latter acting as the electrolyte in this case. Water is made of polarised dipole molecules in which the positive charge has been spatially separated from the negative one. If any ions are present in water, then water molecules will group around these ions under the effect of the electrostatic attraction forces. This process is termed hydration.

Electrochemical corrosion is characterised by microgalvanic elements on the metal surface with dynamic balance between two processes: anodic process in which ionisation takes place and dissolution of the metal atoms, and a cathodic process in which metal atoms are restored.
As the metal surface and the electrolyte composition are not uniform and have dissimilar electrode potentials, the different surface areas will dissolve at different speed. Moreover, part of the displaced electrons are transferred from areas with more negative values of potential (anodes) to areas with less potential values (cathodes). As a result, a number of micro galvanic elements form and they predetermine the direction of the corrosion process.
When components operate in water medium, two processes may take place - polarisation and depolarisation. The polarisation processes of the cathode and anode reduce the difference between potentials, and, therefore, the corrosion current and the corrosion rate will diminish. The reverse is true about the depolarisation processes: they enhance the difference between the potentials of anode and cathode, which leads to faster corrosion rate. The depolarisation process depends on a number of factors - the value of electrode potential of the electrode material, presence of protective barriers on the surface of electrode material, the solution composition, etc.
At the cathode, hydrogen and oxygen depolarisation processes prevail:

$$H^+ + e^- \rightarrow H \quad H + H \rightarrow H_2$$

$$O_2 + 2.H_2O + 4.e^- \rightarrow 4OH^-$$

where O_2 - oxygen atoms, H_2 - hydrogen atoms, e^- - electrons.

Concentration of OH^- ions increases either due to oxygen depolarisation, or as a result of H^+ ions discharge and increased rate of water dissociation through the formation of OH^- ions in the process of hydrogen depolarisation.

Ionising radiation excite water molecules and set the conditions for its disintegration with the following processes under way:

$$H_2O \rightarrow H_2O^+ + e^-$$

$$H_2O \rightarrow H + OH^+ + e^-$$

$$H_2O \rightarrow H + OH^-$$

$$H_2O \rightarrow H^+ + OH^-$$

$$H_2O^* \rightarrow H + OH$$

$$2H_2O + H_2 \rightarrow H_2 + H_2O_2$$

where H_2O is the excited water molecule.

As a result of the water irradiation, unusually active agents are formed, such as ions H^+, OH^+, OH^-, H_2, OH. During their interactions in the irradiated water in the primary circuit, they generate gaseous hydrogen and hydrogen peroxide. If the reactor water contains dissolved gases - hydrogen and oxygen, the water dissolution process is significantly retarded. Thus, if hydrogen is present in the water, hydrogen peroxide does not form. When dissolved oxygen is present in the water, the hydrogen atoms concentration decreases as water molecules form.

The increased concentration of OH^- ions and metal ions in the electrolyte leads to the formation of insoluble corrosion products mainly made up of hydroxides. This layer of corrosion products on the metal surface is porous and practically has no protective action. The coolant flow washes it away, which, during the operation a nuclear power plant, will result in increased radioactivity of the coolant, deteriorated heat exchange, diminished mechanical properties of the structural materials and other undesirable consequences.

One of the key factors affecting the corrosion rate is the hydrogen ions concentration characterised by the hydrogen indicator:

$$pH = -\lg C_{H^+}$$

where C_{H^+} is the concentration of hydrogen ions in the solution.

With $pH = 7$ the medium is considered neutral, with $pH < 7$ – acidic, and with $pH > 7$ - alkali. The pH indicator also characterises the concentration of OH^- ions in the solution. It has been found that to reduce the corrosion rate, $pH > 7$ needs to be maintained. However, one also needs to take into account the impact of pH on the solubility of corrosion products in water and the formation of a protective layer in the structural materials.

Effects of oxygen on corrosion

Currently, opinions differ on the influence of oxygen on the rate of electrochemical corrosion. Some believe that oxygen acts as a depolarisation agent and accelerates corrosion, while others, on the

contrary, maintain that oxygen can oxidise the anode material and create anodic polarisation to reduce the rate of corrosion. Therefore, in order to reduce the rate of electrochemical corrosion, it is necessary either to reduce the concentration of oxygen in the water or to increase it to a level corresponding to the passive state of the anode. However, it should be noted that increased oxygen concentration leads to inter-granular corrosion and corrosion embrittlement. The common practice adopted on NPPs is to reduce the oxygen content in water to a concentration of $(1-2).10^{-2}\, mg/kg$. The most radical method of decreasing oxygen content in water consists in adding hydrogen to it.
A significant role in corrosion damage of structural materials of components in NPPs with water coolant is played by the so called corrosion cracking. The mechanism of corrosion cracking consists in that in the congested zones along complicated transition pathways, water does not mix sufficiently with the main mass of fluid. It is quickly saturated with corrosion products, insufficient oxygen reaches the surface of the metal; the metal is not passivated and the corrosion rate grows rapidly. To ensure prevention against corrosion cracking for structural materials it is necessary to use alloyed steels and alloys on the surface of which resistant protective layers can be formed.

Effects of temperature on corrosion

Usually, as temperature rises corrosion processes also intensify on account of the growing ion mobility within the solution. As a rule, corrosion rate V is described by an exponential law:

$$V(T^0) = A.\exp(-\frac{B}{T^0})$$

where A and B are constants, and T^0 - absolute temperature.

Effects of irradiation on corrosion

In NPPs, the coolant is subjected to irradiation, and this is why the corrosion rate of structural materials changes significantly under the impact of irradiation. Influenced by irradiation, the coolant composition also undergoes changes - radiolysis of water takes place, atomic O_2 and H_2 form, as well as hydrogen peroxide and short-lived radicals. Their interaction with the gases dissolved in water leads to modification of the oxydising-regenerative properties of the coolant. This alters the pH value and exercises major effects on the rate of corrosion processes. The water saturated with air during the initial period of operation of the NPP and under the action of irradiation, accumulates nitric acid, wherein the value of pH drops to values of $3-4$, and the concentration of O_2 in water decreases. These processes are conducive to the formation of ammonia and the coolant pH reaches values of up to $9-10$, which, in turn, increases the corrosion rate.

Effects of grain size on corrosion

Grain size is important for structural materials subject to inter-granular corrosion. As the grain size increases, the corrosion rate also goes up. This process is caused by decreasing the extent of the grain boundary, i.e. by high-density grain boundaries due to increased phase quantities segregated along the grain boundaries. The grain boundary sections get considerably impoverished of alloying elements. Steels and alloys whose alloying elements are in quantities that exceed the solubility limit under working temperature values feature the greatest propensity for inter-granular corrosion.

Effects of external loads and internal stresses on corrosion

Corrosion toughness of NPP structural materials is highly affected by external loads and internal stresses. Stresses will lead to a considerable change in the metal electrode potential. Tensile stresses (tensions) shift the electrode potential to the negative side, while the compressive stresses shift it to the positive side. The stretched sections act as anodes with regard to the rest of the metal and dissolve (degrade) most intensively. The compressed sections act as cathodes. The value and the stress direction significantly affect the condition of the protective layer, determining the metal corrosion resistance in aggressive environments. Tensile stresses decrease the protective properties of the surface layer and cause its embrittlement. Compressive stresses are conducive to improvement of the protective layer. However, the strongest corrosion impact of structural elements at nuclear power plants using water as a coolant comes from the aggressive medium and stresses that can lead to stress corrosion cracking.

Corrosion environment as a single acting factor does not cause crack length growth. Only the combined effects of mechanical stresses and the corrosive environment cause an increase or acceleration of the crack propagation at stresses significantly lower than the stresses which in an inert medium will cause the same effect. Tests are conducted on samples placed in a special chamber simulating a corrosion environment and loaded with a constant force. The crack propagation is tracked by measuring its increment Δl over a given time interval Δt Thus, the average crack propagation rate is defined:

$$V = \frac{\Delta l}{\Delta t}$$

Calculations are made of the values of l, the stress intensity factor K_I and on the basis of the results obtained, a diagram is drawn of the static crack toughness, Fig. 6:

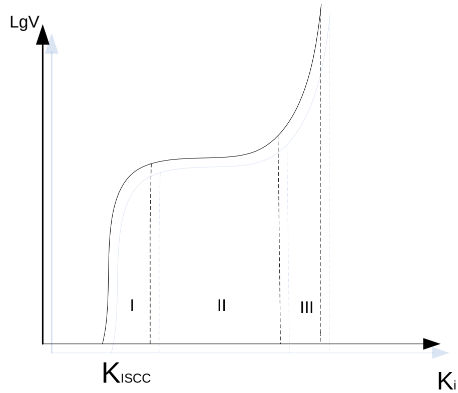


Fig. 6. Diagram of the static stress corrosion cracking toughness

The lower threshold value K_{ISCC} is the greatest value of the stress intensity factor K_I , at which the crack of the respective corrosion environment stops growing, K_{ISCC}, is a very important characteristic of the material corrosion crack toughness, as it determines the safe level of stresses in the structure in the presence of cracks. In corrosion cracking, a crack is formed and starts growing as a result of degradation of the protective layer and the selective anode dissolution of flawed sections on the surface of the stressed metal. The initial sub microscopic cracks propagate in depth of the metal at a high speed: $0{,}5-2{,}5mm/h$. The growth of cracks is explained by the fact that the local plastic deformation of metal at the top of the crack caused by concentration of stresses, considerably intensifies the anodic dissolution of metal at the peak of the crack.

Those sections of the metal that are subjected to periodic moisturising and drying are running the highest risk of corrosion cracking. Only chemically clean and deaerated water is used at nuclear power plants. The water supplied to the primary circuit and the feed water have strict norms determining their content of chlorine ions. However, regardless of the low distribution of chlorides in the reactor water $0{,}1\div 0{,}5mg/kg$ and in the steam generator water, in those sections where circulation is slow (almost missing) in the SG pipe grid nodes evaporation is possible, as well as chlorides content growth reaching dangerous values in terms of corrosion cracking. Corrosion cracking may result both from high temperature and also from relatively low temperature values $\left(80-90^0 C\right)$. Upon water dropping (e.g. due to a leak) on the boundary surface of a pipeline heated to $100^0 C$, it will evaporate and thus increase the chlorides concentration on the pipeline surface, which may lead to corrosion cracking.

Corrosion cracking of austenitic stainless steels in water containing high levels of inhibitors can occur only if chlorine and oxygen ions are present. As a rule, the destructions are transcrystalline in nature. In case chlorides are not present, the degradations are intercrystalline (inter-granular).

Erosion

Erosion on the walls of equipment is caused by particles of various origin such as particles of metal corrosion products, sand, silicates, water drops, etc. The erosion process evolves through brittle or plastic fracture depending on the temperature.

1) Under normal temperature conditions in the plastic materials (metals), erosion dissociation of metal occurs as a result of a plastic deformation on the surface. With brittle materials, erosion takes place through surface degradation in the form of cracking (radial or elongated shapes, or Hertz circles).

2) High temperature erosion is associated with the release of composite material - metal alloy and brittle surface oxide. The oxide layer on the metal surface may modify the process mechanism depending on the layer thickness. If the oxide layer is thin, the prevalent mechanism is associated with metal creep (elastic-plastic area). Upon the oxide layer reaching a critical thickness, the dominant mechanism is that of brittle erosion fracture.

The temperature and the characteristics of the force impact of the particles are the erosion determining parameters. The speed of oxide formation is dependent on temperature and, therefore, the same applies to the oxide layer thickness within a given timeframe. The force effect of particles is characterised by the time intervals of particles impacting on a specified point on the metal surface. Several mathematical models exist to describe erosion processes.

Erosion model - growth of fatigue cracks on the basis of Paris equations

In the Paris formula, the crack growth is a function of the stress intensity factor (SIF) amplitude:

$$\frac{dl}{dN} = C.\Delta K_I^n ,$$

where

$2l$ - length of the crack;

$N -$ number of load cycles;

C, n - material constants;

ΔK_I - amplitude excursion of SIF.

In a number of published works, asymmetry of load cycles has been introduced to the Paris formula, which is characterised by the asymmetry coefficient of cycles:

$$r = \frac{\sigma_{\min}}{\sigma_{\max}} ,$$

where $\sigma_{min}, \sigma_{max}$ stand for, respectively, the minimum and the maximum values of the stress applied.

Neutron embrittlement

The operating conditions of the reactor pressure vessel metal are characterised by intensive neutron flux under high temperature and pressure conditions [6]. Being particles of small mass and great energy, neutrons easily penetrate the crystal lattice of the reactor pressure vessel. There are two major mechanisms of the interaction between neutrons and the particles of materials:

1) The collision between neutrons and the lattice atoms causes dislocations within the crystal lattice; neutrons may either transfer their energy to atoms through elastic impacts, or serve as the source of charged particles formation. Such processes will impair the correct position of atoms within the metal crystal grid and this will lead to defects formation. In case of sufficiently high neutron energy, the atom initially displaced from its balanced position may be followed by a cascade of displaced atoms.

2) Radiation impact largely facilitates diffusion of the ingredients' atoms, which is another important cause for alloy embrittlement. Moreover, as a result of vacancies merging in those diffusion processes, additional pores may form in the metal, which can result in noticeable changes in the shape of the structure.

The density of radiation defects depends on the type of radiation, its parameters and the nuclear-physical characteristics of the material. The spot defects that occur - vacancies, internodal atoms, embedded atoms, etc, at sufficiently high temperatures can recombine, migrate to body or surface directed leakages (dislocations, grain boundaries), form radiation stacking faults in the shape of pores and dislocation nodes. The irradiation of metal with fast neutrons results in microscopic areas of structural damages, and with high concentration of spot defects. Due to irradiation, the creep (yield) stress limit of steel may grow up to twicefold, while the strength limit increases to a lesser degree - the two limits come closer and metals harden while also losing plasticity. Current knowledge of radiation degradation assumes that the occurring defects may lead to material hardening either directly via interaction with the dislocations, or indirectly - through the changing kinetics of metallurgical reactions leading to phase drop, for example. These effects harden the material and are dependent on neutron fluence density. The main effect of radiation degradation of metals consists in the highly limited number of active slip planes, and the increased number of dislocations moving across the slip planes. This highly localised movement affects the process of local degradation in the peak of the crack. Determining the transition from elastic to brittle state or the evaluation of ΔT_F may be performed through experimental testing of surveillance specimens, or it can be assessed numerically through the neutron fluence. Numerical assessment of neutron embrittlement of the reactor vessel metal is carried out using norms and standards of the country manufacturing the reactor equipment.
Due to the neutron diffusion, near the peak of the crack a circle section of embrittled metal forms, Fig. 7. The embrittling action of metal neutrons is dependent on their density of distribution. Until the

neutron distribution density stays below a certain value, Φ_0, the metal remains plastic. As soon as the density Φ exceeds Φ_0, the metal state changes to elastic-plastic.

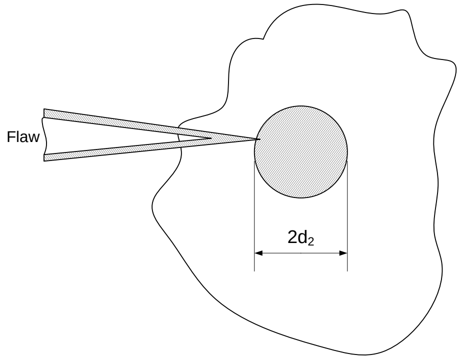


Fig. 7. Material embrittlement around the crack peak

Effects of the chemical composition of steels on the embrittlement process

The elevated levels of nickel (Ni) and manganese (Mn) in reactor steel grades enhance embrittlement due to the formation of Ni-Mn-Si clusters (dislocation nodes), while silicon (Si) reduces embrittlement. Fig. 8 shows photos of microscope examination of samples with various weight percentage of Ni (sample compositions $0{,}22Cu - xNi - 1{,}6Mn$), subjected to neutron fluence irradiation, with neutron energy exceeding $1{,}6MeV$ at temperature of $T = 290 \div 310^0 C$, [7].

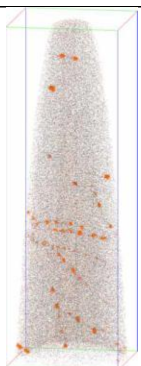
		
$0{,}02\%Ni$	$0{,}82\%Ni$	$1{,}59\%Ni$

Fig. 8. Formation of dislocations in samples of varying weight percentage of Ni ($0{,}22Cu - xNi - 1{,}6Mn$) at temperature of $T = 290 \div 310^0 C$

During irradiation the structure of materials containing copper, Cu, changes and Cu-enriched clusters form. The Cu-nucleus stays in the middle of the formation, while the elements Ni, Mn, Si accumulate in the outlying sections. These formations disrupt the correct structure of the crystal lattice. Under the impact of the operating temperature of $320^0 C$, higher phosphorus content will result in thermal brittleness of metal following a mechanism based on the phosphorus segregation at the inter-phase boundaries and the grain boundaries. Radiation embrittlement is determined by the formation of dislocation nodes. The occurrence of these defects results in 1) facilitating the emergence of cracks and development of micro cracks on account of the active stresses, 2) additional micro stresses begin to act in the grain bodies, and 3) increased probability of formation of dislocation aggregates at the barriers where micro cracks form. The neutron embrittlement mechanism is associated with the segregation of phosphorus at the inter-phase boundaries of the carbide matrix and at the grain boundaries, as a result of which their strength diminishes.

Neutron irradiation and thermal ageing

Neutron irradiation is expressed in radiation brittleness temperature ΔT_K shifting in the direction of higher temperature values. Regarding the reactor vessel materials, neutron irradiation also causes thermal ageing of metals. According to the Russian strength norms, PNAE G 7-002-86 [8], the shifting of brittleness critical temperature resulting in thermal ageing is considered 0º for type 15X2HMΦA steels, as well as for the welded joints metal. However, recent studies have shown that this is not true. These steels undergo thermal ageing according to a mechanism that has been determined by the carbides formation process. In the course of thermal treatment, carbon bonds in stable carbides that do not change under the operating temperatures over the whole service life of the materials. Upon carbides emergence and as their amount grows, the material hardens and, as a result of this, it also becomes brittle.
The embrittlement process depends not only on the chemical composition of the alloys, but also on the of neutron fluence, operating temperature and running hours, which can be expressed as [9]:

$$T_K = T_{K_0} + \Delta T_K(F,t) \qquad \text{Eq.1}$$

The value added to the temperature $\Delta T_K(F,t)$ has two components: one of the components is added on account of neutron fluence $\Delta T_K(F)$, and the other one is due to thermal embrittlement $\Delta T_K(t)$. Both components are calculated using different formulas,

or $\Delta T_K(F,t) = \Delta T_K(F) + \Delta T_K(t) + \omega$

T_{K_0} is the initial critical temperature of metal, $[^0 C]$, which implies the beginning of NPP operation;

T_K is critical temperature of metal at the end of reactor operation, $[^0 C]$;

$\Delta T_K(T)$ is the shift of the critical brittleness temperature due to thermal ageing, $[^0 C]$;

t [hours] running hours;

$\Delta T_K(F)$ is the shift of the critical brittleness temperature due to neutron fluence F, $[^0C]$;

F is the neutron fluence with energy of neutrons greater than $0{,}5MeV$ at the RPV, $[\frac{n}{m^2}]$

$F_0 = 10^{22} n/m^2$ is a standardised coefficient;

A_F is the irradiation embrittlement coefficient, $[^0C]$;

ω – double standard deviation of ΔT_K;

$\Delta T_t^{\inf}$ - is the shift of the critical brittleness temperature when $t = \infty$;

t_{OT}, t_T, b_T – constants of materials;

Ni, Mn, Cu и P is the concentration of chemical elements in the composition of material, [weighing units];

$D = 72.10^{22}, [\frac{n}{m^2}]$ is a standardised coefficient.

$$\Delta T_K(F) = A_F \left(\frac{F}{F_0} \right)^m \qquad \text{Eq. 2}$$

<u>for base metal</u> $m = 0{,}8; A_F = 1{,}45^0 C$

<u>for weld metal</u> $m = 0{,}8; A_F = \alpha_1 . \exp(\alpha_2 . C_{eq})^0 C$

$C_{eq} = Ni + Mn - \alpha_3 .Si$ if $Ni + Mn - \alpha_3 .Si \geq 0$

or $C_{eq} = 0$ if $Ni + Mn - \alpha_3 .Si < 0$

$\alpha_1 = 0.703;\ \alpha_2 = 0.883;\ \alpha_3 = 3.885$

$$\Delta T_K(t) = \left(\Delta T_t^{\inf} + b_T \exp\left(\frac{t_T - t}{t_{OT}} \right) \right) \cdot th\left(\frac{t}{t_{OT}} \right) \qquad \text{Eq. 3}$$

Table 1. The values of $\Delta T_{\inf}, b_T, t_{OT}$ of RPV metal.

Material	$\Delta T_{\inf} [^0C]$	$b_T [^0C]$	$t_{OT} [hours]$
Base metal	18	26,2	32 700
Weld metal, Ni>1,3%	18	10,1	23 200

Weld metal, Ni<1,3%	18	26,2	32 700

There are two methods for determining of the critical temperature shifts, $\Delta T_K(F,t)$. The first method is a theoretical one – through calculations using certain numerical models adopted in normative and methodological documents. The second method is a practical one - through analysis of surveillance specimens of the material.

The shifts of critical temperature $\Delta T_K(F)$ due to the neutron fluence for both base and weld metal (Eq. 2) are presented on Fig 9 [20].

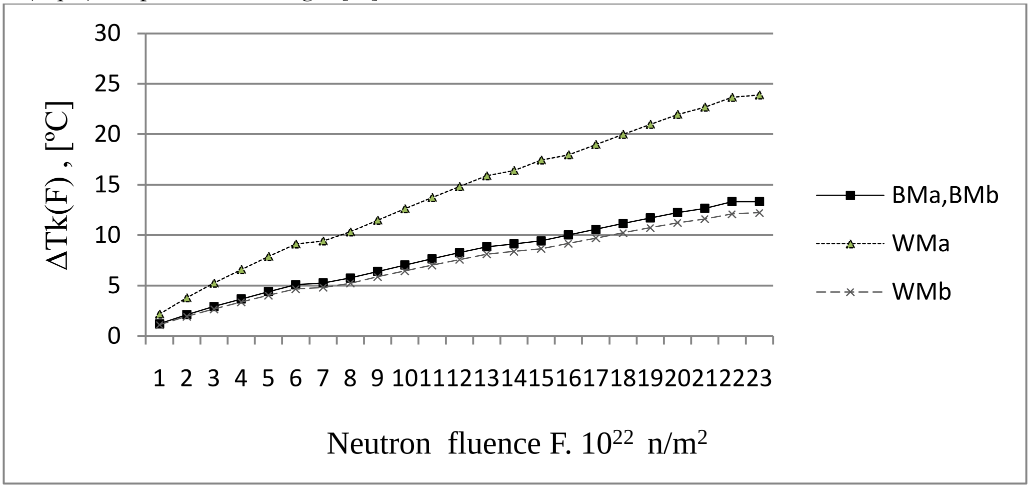


Fig. 9. Neutron ageing - dependency of $\Delta T_K(F)$ on fluence F for BM and WM, or a neutron inducted part of $\Delta T_K(F,t)$

The values of $\Delta T_K(F)$ for both base and weld metal exponentially increase with the growth of the fluence F. The trend curves $\Delta T_K(F)$ for base metal (BMa and BMb) coincide, because A_F does not depend the metal chemical composition for base metal (Eq. 2). The difference in the neutron embrittlement rate for weld metal (WMa and WMb) can be seen. The embrittlement process is faster for WMa. For RPVb, the trend curves $\Delta T_K(F)$ for base metal BMb and weld metal WMb almost overlap.

The curves denoting the critical temperature shift due to thermal embrittlement $\Delta T_K(t)$ for base metal and weld metal (BMa, BMb, WMa, WMb), Eq. 3 are presented as curves on Fig. 10.

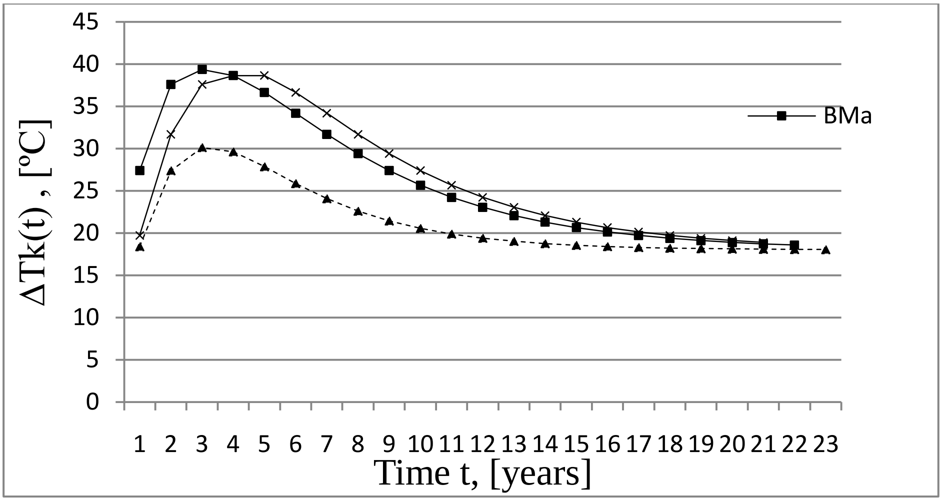


Fig. 10. Thermal ageing: dependency of $\Delta T_K(t)$ on time t (or thermal inducted part of ΔT_K) for BM and WM

The thermal inducted $\Delta T_K(t)$ trend curves for base metal (BMa, BMb) prevail over the trend curves for weld metal (WMa, WMb). A peak in the thermal embrittlement values can be observed in the initial period of operation (between the second and fifth year), after which the thermal embrittlement rate quickly decreases. After the first $10-11$ years of operation, the function $\Delta T_K(t)$ retains almost constant values over the subsequent reactor operation period, for both base and weld metal.

The sum of the critical temperature shifts due to both neutron and thermal embrittlement is:

$$\Delta T_K(F,t) = \Delta T_K(F) + \Delta T_K(t) \qquad \text{Eq 4}$$

Regarding both base and weld metal the general ageing dependency on time is presented on Fig. 11, Eq. 4.

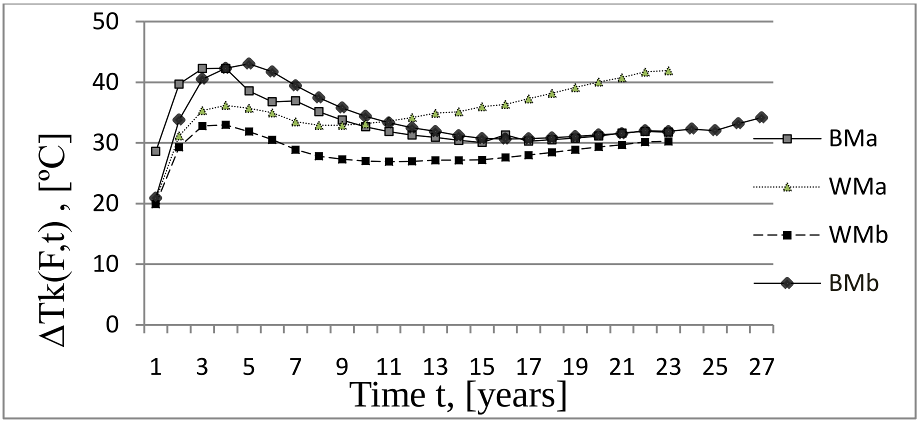
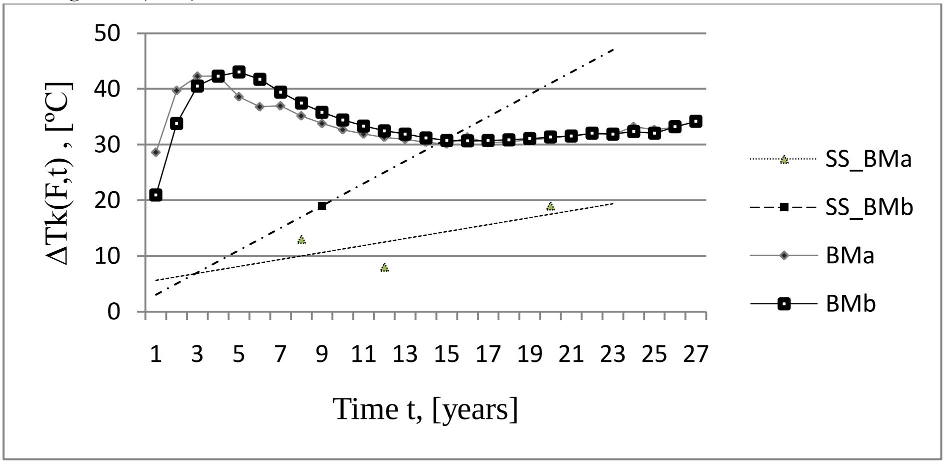


Fig. 11 General ageing (neutron+thermal) dependency of $\Delta T_K(F,t)$ on time t for BM and WM

The thermal inducted embrittlement process prevails over the first years 10 of reactor operation. Then, the neutron inducted embrittlement process gains prevalence. In the beginning of reactor operation, the embrittlement rate of base metal BMa and BMb exceeds that of the weld metal WMa and WMb. This is followed by the reverse process of weld metal embrittlement prevalence. A comparison was made between the values for the critical temperature shift $\Delta T_K(F,t)$ based on calculations and experimental data from surveillance specimens. The results are shown on Fig. 12a (BM) and Fig. 12b (WM).



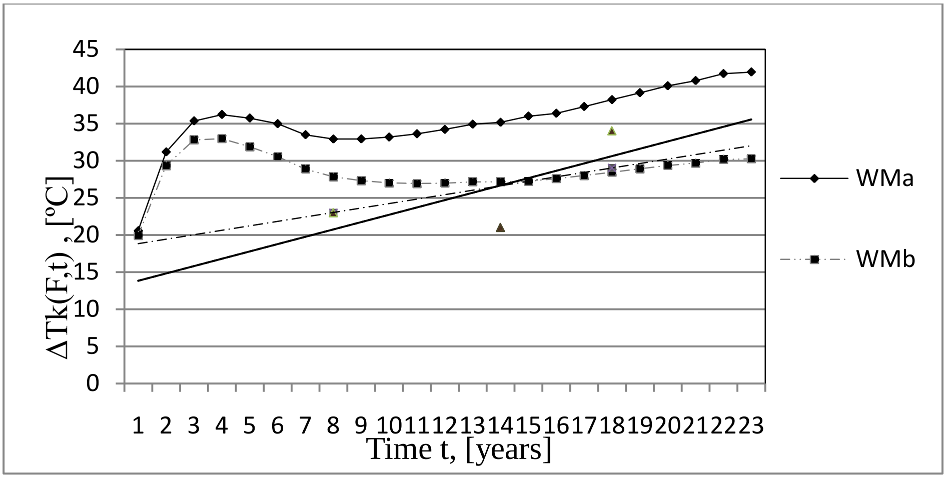


Fig. 12. Dependency of $\Delta T_K(F,t)$ on time t for a) BM and b) WM

The averaged curves of experimental data from surveillance specimens (SS) for a) BM and b) WM. For base metal – the calculated results are higher than the experimental ones. The $\Delta T_K(F,t)$ function trend exceeds the values of the experimentally obtained data for the surveillance specimens of base metal, BMa, contrary to the case with base metal, BMb.

For weld metal, WMa, the trend curve $\Delta T_K(F,t)$, based on the calculations is high and quickly grows proportionally to the operating time growth. The trend curve $\Delta T_K(F,t)$ for WMb (almost) coincides with the averaged line of the experimental data.

Material fatigue

Engineering structures are subjected to pulsating (cyclic) loads [10]. Under the influence of cyclic loading, it is difficult to notice any progressing changes in the structure of the material. Destruction happens suddenly, without any noticeable signs of imminent occurrence. Moreover, in times of "relaxation" when stress stops acting, defects do not disappear - they accumulate and are irreversible. Fatigue can be described as a process of gradual degradation, composed of sub elements such as:

1) the process of crack emergence; and

2) crack growing to a size when its further progress is rapid and unstable. It is assumed that a crack originates as a result of the movement of dislocations, which generates thin sliding planes on the surface of the crystal lattice, Fig. 13.

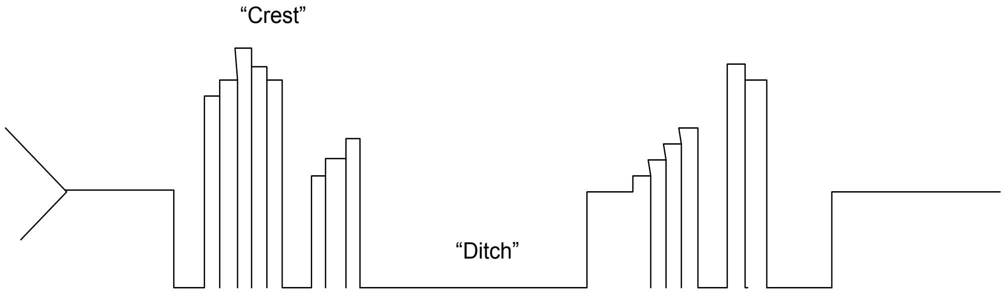


Fig. 13. Slip planes in material fatigue

Several stages can be outlined in the crack propagation [7]:

Stage 1 of crack growth - consists in slipping in variable directions along planes, tangential to those of the maximum tangential stresses. While the crack propagates along the slip plane, no changes are observed in its growth. This stage may be short or long, and is characterised by small stresses and slow crack growth. Under the effect of intense cyclic stresses, in the presence of sharp geometric corners (cuts), or under conditions where the ratio of the tensile stress to the tangential one is large, the crack moves to the next stage of growth, Fig. 14.

Stage 2 of crack growth - it progresses under the influence of maximum normal stress in the vicinity of the tip of the crack, rather than local tangential stresses. In addition, the crack tip can deviate from the slip plane and the crack may propagate in another direction.

Stage 3 of crack growth - the crack reaches a critical size and at the next set of load cycles the degradation ends.

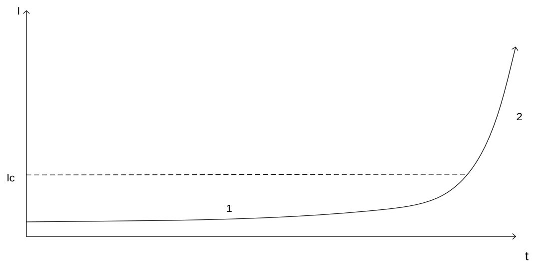


Fig. 14. Progress of the crack length l within the time period t.

1 – slow, stable growth (stage 1) ; 2 – rapid, unstable growth (stage 3)

The long term operation at a constant amplitude of stresses, follows a logarithmic law. The fatigue limit is the highest value of the amplitude of stress below which the material can withstand an infinite number of cycles without degradation, Fig. 15.

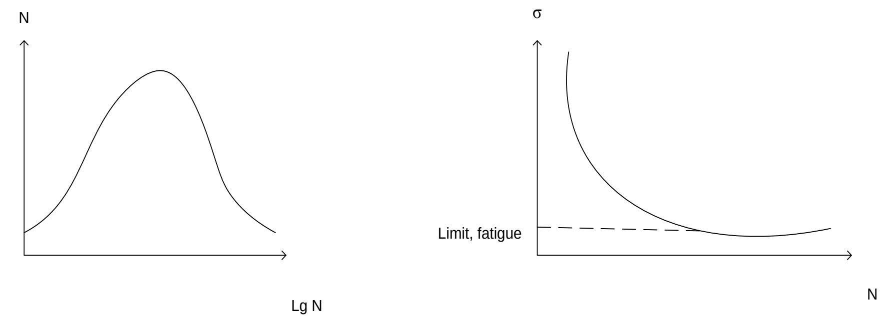


Fig. 15. Main material fatigue curves

Factors affecting the fatigue limit:
- material composition;
- grain size and grains orientation;
- thermal treatment;
- welding;
- geometric features;
- effect of the surface condition;
- residual surface stresses;
- operating temperature;
- corrosion;
- fretting – surface damage at the points of contact.

Types of fatigue

High-cycle fatigue is characterised by small loadings of the material below its yield stress limit, and long duration - i.e. large number of cycles occur before the material is finally destroyed.

Low-cycle fatigue or cyclic deformation fatigue occurs when nominal stresses are above the ultimate yield stress limit. It has been established that for a great number of materials subjected to cyclic deformation in the plastic areas, the diagram for stress-load $\sigma - \varepsilon$ significantly fluctuates - some materials get hardened, others embrittled, Fig. 16.

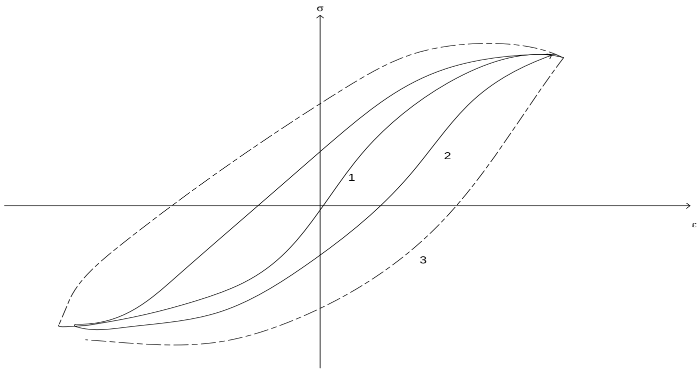


Fig. 16. Diagram $\sigma - \varepsilon$ for repeated monotonous loading (1); during cyclic loading (2); curve envelope (3)

The structural materials of the reactor unit need to retain their operability over a long time period under high temperatures – or possess long-lasting strength - σ_t^T stands for the stress that leads to sample destruction at temperature of T and over the time period t. Under high temperature values T and persistent stress, a slow process of plastic deformation is initiated in the material, which is called creep (yield), Fig. 17.

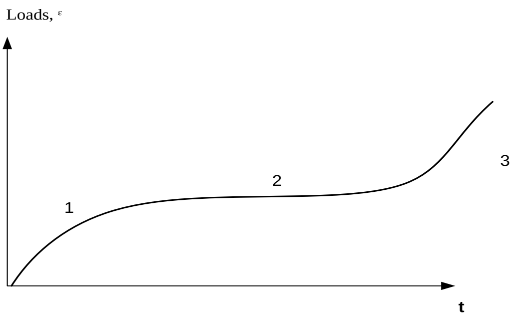


Fig.17. Section 1 – undetected creep; Section 2 – constant speed creep;Section 3 – increasing speed creep, terminating with fracture

Thermal ageing

The NPP facilities in operation undergo the impact of high temperature values $(290-322^{0}C)$. These working medium factors may cause thermal ageing of the base metal and weld metal in terms of alteration of their mechanical characteristics [8]. Thermal ageing is associated with displacement of atoms in the lattice of the crystalline structure; it is mainly dependent on temperature and the time period over which the metal has been exposed to its effects, while the presence of mechanical loads further aggravates the process. In addition to the reactor vessel and the reactor internals, all other primary circuit reactor components of the reactor installation are subjected to the influence of thermal ageing.

Wear

Multiple studies have demonstrated that the process of gradual loss of functionality of components in operation can be subdivided in 3 (three) stages: stage of alignment, normal operation stage, and wear, caused by the facilities' normal operation (Fig. 18).

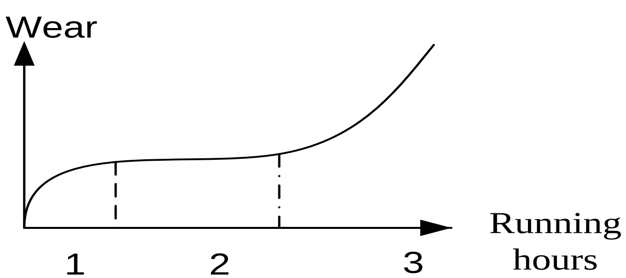


Fig. 18. Wear depending on the hours in operation

1 – alignment period, 2 - normal wear during operation, 3 – progressive growth of wear

Throughout the stage of alignment (1) mutual changes occur in the macro- and microgeometry of the working faces, and products of wear and oxidation are formed. The working faces wear rather intensively during this stage. Gradually, wear weakens and stabilises to a stage of normal operation wear (2). Once an energy limit has been exceeded (3) the wear value progressively increases, the components functioning deteriorates and the need of repair arises. The following factors determine the level of wear in friction:

physical, chemical and mechanical properties of the surfaces subjected to friction;

combination of materials for the working surfaces;

interactions of the working surfaces with the environment;

clean processing of the friction surfaces;

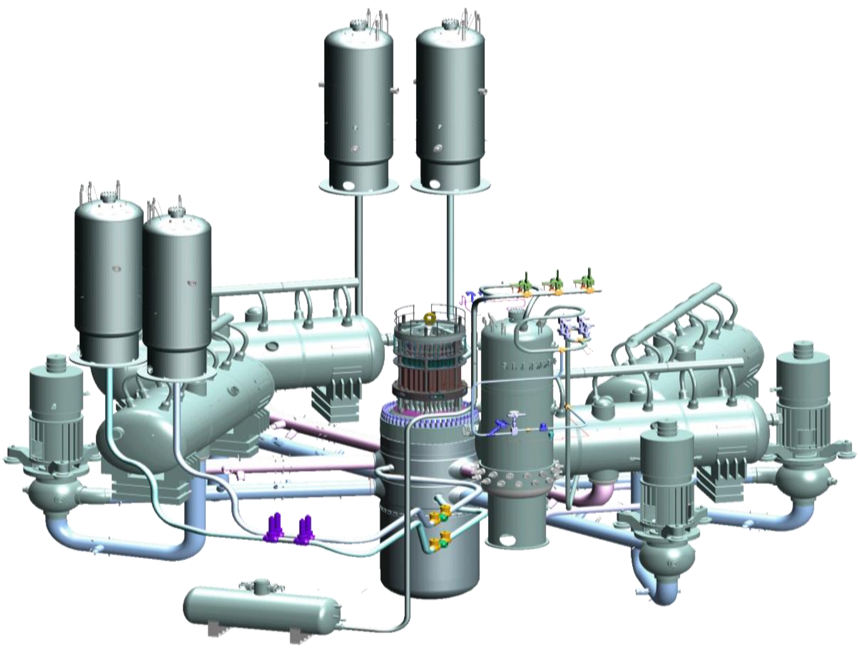
type of friction (dry, boundary, semi liquid, liquid);

values of the normal pressure and the velocity of working surfaces one against the other.

Of the large number of wear types on the working surfaces of machine parts, major importance is attached to abrasive wear in the presence of grease, because the wear products that invariably arise from the machine components friction are oxidised and turn into a sort of abrasive materials and it is rather complicated to clear the lubricants from the components surface. Friction wear is one of the major contributors to the gradual loss of operability of mechanical elements. Therefore, the consideration of factors affecting the level of wear of machine parts during design and operation of mechanical systems is one of the main tasks for ensuring the reliability of the working mechanical elements in nuclear power plant.

Effects of degradation mechanisms on the mechanical properties of components and pipelines in nuclear power plants

Fig. 19 shows the installation of a nuclear reactor unit type WWER-1000.



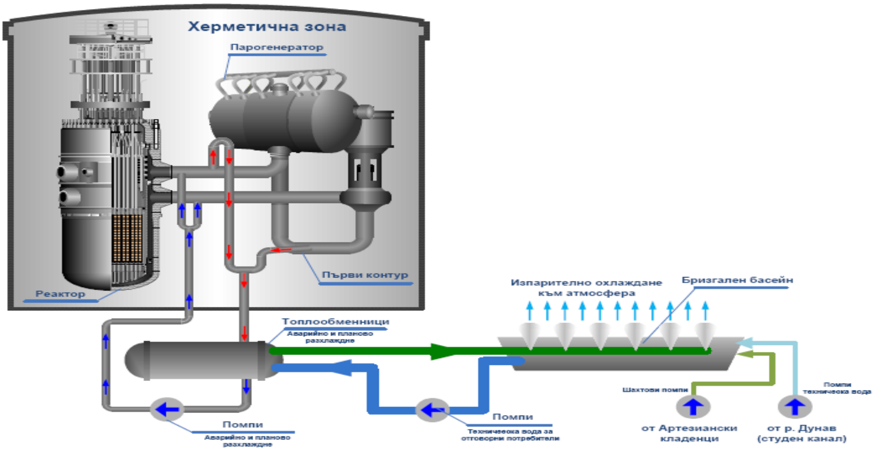


Fig.19. Nuclear reactor unit, type WWER-1000

The NPP types of equipment are mechanical, electrical and buildings/structures.

Fig. 20÷22 illustrate the main facilities and components of a nuclear power plant and the corresponding degradation mechanisms of their mechanical properties.

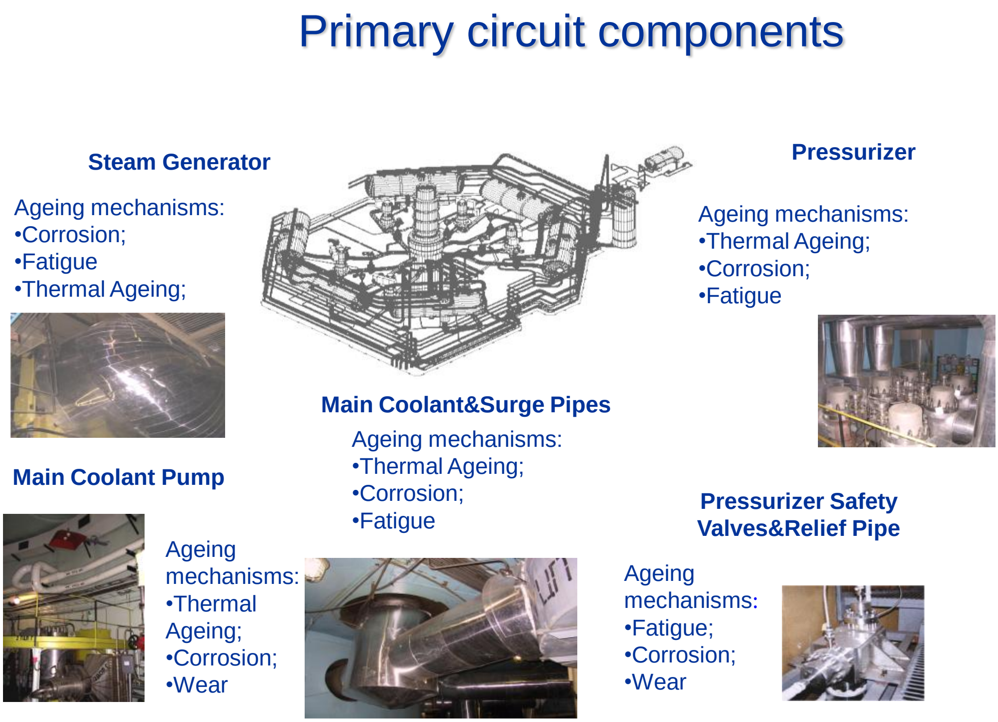


Fig. 20. Primary circuit main components at WWER type of NPPs, influencing the mechanical properties degradation mechanisms

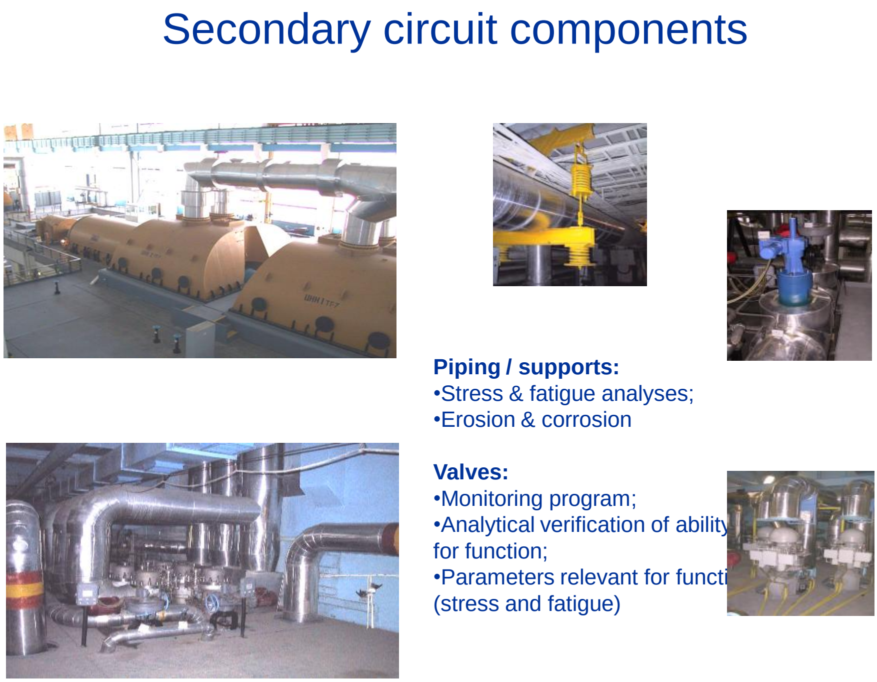


Fig. 21. Main secondary circuit components at WWER type of NPPs, influencing the mechanical properties degradation mechanisms.

Fig. 22. Electrical and computer equipment of NPPs and their degradation mechanisms

The NPP components and pipelines are subjected to continuous and periodical condition control (inspection) and monitoring. This control is (mostly) scheduled or implemented following a breakdown, after which failure-driven maintenance or repair is performed. Fig. 23 shows control and monitoring programmes applicable to nuclear power plants.

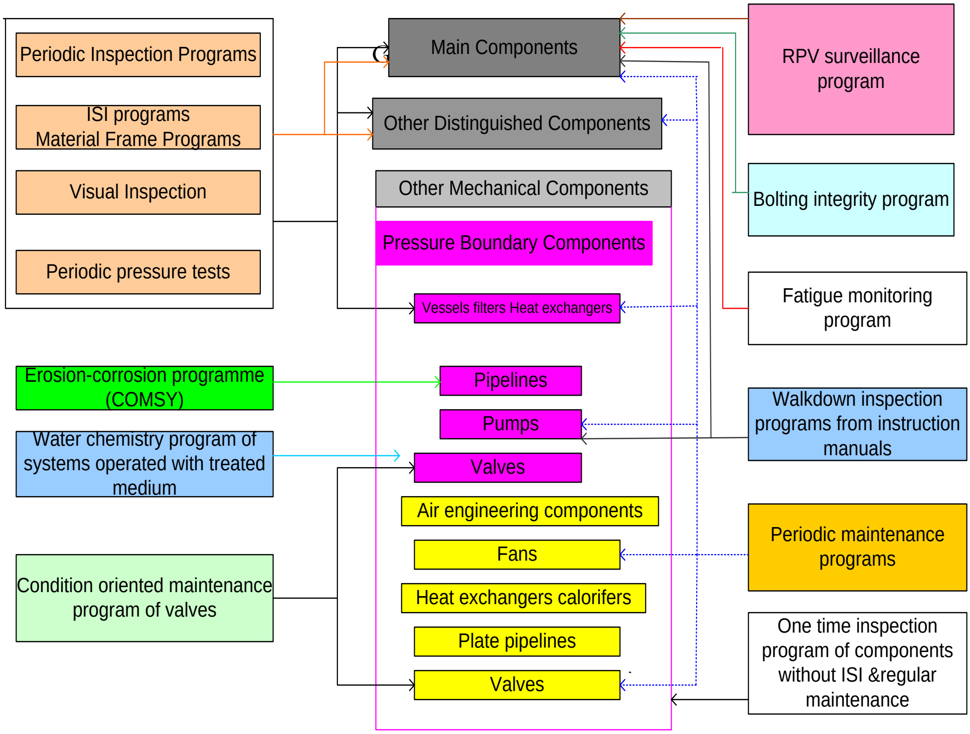


Fig. 23. Inspection programmes for NPP facilities

INSPECTION METHODS IN NUCLEAR ENERGY

This chapter describes the methods of inspection (control) used in the process of a nuclear power plant operation.

Visual and measurement testing (VT as per EN ISO 9712)

Visual inspection (testing) is a standardised method of material control. Visual inspection of the base materials of NPP equipment is conducted to identify surface imperfections (discontinuities) such as cracks, flaking, unacceptable dints, pits, slag inclusions, etc. Visual inspection of welded joints and welded surfaces is carried out to identify imperfections of the type of cracks, nonpenetrations, delaminations, burn-on defects, voids, metal splashes, inacceptable undercuttings, surface inclusions or deposits. Measurement inspection of intermediates and components has the purpose of checking that their geometrical dimensions comply with the requirements of standards or of technical conditions; also verifying the acceptability of the size of VT-identified surface imperfections such as pores, pits, slag inclusions, etc. imperfections against corresponding norms, standards or technical specifications. Measurement inspection of welded joints aims at checking the compliance of size, position and quantity of the identified inclusions (from a different metal), and also the size of undercuttings, of dints between welding transition areas and their surface undulation, weld root width, protrusion or groove, lack of alignment between the edges of the welded components, the minimum distance from the edge of weld reinforcing to the boundaries between the transitional filler material and the base metal, the thickness of the first layer and the overall thickness of the build-up anticorrosion coating, and other weld depositions. Visual testing and measurement inspection of welded joints and build-up surfaces are performed on a sample scope of pipelines and facilities of a nuclear power plant. It is mandatory for this sample to comprise the most challenging welded joints. The areas for visual examination of welded joints (inspected areas) need to extend over the whole volume of the weld metal, as well as the adjacent patches of base metal on both sides of the weld seam.

Visual inspections and measurement evaluation of components precede all the rest of the inspection methods. The technical tools for visual testing include magnifying glasses, micrometers endoscopes and boroscopes, Fig. 24, and measurement tools for measurement inspection, Fig. 25.

Fig. 24. Visual testing technical tools; magnifying glasses (above), boroscopes and endoscopes (below)

Fig. 25. Measurement inspection technical tools

Fig. 26 illustrates results from visual testing - images of the interior surface of vessels and pipelines.

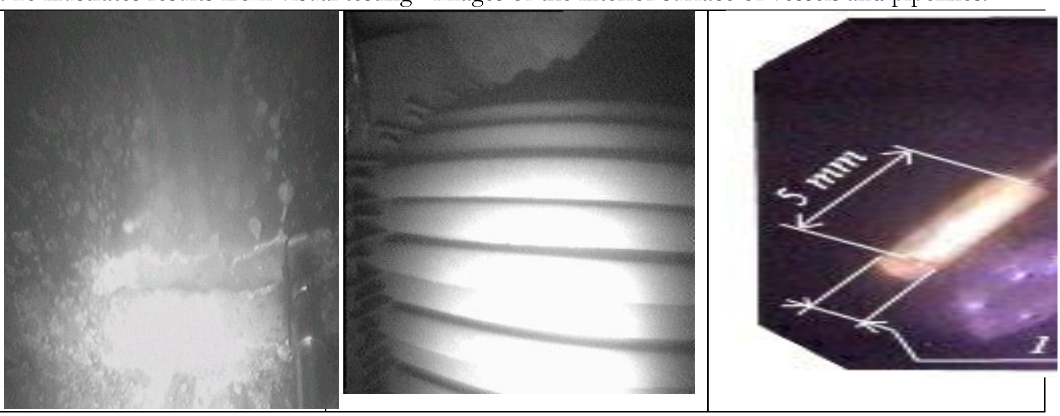


Fig. 26. Visual testing and measurement inspection of vessel interior surfaces

Testing (inspection) using penetrant liquids is a surface testing method that follows VT, but precedes the ultrasonic testing (UT) and radiographic testing (RT) methods. The dye penetrant inspection is a standardised testing method.
The essential steps in this method are as follows: suitable penetrating liquids are applied on the inspected areas; then they are left for a sufficient (dwell) time to penetrate into discontinuities that have reached and opened up at the surface. Once the required dwell time has elapsed, the excess liquid is removed from the surface, and developer is applied that draws out and absorbs the penetrant and provides a clear and visible indication of the imperfections.
The materials used should be such as to permit the identification of defects with 2-3 μm wide orifice and depth of up to 10 μm, Fig. 27.

Dye penetrant testing (PT)

Fig. 27 Technical tools for inspection with penetrant liquids - penetrants (the kit consists of penetrating, washing and developing liquids)

Eddy current testing (ET)

The method is based on inducing of eddy currents (also called Foucault currents) through electrically conductive material. In case a flaw is present (a magnetic anomaly, structural nonuniformity, etc.), changes occur in the configuration of the induced magnetic field lines. A probe then registers the changes in the resultant electromagnetic field, and through the nature of these changes indirect conclusions are drawn about the condition and properties of the conductive material. The depth of penetration of the eddy current signal into the material of the component under examination is about 5 mm from the surface. The eddy current testing method is a standardised one.

It is implemented at nuclear power plants to detect and assess the size of defects of the heat-exchange tubes in the re-rolling section of steam generators. Fig. 28 shows a handling device for automated eddy current testing, and Fig. 29 displays the technical tools for the testing process.

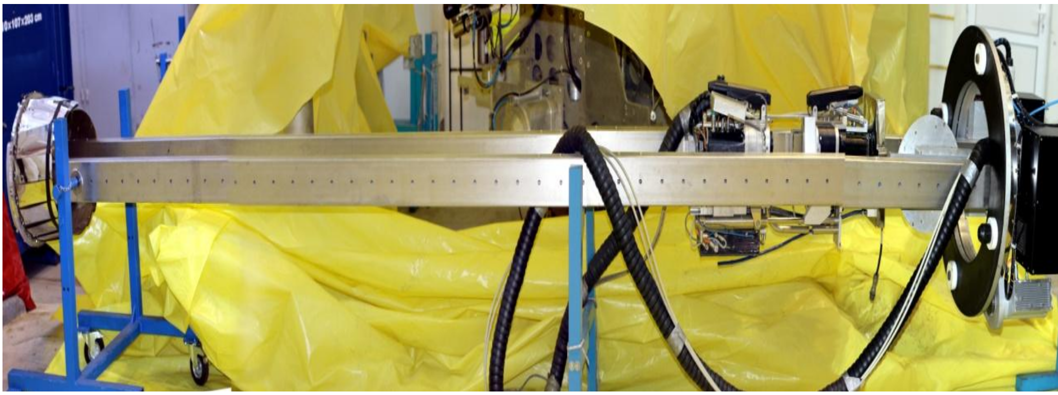


Fig. 28. Handling device for automated eddy current testing

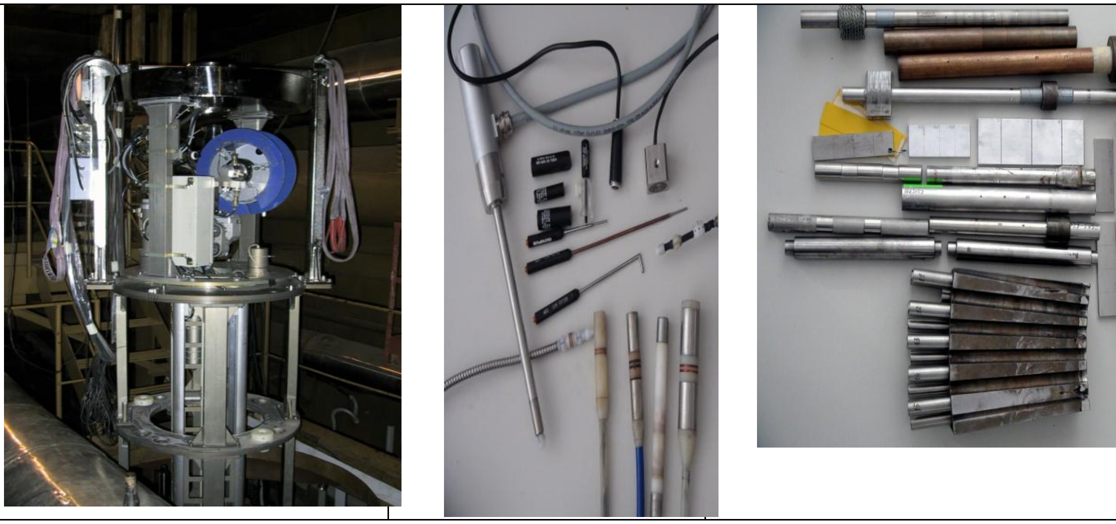
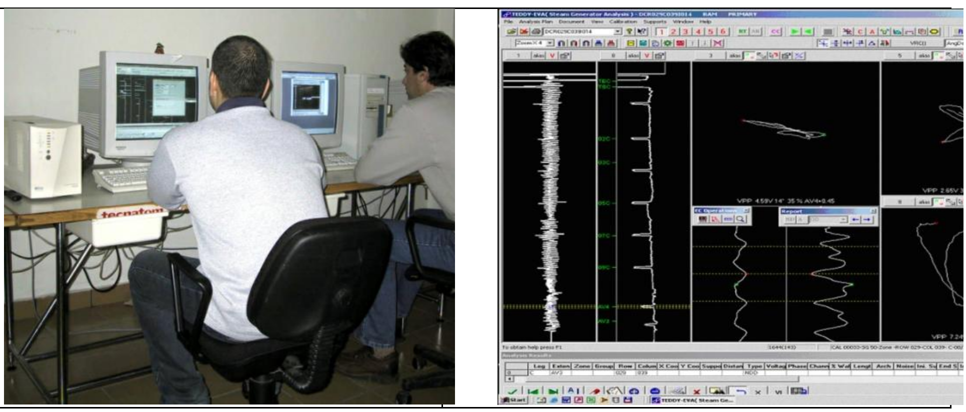
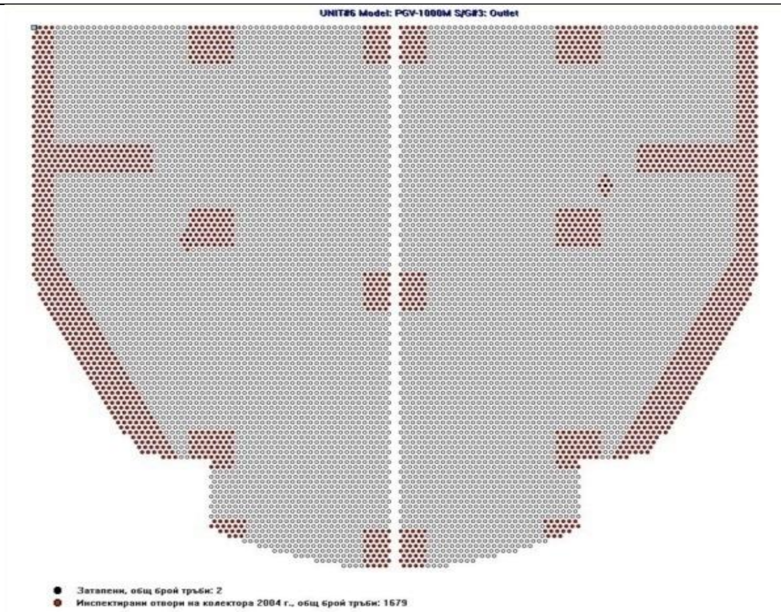
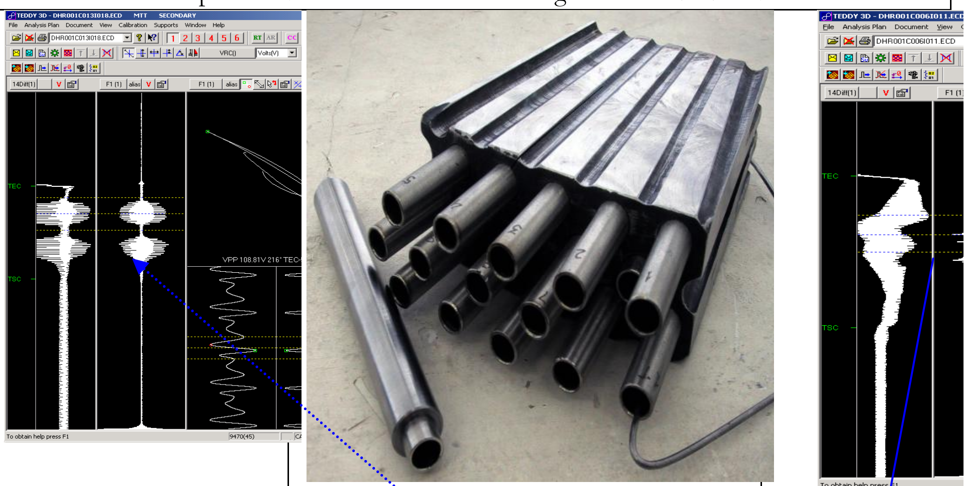


Fig. 29. Testing tools for the ET process (left to right: handling device, probes and reference pieces - tubes with implanted flaws used for tuning the signal)





Computerised cross-section of a steam generator tube bundle.



In the left, there is the probe signal from the end of the tube (end-off effect); in the right is the eddy current signal from a hole in the tube wall (100% wear of the tube wall).

Fig. 30. Results from eddy current testing

Radiographic testing (RT)

The radiographic testing (examination) method, RT, aims at detecting in fillers and welded joints (weld seam and the surrounding area) any imperfections such as nonpenetrations, pores, tramp material, undercuttings, burn-on defects, cracks, etc. The radiographic method is a standardised one. It uses ionising radiation sources of X-ray or gamma radiation. Using collimators, the beams are directed to the examined object and the radiation that has run through the object is registered on photographic materials, Fig. 31. Any imperfections in the material appear as dark spots on the radiograms developed.

X-ray instrument - control panel

X-ray instrument - X-ray tube and collimator

Gamma flaw-detector with an iridium (Ir) source

Gamma flaw-detector using a selenium (Se) source

Collimators and hoses for gamma flaw-detectors

Light and beeper detectors of radiation

X-ray films

Radiogram scanner

Digital analysing of radiograms

Film developing machine

Negatoscope

Fig. 31. Technical tools for radiographic testing

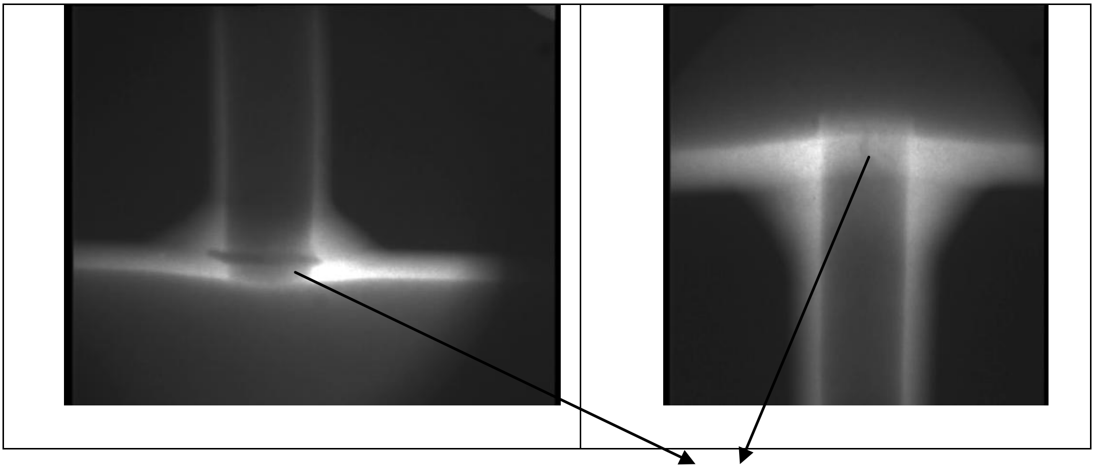


Fig. 32. Results from radiographic testing - discontinuities in metal are visible

The thermal imaging method of inspection and testing (infrared thermal imaging) registers thermal irradiation form the surface of the examined object; the analysis of the temperature differences evident on the thermogram provides information on any disturbances in the structural integrity of mechanical equipment or electrical connections of electrical equipment. The thermal imaging testing method is a standardised one. Using thermal imaging of electrical equipment provides opportunities to detect major deviations from the operating conditions such as 1) enhanced electrical resistance, 2) degraded integrity of electrical connections and couplings, 3) changes in the object material structure, Fig. 33.

Thermal imaging testing(infrared thermal imaging, TT)

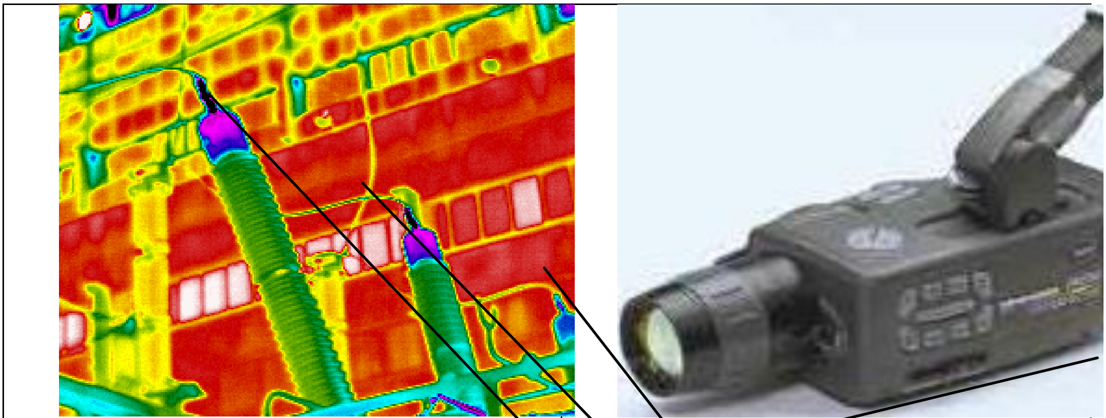
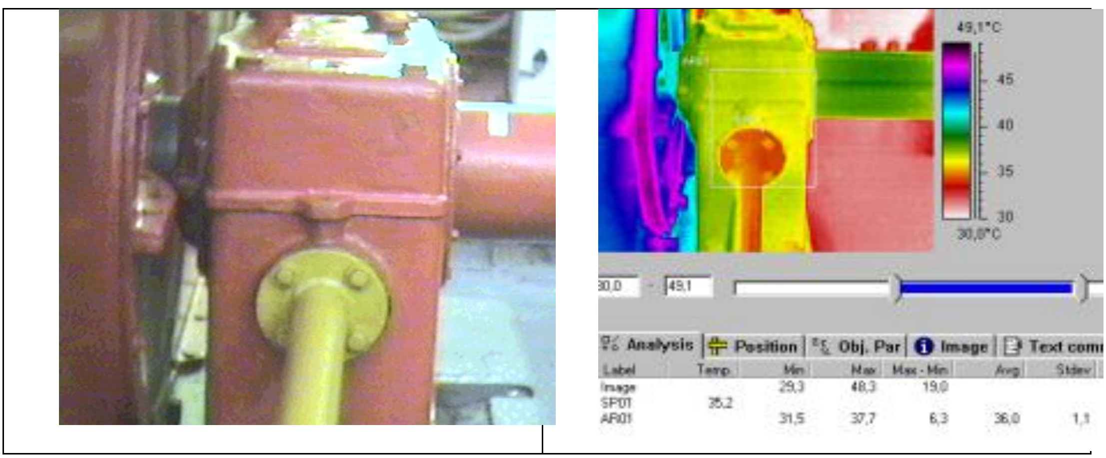


Fig. 33. Thermograms of electrical equipment - elevated thermal emissivity is observed for the voltage inputs; thermal imaging camera

Implementing thermal imaging examination of mechanical equipment detects major deviations from the operating conditions: 1) increased friction, 2) damaged inner or outer tightness of facilities operating under high temperature conditions; 3) impaired cooling of the examined object, 4) damaged insulation.

Fig. 34 shows a photo and a thermogram of a pump (top), and a thermogram of a reactor pressure vessel (bottom).



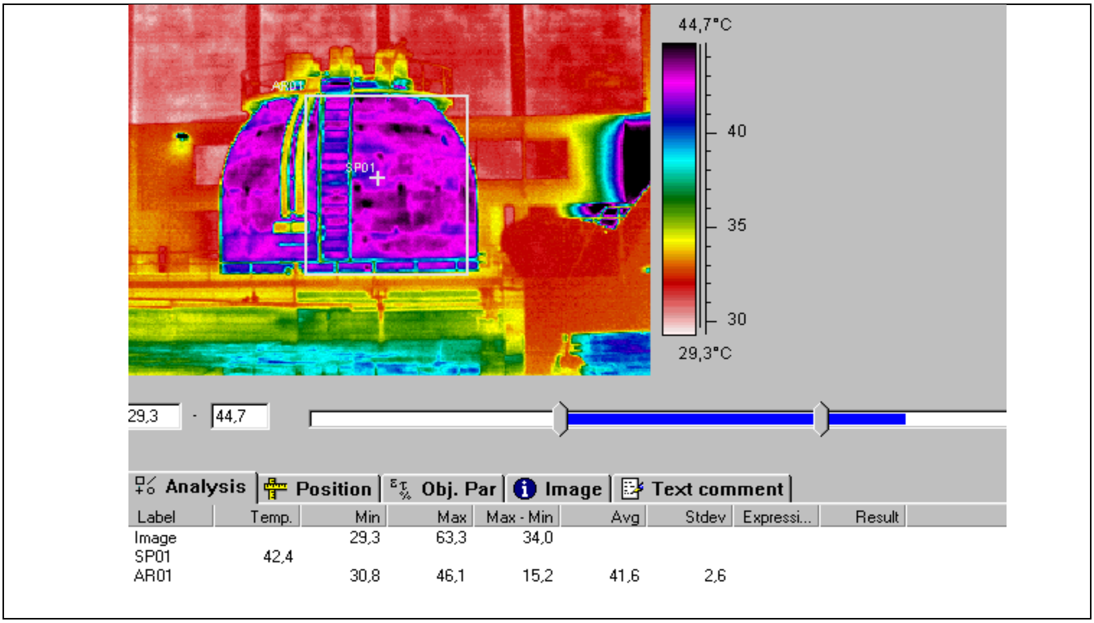


Fig. 34. A photo and thermograms of mechanical pieces of equipment. (top images - a pump; bottom one - reactor pressure vessel)

The thermal imaging method (infrared thermal imaging) is suitable for diagnosing of facilities and systems as it is applied to in-service equipment and does not necessitate shutting down of the facility or system. It is a remotely applied method that does not require direct access to the object, and also no special preparation of the surface of the object is needed.

Ultrasonic testing (UT)

The ultrasonic signal in metal environment is a forced mechanical vibration of particles with a frequency from 20 kHz to $10^{12} \div 10^{13}$ Hz. Ultrasonic beams refract and reflect just as the light rays do. Using a piezocrystal (ultrasonic sensor), an ultrasonic signal is introduced into the metal and then the sensor captures the signal reflected from edge surfaces such as imperfections in the middle part or the bottom surface of the object. Variations of the ultrasonic testing method are applied for inspection of facilities at nuclear power plants: the pulse-echo method, mirror-echo method and the transmission technique. The ultrasonic inspection (testing) is a standardised method of material control. Fig. 35 shows ultrasonic flaw detectors and automated ultrasonic testing (AUT) systems.

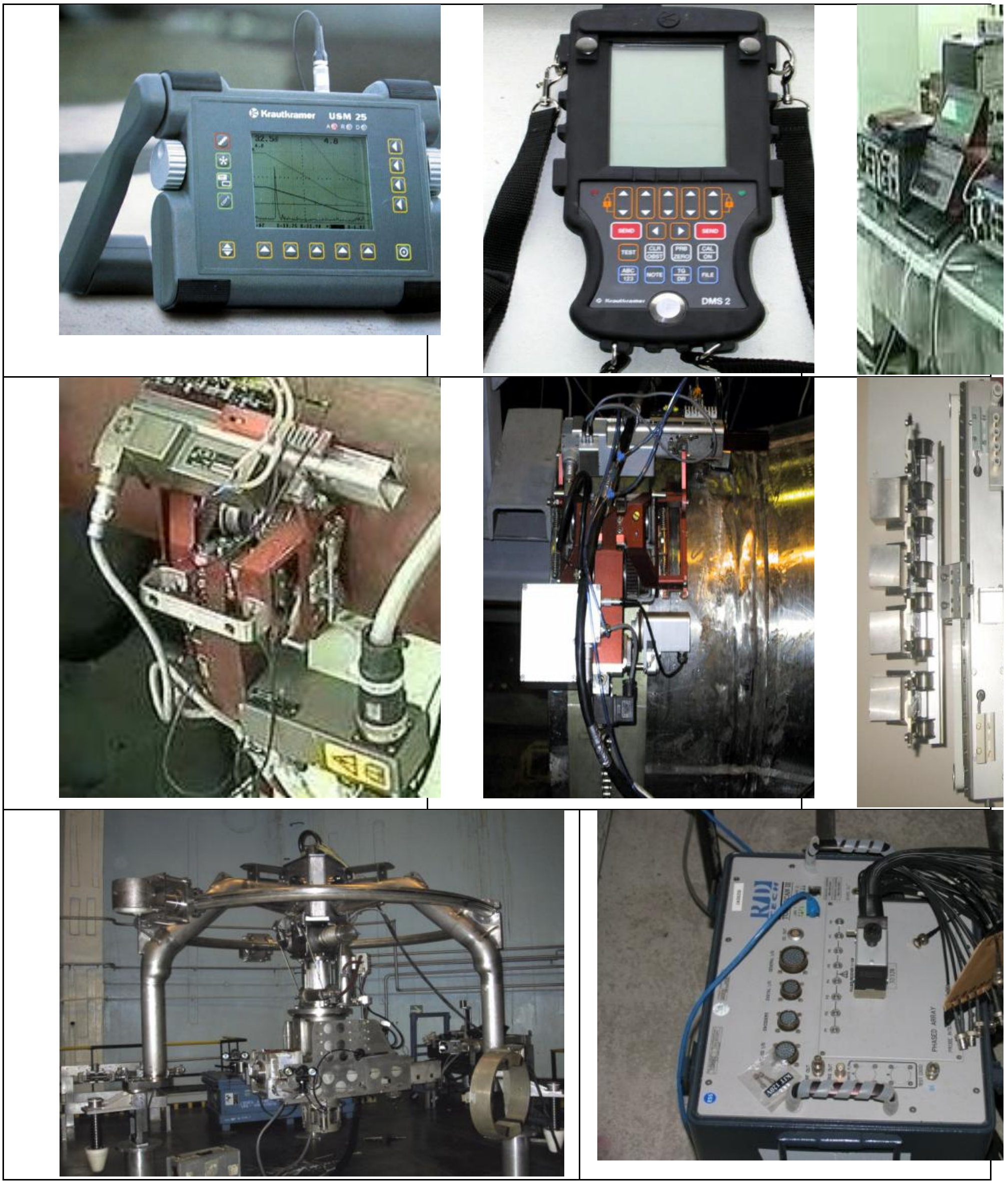


Fig. 35. Ultrasonic flaw detectors and automated ultrasonic testing systems

There are several specific conditions for implementing this technique, namely as follows: the objects should be easily accessible for inspection; rough contact surfaces of $R_a = 6,35$ μm, $R_z = 40$ μm should be available. The pipes and vessels where the testing techniques require reflection of the ultrasonic waves should be clear of fluid. Fig. 36 shows a nuclear reactor diagram (left) and results from UT of the reactor vessel (right).

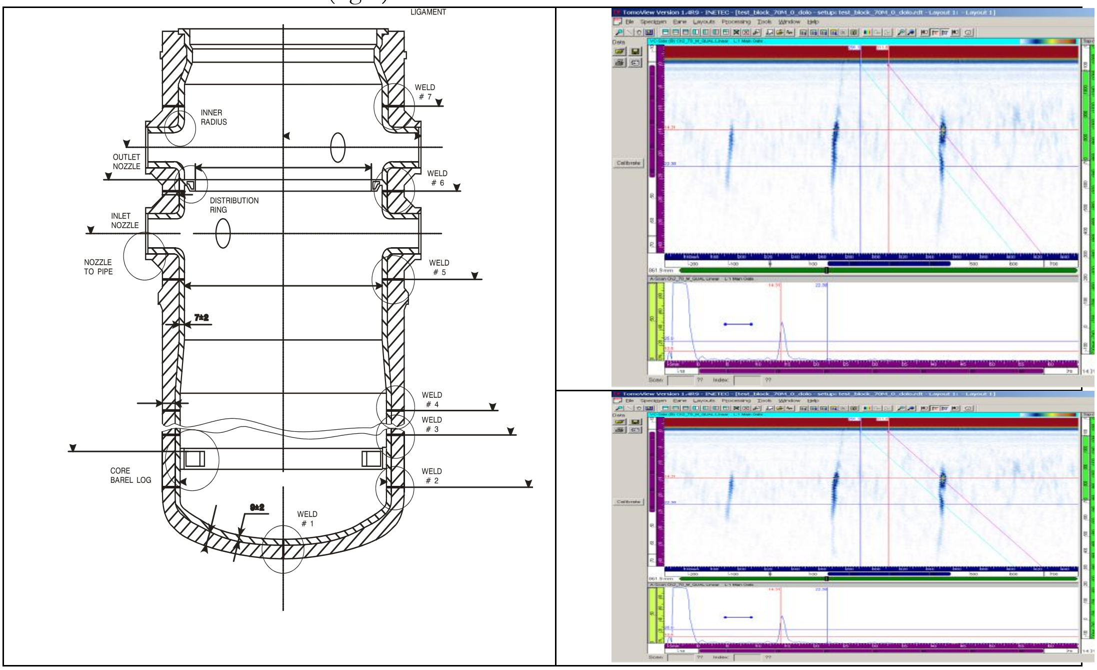


Fig. 36. Ultrasonic testing of a reactor pressure vessel - a schematic view of a nuclear reactor (left) and results from UT (right)

Ultrasonic thickness measurement

The processes of corrosion and erosion wear reduce the wall thickness of pipes, elbows and valves. One-sided ultrasonic thickness measurement is performed to detect changes in wall thickness over a certain period of service time by comparing the measurement data with data from previous measurement, or with nominal wall thickness data.

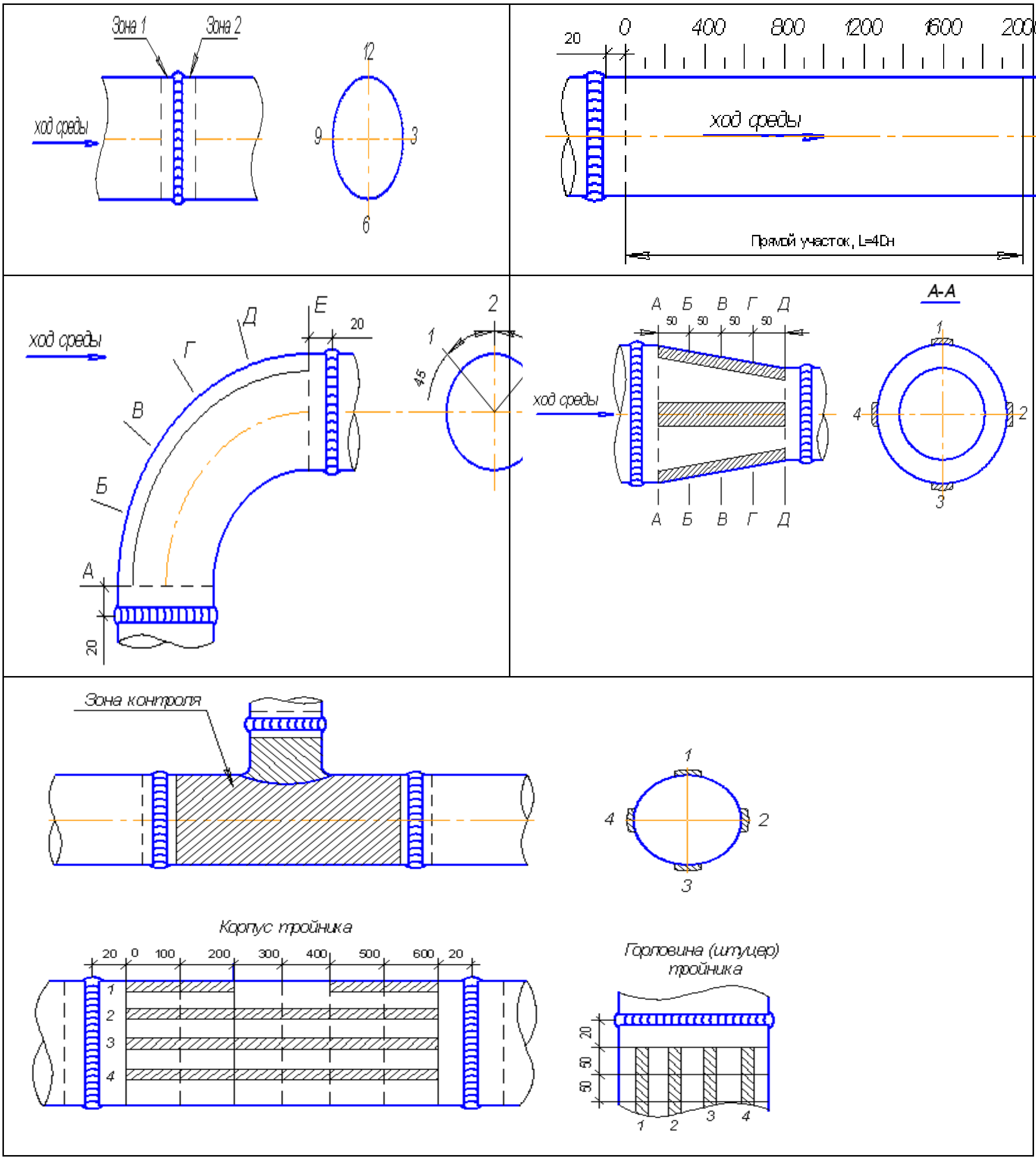


Fig. 37.Thickness inspection measurements of a pipe, a bended section, and a T-joint (inspection schemes)

Ultrasonic thickness measurement is an extremely efficient inspection (testing) method of corrosion-erosion wear because it is a quick testing technique, the results of which are expressed in linear dimensions, and only one-sided access to the object is required (not access from both sides). The problem arising with this testing method is that it requires establishing of the acceptable limits for evaluation of the conformity of the inspected object (nominal values). For the entire NPP equipment subjected to corrosion-erosion wear, reference norms (nominal thickness values) need to be developed for pipes, elbows, T-joints and valves, which is an effort of a considerable scope. Nominal size assessments will include strength calculations of the dynamic, static and seismic strength, and also of the corrosion rate found for the inspected component.

Metallographic methods

Metallographic methods are used to inspect (test) the metal macrostructure, in order to classify the flaws of the macrostructure and the fracture. Macrostructure inspection is performed on acid-stained samples. The method is based on the different response of defect-free metal and defective metal (with pores, segregations, etc.) to aggressive media. Prior to inducing corrosive effects, the samples' surface has to undergo cold working: face turning, milling and grinding. The polished samples are corroded using alcohol solution of nitric acid, HNO_3, (in the case of carbon and low-allow steels), or other solutions. The macrostructure evaluation of the corroded samples - the type and size of the defects, is carried out by comparing the actual appearance of the corroded samples against reference scales applied in standards. The micro structure is evaluated by observation on a microscope, employing magnification of 100, 500 or 1000 times, and classifying the elements of the structure. The characterisation as per quantity and quality of the main elements of the microstructure - of perlite, martensite, nitrides, carbides, and grain size is performed through comparing the microstructure against references of the respective scales provided in standards. The inspection aimed at identifying any susceptibility to intergranular corrosion is performed in accordance with the respective standards. Evaluation of the monitored bended surfaces of the sample bodies is carried out by inspecting visually through a magnifier ensuring magnification of 8 ÷ 12, and following sample pre-treatment in hot acid solution.

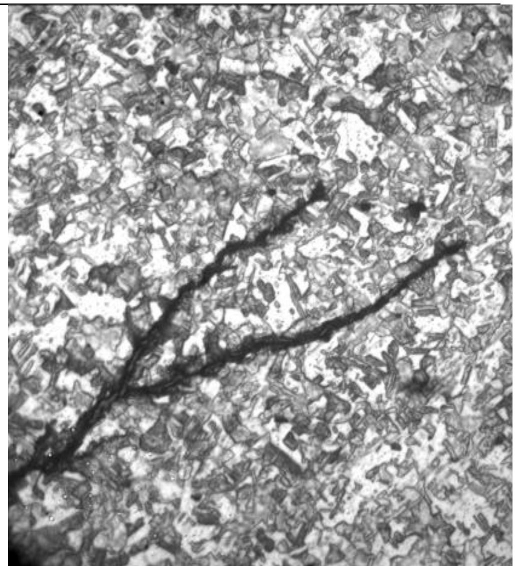
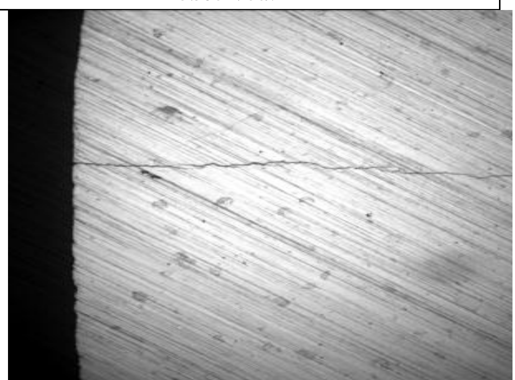
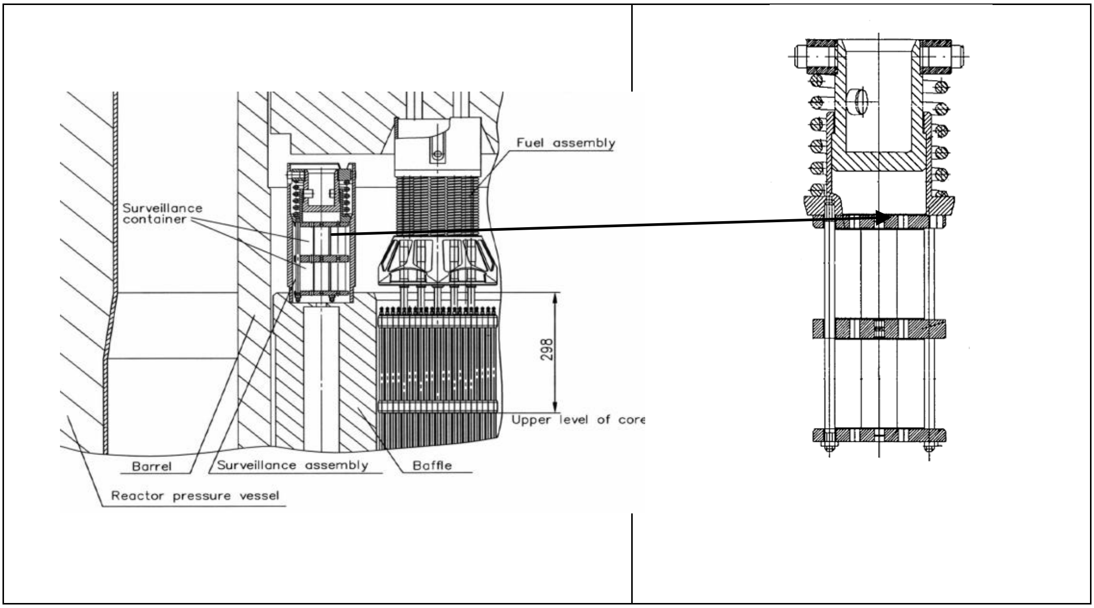
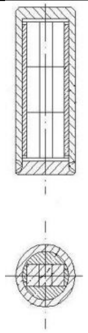
	
A picture of a fracture.	Developed microstructure - a crack can be observed.
	
Surface of a metallographic sample of metal with a crack, undeveloped microstructure.	

Fig. 38. Microstructures

Testing of surveillance specimens

The reactor pressure vessel metal is exposed to intensive neutron fluence with neutrons having energy that exceeds $1{,}5 MeV$, and also to thermal-and-mechanical loading of the fluid. These loading contributors change (or they may change) the structure and mechanical characteristics of the metal. The design of modern reactor plants envisages availability of surveillance specimens that are to be used for metallographic (destructive) tests - these include samples from the reactor pressure vessel that contain base metal, welded metal, and metal from the thermal impact area. In order to achieve similar working conditions, these specimens are positioned in the core in a way such as to be exposed to neutron irradiation the same way as the materials of the reactor pressure vessel are, Fig. 39. At some NPPs these specimens are placed in dedicated hollows in the reactor wall (as is the case for instance with reactor type WWER-1000 B320), while at other NPPs they hang from a rope within the reactor core.





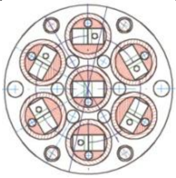


Fig. 39. Containers with surveillance specimens

The surveillance specimen sets are withdrawn one after the other on a regular basis, within periods of several years and are subjected to tests. Using an optical microscope and a scanning microscope the specimens' metal microstructure is examined. The critical brittleness temperature of the specimens is determined through Charpy test with a V-notch. Metallographic tests of the mechanical characteristics are performed by means of tensile forces (applied on a single axis and statically). The testing methods for mechanical characteristics are standardised. Fractographic examinations are undertaken using a scanning electron microscope (SEM). The intervals in-between the tests of the surveillance specimens depend on the NPP surveillance programme in place.

The metal magnetic memory (MMM) method

Modern diagnostics of the condition of structural materials has a large array of different physical methods and tools. Residual and working inner stresses measurement techniques and tools are getting wider application for determining the mechanical characteristics of materials. In this process, a central role is played by the methods and tools for measuring residual and working internal stresses. All the known magnetic diagnostics techniques can be classified as follows:

Active methods, in which a forced magnetic field with a predefined orientation is created in the material;

Passive methods, which use residual magnetism in the material caused by an external magnetic field of natural or man-made origin.

MMM inspection is a passive magnetic method for non-destructive testing. The method is effective in evaluating of stress-strain conditions, and is used for early diagnosing of fatigue damages of equipment and pipelines. The MMM method is not a standardised one.

It has been found that the crystal lattice of iron forms only as a result of interaction of electrostatic and exchange forces without the participation of external magnetic fields [12]. The magnetic moment of atom is a vector sum of all elementary moments such as of nuclei, electrons, spin and orbital ones. As ensues from the electronic structure of atom within the lattice, the orbits of thermi 3-d electrons become collective and expand to include two atoms. As a result, each atom within the crystal lattice turns out to be part of 6 elliptic orbits, while its own 3-d electrons are only three in number. These three orbits create uncompensated magnetic moments that are oriented in space in a strictly defined way: Of the acceptable angles between the magnetic moments' vectors (or between the normals to the orbital planes), the 90°-angles appear to be the most favourable ones in terms of energy. In other words, the magnetic moment created by an electron whose orbit includes two atoms positioned in the angles of a cube at one of the crystallographic axes, has to be parallel to another crystallographic axis, Fig. 40.

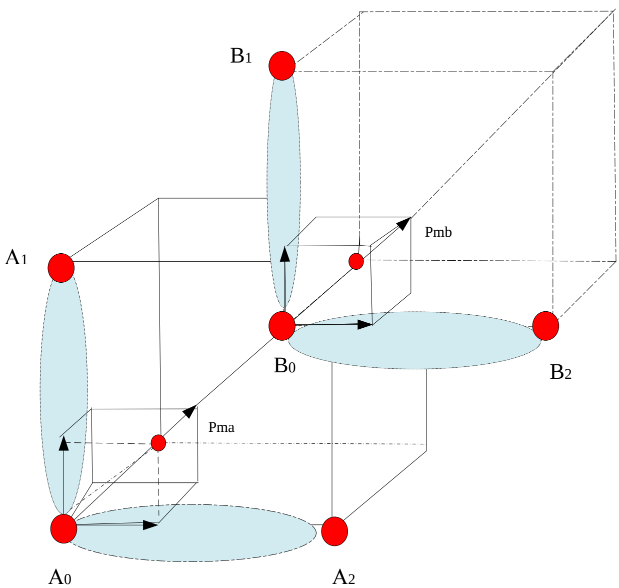


Fig. 40. The magnetic moment of atom is a vector sum of all elementary moments

$$Pm = Pma + Pmb$$

The arrangement of atoms in space results in as follows: in materials with unfilled elliptic envelopes, forced alignment happens of the orbital orientation of the shared 3-d electrons, and, therefore, forced orientation also occurs of their magnetic fields. The resulting magnetic alignment is termed spontaneous magnetism. The essence of magnetic alignment is in that the vectors of elementary magnetic moments p_{mi} existing in each iron-3 atom and equal as per module, are oriented parallel to the cube edges (elementary cell). The resulting magnetic moment of the atom integrated in the crystal lattice is p_m. The direction of the resultant magnetic moment appears to coincide with the spatial diagonal of the cube, and the point of its application – with the center of the atomic nucleus.

The iron crystal lattice contains a large number of elementary cells, and the magnetic moment vectors of the individual atoms provisionally merge in a single vector. When within the material there are areas with concentration of stress, this causes dissipation of their own magnetic fields.
The MMM is a non-destructive testing method, based on the registering and analysis of own magnetic fields. Moreover, the dissipated own magnetic fields have the property of 1) reflecting the irreversible change of magnetisation along the direction of action of the operational loading maximum stress, 2) retaining the structural and technological heredity of elements and welded joints following their manufacturing and cooling in the Earth's magnetic field. The MMM method utilises the natural magnetisation and the after-effect that occurs in terms of magnetic memory of the metal in the actual deformations and structural alterations within the metal of components and equipment.
The technical evaluation tools are apparatuses of the type of multichannel flux-gate magnetometer, Fig. 41. The magnetic field force H_p displayed on the face of the device has a graduation scale in A/m (ampere / meter). The length of the registered movement of the sensor is graduated in mm. The uniqueness of these devices lies in that they identify the stress concentration zones which are the basic sources for development of damages of equipment.

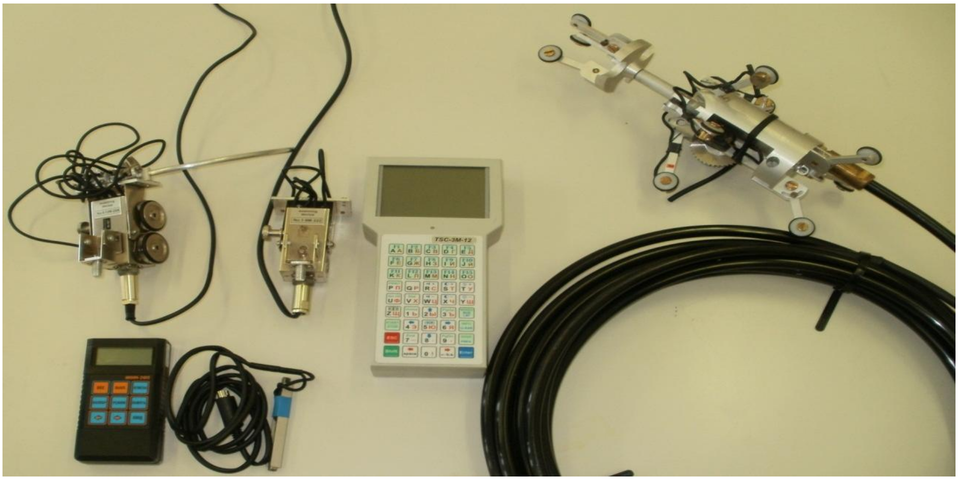
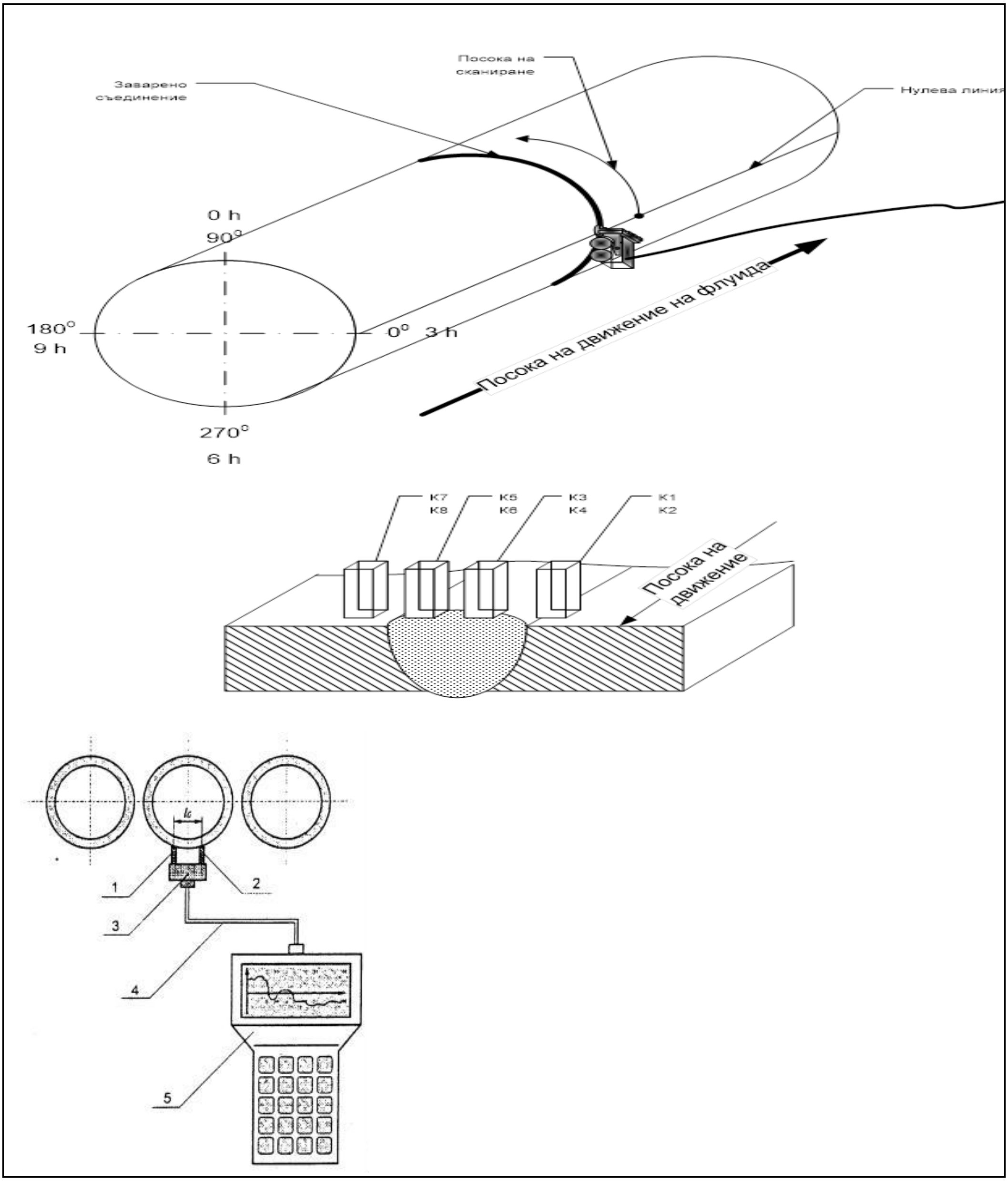


Fig. 41. Technical devices used by the metal magnetic memory testing method

Fig. 42 shows the scanning schemes and technical records for a pipeline that has been tested using the MMM method. The signal peak observed is an evidence that at this point of the scanned object there are zones of stress concentration.


Заварено
съединение
Посока на
сканиране
Нулева лини
0 h
90°
180°
9 h
0°
3 h
270°
6 h
Посока на движение на флуида
K7
K8
K5
K6
K3
K4
K1
K2
Посока на
движение
1
2
3
4
5

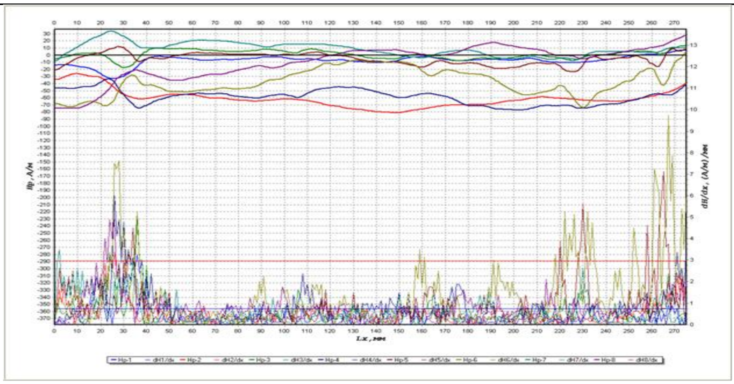


Fig. 42. Testing schemes and technical records of the metal magnetic memory method

The MMM method is a new one and still little used for identifying the metal limit condition. The method provides the link between the magnetic and mechanical indicators of the work hardened material. The results are verified by comparing data from MMM with those obtained through other testing methods applied on one and the same object. Usually, the comparative evaluation makes use of data from ultrasonic non-destructive testing. The results observed in practice show that the UT indications actually coincide with the MMM ones. The method and the apparatus provide the opportunity to assess the lifetime of NPP equipment.

Hardness testing method

The method of testing metal hardness and microhardness implements penetration of the indentor in the surface of the metal sample tested. The principle of this method is based on measuring the metal resistance to penetration, Fig. 43.

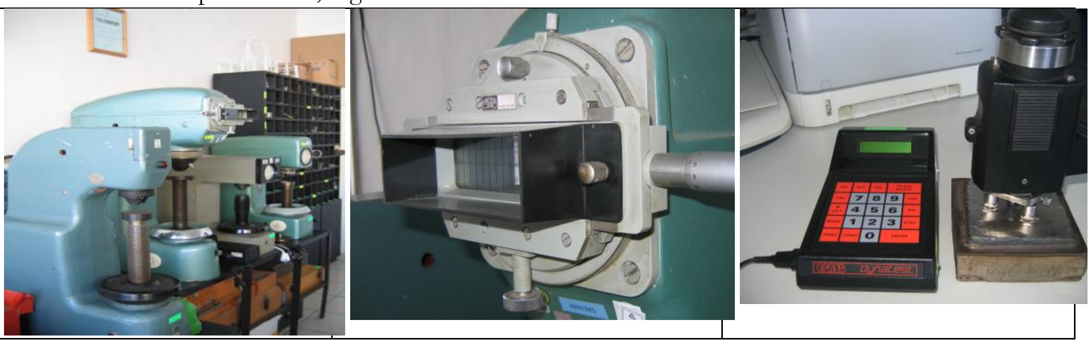


Fig. 43. Hardness meters, indenter footprints on the surface of the tested object (the last one, left)

The results from hardness testing are used to evaluate the changes in the mechanical properties of metal. The kinetic hardness method is used to measure both hardness and mechanical characteristics without collecting samples. It provides data for tensile strength R_m, relative elongation l and relative contraction A of facilities and components. When operating in a radiation environment, metals and alloys will harden and become more brittle (see Chapter 1); it is expected that their indicators for hardness and tensile strength R_m will have higher values.

Spectral testing method (Optical Emission Spectroscopy, OES)

The spectral examination (testing) method is based on the functional dependence between the intensity of spectral lines of the tested object and the concentration of its atoms within the plasma cloud that forms upon applying of sparks on the tested surface. The method has not been standardised.

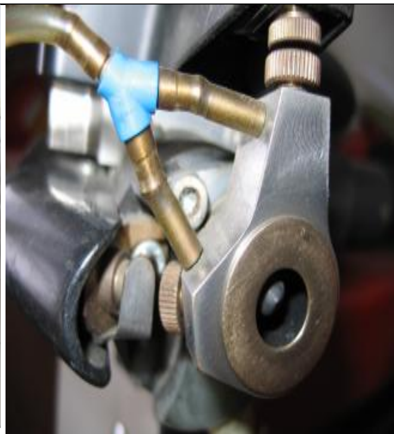
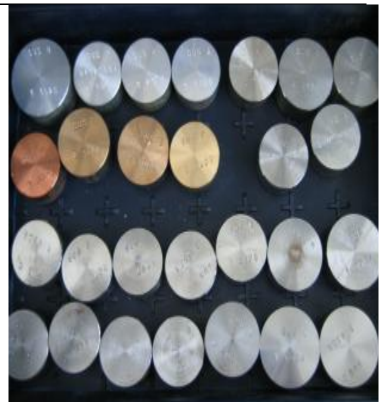
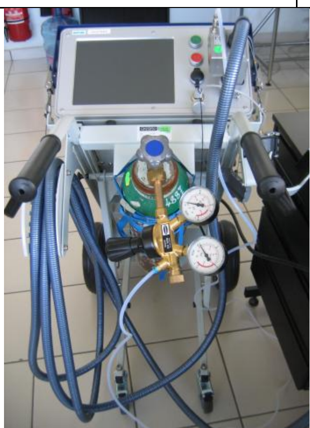
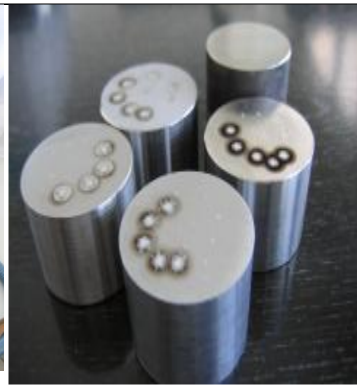
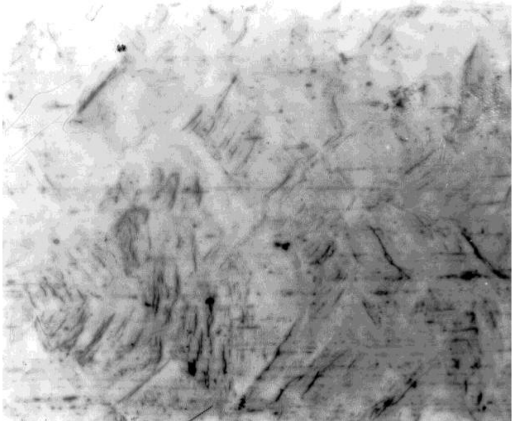
		
		
OES analysers	Gun (end tip) for spark application on the sample	Samples

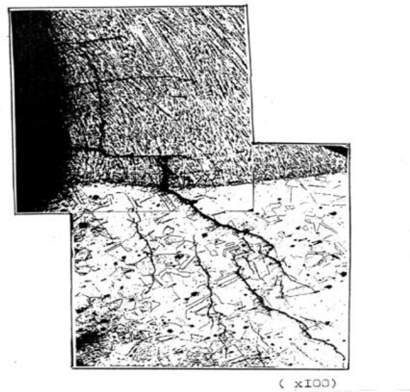
Fig. 44. Technical instruments for the spectral testing method

Acoustic emission

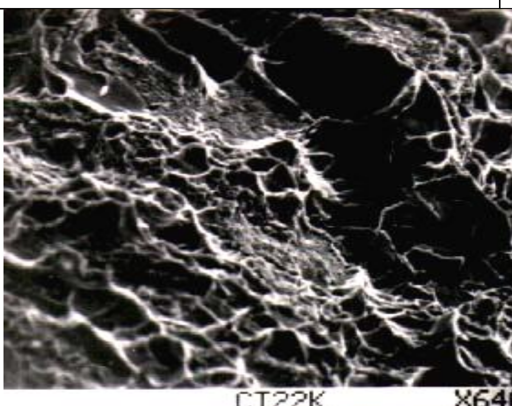
The acoustic emission method is based on the generation of acoustic waves from the tested object. These waves are caused by dynamic and local movements within the object structure. In this case, the nondestrucive testing uses the acoustic signal that is propagated within the material as a result of a discontinuity propagation, Fig. 45.



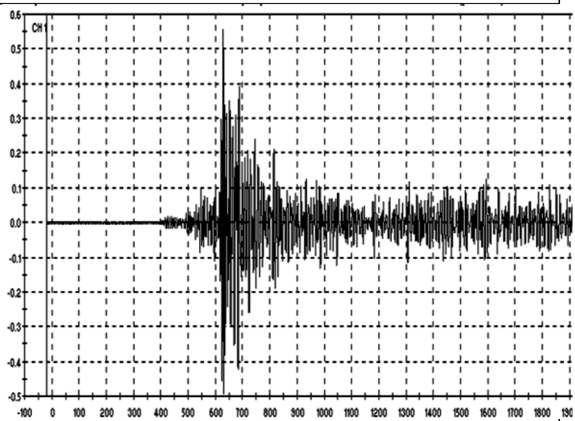
Discontinuities within the material



Micro cracks in a metallographic sample of a welded joint



Micro crack in the material - a source of an acoustic wave



Signal generated from a micro crack in the material

Fig. 45. Acoustic emission method of testing (examination)

The acoustic emission method is based on the analysis of the acoustic waves' parameters. The method has been standardised. The technical instruments employed by the acoustic emission method are devices for receipt, registering and processing of an acoustic signal (Fig. 46).

Fig. 46. Acoustic emission (AE) method technical tools. The sensors are wrapped around the tested pipeline; the registered signal is transmitted to the AE detection instrument

The acoustic emission method enables gauging the condition of the whole object (a pipeline system), and not just of separate localised parts; moreover, the signals are registered and analysed over a longer period of service of the tested object. The method is used to diagnose the condition of systems in service (i.e. objects inside which there is pressure exercised by the fluid).

AGEING EFFECTS AND PREVENTIVE MEASURES

The methods for testing and monitoring are among the most important measures to prevent ageing effects. Table 2 contains descriptions of the ageing mechanisms, effects and indicators, and the corresponding methods applicable for NPP equipment testing and diagnosing [13].

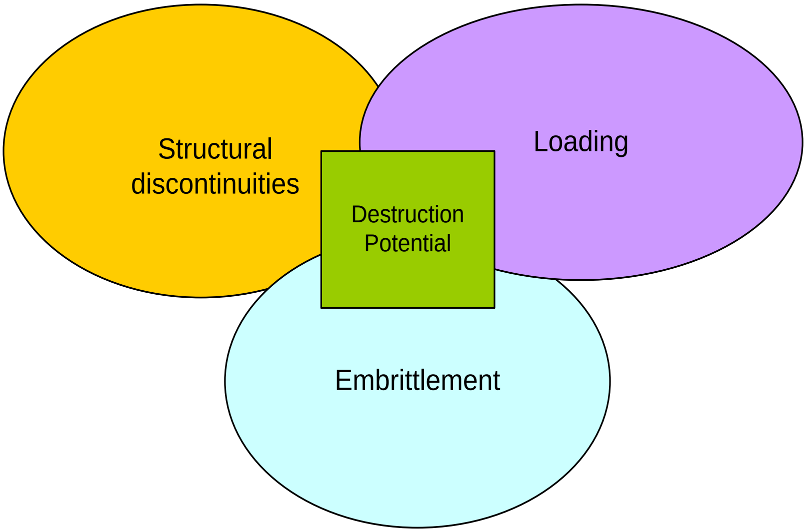


Table 2. Ageing mechanisms, ageing effects and expected loss of functions, ageing indicators and methods for testing

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
Corro-sion-erosion, Fig. 47.	The **corrosion-erosion processes** that are typical for PWR type of NPPs consist in corrosion degradation of materials followed by erosion wear under the impact of the fluid flow rate. **Factors affecting the process include:** fluid composition, velocity and temperature, the component material and geometry, the active stresses, the periodicity of surface moisturising/drying. **Localised corrosion:** in steam generators (SG) and reactor sealing surfaces, pressurisers, and emergency core cooling systems (ECCS).	The erosion-corrosion processes decrease pipeline wall thickness. There is increased probability of pipeline rupture and leaks of coolant. The change in the geometric dimensions of the pipeline walls leads to a change of the internal stresses. The systems' failure rate increases on account of material degradation.	The pipeline wall thickness is measured periodically. The corrosion rate is inspected on a periodic basis. Tests are performed to identify presence of, number, type, location and growth of surface defects, pits, and blow-holes in metal, and percentage of wear of the wall thickness of heat exchanger tubes.	Conduct regular thickness measurement testing of walls and bends. Ultrasonic thickness measurement is applied to the expanded sections or to the external generating line of the elbow bend. The area surrounding the weld joints is monitored. Corrosion evaluation for presence of sludges or deposits is to be performed of the critical areas.

Ageing management effectiveness for NPPs

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
	Intergranular corrosion: reactor, steam generator **Corrosion fatigue:** steam generator, pressuriser. **Stress corrosion:** reactor, steam generator (heat exchanging tubes), pipelines of the pressuriser system and ECCS piping. **Regarding the bends in the pipeline systems:** Stresses will lead to a considerable change in the metal	The erosion-corrosive processes are the cause for loss of tightness of the pipeline systems. Thus the normal operating conditions are compromised. Abnormal operation of the heat exchangers occurs as a result of the rupture of heat exchanging	Monitoring is performed of the water chemistry of the fluid inside the pipeline. The radioactivity indicators are measured.	In-service inspection of metal is performed (visual, penetrant, eddy current and mechanical testing). To prevent localised corrosion, visual inspection and chemical analysis of the depositions are

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
	electrode potential. Tensile stresses (tensions) shift the electrode potential to the negative side, while the compressive stresses shift it to the positive side. The stretched sections act as anodes with regard to the rest of the metal and degrade (dissolve) most intensively.	tubes. The presence of sludge/deposits in the tubes causes deterioration of heat exchange. The general radioactivity levels increase due to activation of the corrosion products.		implemented. To prevent intergranular corrosion, visual inspection, surveillance specimens testing, penetrant, ultrasonic and hydraulic testings are undertaken. To prevent corrosion fatigue, visual inspection, penetrant, ultrasonic and hydraulic testings are undertaken. The water chemistry regime (WCR) is analysed, maintained and improved.





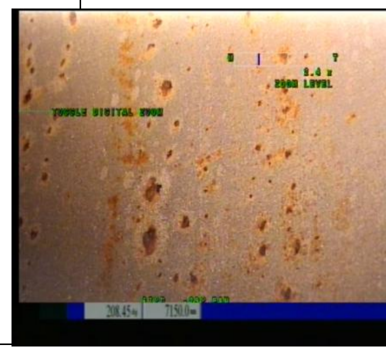


Fig. 47. Photos of outbreaks of corrosion and corrosion-erosion wear

Ageing management effectiveness for NPPs

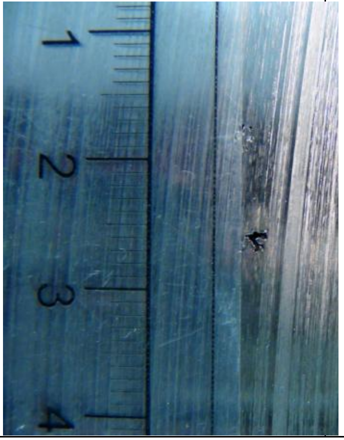
Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
Neutron embrittlement	**Neutron embrittlement** affects the reactor pressure vessel, barrel, core baffle, and reactor guard-tube bank. Factors affecting the process include: Fluence values and direction; The chemical composition of materials. The elevated contents of nickel (Ni) and manganese (Mn) enhance embrittlement due to the formation of clusters in the radiation environment, while the content of silicon (Si) reduces embrittlement.	There is a growing probability of brittle fracture of materials especially for the welded joints of the reactor vessel located opposite the reactor core. As a consequence of radiation swelling of metal there is growing probability of shape changing of components (core barrel); this will lead to altered load bearing capacity of the structure.	There is a limit value for the neutron fluence equal to $5.7x10^{19}$ n/cm^2 in the reactor vessel. Monitoring is performed of the trend of the embrittlement function $\Delta T_K(F,t)$. The critical temperature of radiation embrittlement T_K is calculated and analysed. The radiation embrittlement critical temperature variation ΔT_K needs to be within the acceptable design limits. The parameters monitored are presence of, number, type, location and development of surface, below surface and internal discontinuities.	The neutron flux values following each fuel cycle are recorded. In-service inspection of metal is performed (visual, penetrant, ultrasonic, eddy current and mechanical testing). The mechanical characteristics are studied periodically, including the variation of the radiation embrittlement critical temperature (ΔT_{kF}) of surveillance specimens from the reactor vessels.

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
			The barrel geometry dimensions are monitored.	Thermal hydraulic analyses are conducted. Strength analyses are conducted to assess the defects' propagation resistance. Low-leak schemes of core refuelling are used. Visual and measurement inspections of the core barrel are performed.
Cyclic fatigue Fig. 48.	Cyclic fatigue affects all the main equipment pieces of the primary circuit (reactor, SG, pressuriser, main circulation pipeline, main coolant pump). Low-cycle fatigue affects the	There is increased probability of fatigue degradation of materials. Subsequent change in the load-bearing capability of structures is expected.	The number of load cycles is monitored for the different operating modes. Monitoring is performed of the following parameters: presence of, number, type,	The load cycles are registered and monitored for the different design operating modes. A register is

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
	secondary circuit equipment (turbine, deaerators, separators). Factors affecting the process include: Number of the work cycles, amplitude excursion of the stress intensity factor ΔK_I.  Fig. 48. A photo showing		location and development of surface, below surface and internal discontinuities. The fatigue accumulation factor is periodically calculated.	maintained of the number of loading cycles. Surveillance specimens are tested. In-service inspection of metal is performed (visual, penetrant, ultrasonic, and eddy current testing). Hydraulic testing is implemented. Fatigue analyses are performed.

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
	material fatigue defects			
Thermal ageing	Thermal ageing affects reactors, steam generators, pressurisers, pipelines of the pressuriser system; main circulation pipelines and emergency core cooling systems. Factors affecting the process include: Values for temperature and service life (the period of operation).	Probability of brittle fracture of materials. Subsequent change in the load-bearing capability of structures.	Monitoring is performed of the following parameters: presence of, number, type, location and development of surface, below surface and internal discontinuities. The temperature values are monitored.	Surveillance specimens are tested (of the reactor vessel). In-service inspection of metal is performed using visual, radiographic and metallographic tests. The fluid temperature is monitored on-line. Hydraulic testing is implemented.
Wear, Fig. 49.	Wear affects hydraulic snubbers, sealing faces, fixing elements, internal parts of cylindrical vessels and pipelines. Factors affecting the process	Regarding hydraulic snubbers: under normal operating conditions the hydraulic snubbers components are subjected to negligible loads, and the hydraulic snubber is capable of performing its dedicated functions.	Visual testing is performed to identify presence of, number, type, location and development of any surface discontinuities.	Visual inspection is conducted. Maintenance and repair activities are performed as applicable.

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
	include: Physical, chemical and mechanical properties of the surfaces subjected to friction; Combination of materials for the working surfaces; Interaction of the working surfaces with the environment; Clean processing of the friction surfaces; Type of friction (dry, boundary, semi liquid, and liquid); Values of the normal pressure and the velocity of working surfaces one against the other. Of the large number of wear types on the working surfaces of machine parts, major importance is attached to abrasive wear in the presence of grease, because	With degradation due to wear, a hydraulic snubber is incapable of performing its protective functions in case of strong vibrations, or an abrupt displacement of equipment caused by seismic loads. • Regarding pins (their cylindrical part) and pin sockets - their fixing function is impaired and it is probable that fixing will not be tight enough.		

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
	the wear products that invariably arise from the machine components friction are oxidised and turn into a sort of abrasive materials and it is rather complicated to clear the lubricants from the components surface. 			

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
	Fig. 49. Photo of contact surfaces wear			
Erosive wear	Erosive wear is an issue for pipeline operation in the turbine hall. Defects of erosive nature occur at pipeline bends, and also in pipeline sections downstream of throttle and control valves. The cause for such defects is the presence of two-phase medium in the pipes and development of cavitation processes.	Erosion-corrosion processes decrease pipeline wall thickness. There is increased probability of pipeline rupture and leaks of coolant.	The pipeline wall thickness is measured periodically.	Regular thickness measurement testing of pipeline walls is conducted. In current inspection programmes the ultrasonic testing of turbine hall pipeline elements and assemblies has been increased several times. This allows bringing to a minimum any unscheduled shutdowns of the power unit on account of pipeline erosive wear.
Plastic (gradual)	Plastic deformation affects steam generators,	The load-bearing capacity of the affected structures is changed.	Visual testing is performed to identify presence of,	Visual and measurement testing

Ageing mechanisms	Ageing effects	Loss of functions	Ageing indicators	Testing methods
deformation	pressurisers, pipelines of the pressuriser system; main circulation pipelines and pipelines of the emergency core cooling system.		number, type, and location of any surface discontinuities.	is implemented.

The monitoring and testing methods should cover the identified and the potential mechanisms of degradation of the mechanical properties, Table 3.

Table 3. Equipment, degradation mechanisms, and testing methods

No.	Equipment	Degradation mechanisms	Testing methods as per the work programmes
1.	Reactor pressure vessel (RPV):	Thermal embrittlement Neutron embrittlement Change in geometric dimensions Fatigue	VT, PT, ET, UT
2.	Steam generator	Corrosion Fatigue Thermal ageing	VT, PT, ET, UT
3.	Main circulation pipeline Pressuriser	Pressuriser Thermal ageing Corrosion Fatigue	VT, PT, UT
4.	Main Coolant Pump, (MCP)	Thermal ageing Corrosion Wear	VT, PT, UT
5.	Pumping equipment	Fatigue Corrosion Wear	VT, PT, UT
6.	Turbines	Fatigue Erosion-corrosion	VT, PT, UT
7.	Pipelines Composite welded joints	Corrosive wear Along the weld fusion boundary there form: iron-oxide depositions + metal of steel 20; metal of steel 20 + metal of the weld. Corrosion is accelerated along the weld fusion line	VT, PT, RT

In a nuclear power plant there thousands of components, pieces of equipment and pipelines. They are tested in the field, at their respective operation site and not in laboratory conditions. Due to the large scope of objects for testing, the testing and inspection activities are performed periodically, within certain time intervals.

At all NPPs, facilities and components are classified as per their importance for safe operation. The facilities classified as group I need to be tested most frequently for integrity and absence of defects in the material. Their interval between inspections should be shortest. Such facilities are the primary circuit components. The periodicity of their inspection ranges from 4 to 8 years. The secondary circuit facilities have inspection periodicity of 4, 6 to 12 years. The inspection programmes of NPPs in the process of lifetime extension have the number of ultrasonic testings of turbine hall pipeline elements and assemblies increased several times. Table 4, below, lists the major components of NPPs with WWER-1000 reactor type, and the intervals between inspections (in working hours).

Table 4. Equipment and intervals between inspections

Equipment in nuclear power plant, type WWER-1000	Intervals between inspections
RPV, reactor internals, control rod drive system, RPV upper unit, RPV equipment, SG, pressuriser, pressuriser pipe-work, MCP Du 850, surge-line Du 300 from RPV to the hydro-accumulators. Composite welded joints of pipelines.	30 000 h
MCP, quench tank, filters, heat exchanger and additional cooling of the blow-down system. Pipe-work: Blow-down line, feeding water, drainage and bypass cleaning of primary circuit; emergency and planned core cooling pipeline; emergency injection of boric acid solution, emergency feed-water inside the containment, SG air ducts, blowers from the pressuriser; SG main steam and feed water pipe-works, non-isolatable section within the containment.	45 000 h
High and low pressure cylinders; OK-12A turbine.	After repair
Outlet pipe-work between low pressure cylinder (LPC) and condenser; low pressure heater drainage lines; condensate from 'fresh' steam pipe-line to low pressure heater.	30 000 h
High pressure deaerator; low and high pressure heaters; main steam lines and fresh steam lines; RL feed-water lines; welded joints, elbows of systems RC, RQ, RM, RD, RB, RN pipe work; pipe lines from low pressure heater to high pressure deaerator; pipe line from high pressure heaters to safety valves; steam lines to separators I and II; pipe lines for the condensed hot steam,	45 000 h

from 'fresh' steam pipe-line to high pressure heater; high pressure heaters drainage lines.	
Welded joints of drainage pipelines from high pressure heater; pipe sections after the control and throttling devices, water pipe line welded joints – emergency feed water.	15 000 h
Elbows, valves, T-joints, pipe sections downstream the control and throttling devices.	22 500 h

EVALUATION OF THE INSPECTION AND DIAGNOSTIC METHODS EFFICIENCY AGAINST DEGRADATION MECHANISMS

Throughout the operation of each nuclear power plant, testing methods are undertaken aimed at eliminating (or mitigating) the effects of degradation mechanisms on the mechanical properties of metal. The principles for in-service inspection of metal of equipment and pipelines are as follows:

The requirements stated in normative documents should be strictly observed;

Conservative approach is to be applied: the intervals between inspections shall be shortened upon identification of critical zones in the metal of equipment;

The NPP equipment shall be classified as per its importance for the safe operation of the facilities. The tests/control of the equipment important to safety have to be qualified as per the IAEA methodology [14];

The testing methods applied have to take into account the reference mechanisms of degradation of the mechanical properties of metal in the working environment, Table 5.

Table 5. Testing methods targeted at degradation mechanisms and key parameters that characterise metal condition

Testing and diagnostic methods	Degradation mechanisms	Key parameter characterising metal condition
VT, PT, MT, ET, UT, RT, metallographic method	Corrosion, erosion	Damaged area, number of damages per unit area and depth of damages; Type, size and location of discontinuities; Wall thickness of vessels and piping systems.
VT, PT, MT, ET, UT, metallographic method	Wear	Type, size and location of discontinuities.

VT, PT, MT, UT, metallographic method	Fatigue	
VT, PT, MT, UT, metallographic method	Thermal ageing	
Mechanical testing, metallographic method.	Neutron embrittlement. Structural changes. Changes in mechanical properties.	Type, size and location of discontinuities. Content of phases, grains and micropores. Strength limit R_m, creep limit, relative elongation l, relative shrinking A, hardness number, impact toughness, KCV.

One of the issues that modern nuclear energy faces is whether the methods employed for inspection and diagnostics, the scope of inspected equipment and the frequency of inspections are effective against the existing degradation mechanisms of mechanical properties. How is their effectiveness checked? This is not an easy task, given that the NPP vessels, equipment, pipelines, welded joints and the adjoining valves and fittings that need to be inspected and diagnosed are thousands units of facilities. The search for adequate solutions has to include a review of all the inspection programmes, and of the methodologies for testing and diagnostics, as well as of the registered data on defects and failures. In other words, regardless of the provisions of the normative documents, after several decades of NPP operation, a revision has to be undertaken of the maintenance and repair activities to check:

what the scheduled inspection is in terms of the scope of equipment (i.e. scope of inspection) and periodicity of the process;

performance of inspection: what is the methodology applied, whether the technical tools are appropriate, is verification of inspection implemented, etc.;

what the final results are of inspection after several decades of operation of the equipment (presence of discontinuities and defects in the material, what the trends are, have there been equipment failures due to discontinuities);

have there been observed any changes in the operability of components and structures;

if there is feedback in place: do the conclusions drawn from activities and the results from inspections impact planning?

The evaluation of the effectiveness of inspection methods gets particularly important towards the expiry of the design lifetime of the nuclear power units and prior to their transition to service life extension. It is necessary to review the Programmes and Methods for Maintenance, Monitoring and Control, as well as the results of their implementation. The process includes various stages of checking and assessment.

The normative and technical documentation currently effective at the NPP is reviewed to check if it is up-to-date, and state-of-the art. This is the first stage - the process is always initiated with review of documentation as per the approved and recognised international practice.

Lists are prepared with components of the NPP safety systems, and lists of components of the systems important to safety. It is possible that the type programmes for in-service inspection [15], drafted almost 40 years ago, may not comprise facilities in which ageing processes have been identified throughout the NPP operation period. It is verified whether the activities for control, maintenance and monitoring have covered all the components and facilities from the safety systems and of the systems important to safety.

Checks are undertaken of the scope of facilities and pipelines which have been scheduled for inspection: for instance, check if all the welded connections of pipelines in the safety systems have been included.

Following 30 or more years of operation of a nuclear power plant, it is mandatory to perform a comprehensive assessment of the physical condition of its structures and components. Components are visually inspected in order to evaluate their condition. The process includes checks on the integrity of facilities, presence of traces of leakages, availability and condition of adjacent equipment, etc.

The information on the manifested defects in metal and failures of equipment undergoes review and systematisation. This includes review of the operational and maintenance documentation of the facilities, their passport data, also the data from the register of the loads performed, of the non-destructive testing reports, of the monitoring and hydraulic tests of pressure vessels.

It is well known that continuous operation under working conditions typical for a nuclear power plant will result in changes occurring in the strength and plastic characteristics of metal, i.e. processes of metal embrittlement and hardening are expected to have taken place. This is why it is absolutely imperative towards the end of the design service life of an NPP to perform tests on the mechanical characteristics of the materials of nearly all the primary circuit facilities. Using the kinetic hardness method, data will be obtained of the tensile strength R_m, relative elongation l and relative shrinkage A of facilities and components. The experimental data obtained are then compared with the passport or the normative specifications data. If the current values have an increase exceeding the limits by 10% or higher, it is accepted that there is an intensive process of embrittlement and strength analyses should be performed. In such cases conducting of strength analyses is mandatory prior to allowing further operation of the facility or the system.

Operating experience has demonstrated that, on the one hand, no significant changes in the steel hardness are observed and the strength characteristics have increased their values up to 5% as compared to the initial condition, but, on the other hand, hardness is measured in separate points of the inspected facility and the scope of inspection is rather local. In order to obtain credible data, numerous measurements need to be made, i.e. for circumferentially welded joints the measurements need to be made at least in four diametrally opposed locations, and in several points of each location.

Verifications are made of the adequacy of individual control tests (i.e. the frequency of inspections) to confirm they are capable of ensuring high probability of "timely" detection of discontinuities developing in metal, and preventing any loss of operability of the component. For example, to identify a pore in a pipe metal prior to any rupture of the pipe and occurrence of a leak in the system. This verification is performed through computer simulation models of the load fields in the facilities. In the fields of highest loads defects are implanted, then a forecast is made of their development during the further operation of the facility.

The defects growth curve is tracked over the next intervals between inspections.

The scope of inspection methods is included in the design documentation of each NPP. The type programmes for in-service inspection and condition diagnosing of equipment require regular use of the VT or PT method, which are surface inspection methods, and also of the volumetric methods - UT, ET (see Table 5). To assess the condition of newly welded joints (during break-down maintenance activities) the methods to be implemented are VT, PT, UT, and RT. For the purpose of inspection upon receipt of new facilities or materials, the methods of hardness testing and spectral analysis of the chemical composition are applied.

On the basis of 35 years of operating experience in technical diagnostics of NPP facilities it may be concluded that the set of surface inspection methods (VT, PT, UT – with surface ultrasonic waves); 2) near surface inspection methods (ET); and 3) volumetric methods (RT, UT) is sufficient for effective detection of discontinuities prior to the facilities reaching loss of operability. The current trend, however, is to try and detect defects in metal at a very early stage of their development - as early as their occurrence at the level of crystalline grid when displacements and dislocations are sought for. This is why the share of innovative methods applied (e.g. metal magnetic memory) tends to grow.

Checks are performed to confirm if the inspection methods are appropriate and adequate to the degradation mechanisms. Irrespective of the existing normative framework (type programmes for in-service inspection), following the performance of assessments of

defects/failures, and

mechanical characteristics of metal

it can be concluded if the employed inspection methods are adequate for the degradation mechanisms.

The appropriateness of the inspection methods' sensitivity is checked. Certainly the inspection methods continuously evolve in terms of methodology, instrumentation and applicability. In-service inspection of components and facilities of an NPP is normally performed during the outage, in the field, on the work site, and not in laboratory conditions. It cannot be expected that the highest sensitivity level of a method will be continuously applied to inspect NPP facilities, bearing in mind the large scope for inspection, the restricted timeframes for outages and the dose limits. Always the target is to achieve the right combination among the method capabilities, its relevance and the price framework. The trend currently observed is one of transition from traditional defectoscopy (VT, PT, ET, UT, RT) to technical diagnostics that employs a comprehensive approach: defects' parameter identification;assessment of the distribution of internal (residual) stresses;identification of the actual structural and mechanical characteristics of metal.

There is a growing share of inspection methods used to provide express assessment of the condition of facilities. The thermal imaging inspection method provides information about critical points of mechanical and electrical equipment; moreover, this is achieved remotely, without the system being removed from service, or undertaking of any preparation of the object for inspection.

The metal condition assessment is followed by integrity and reliability evaluation of structures and facilities. Assessments are made of the thermal-hydraulic loads of facilities. Analyses of strength, fatigue and dynamic stability are conducted. These analyses serve to verify if the methods of inspection, maintenance and monitoring have been efficient. Large part of the equipment and pipelines are regularly subject to, as well as within the in-service inspection programmes, inspection methods such as visual (VT), penetrant (PT), ultrasonic (UT), and eddy-current (ET) testing. These methods, whether applied individually or in combination with other methods of the maintenance and repair system for monitoring of working medium parameters, permit timely identification of defects in a component and their repair. Throughout the operation of an NPP, periodic non-destructive testing is supplemented by measurements of diagnostic systems (leak monitoring system, effective stress assessment system, etc.). Along with the "good practice throughout NPP operation", it should be noted that after evaluation of the effectiveness of methods, some weaknesses of the processes become evident. Apparently, further activities are needed along two lines: enlarging the scope of inspection; modifying the inspection periodicity.

Measures for extending the scope of inspected equipment (beyond the standard programmes)

It becomes evident that regular periodic inspection is necessitated for facilities that have not been included within the maintenance and repair system. These facilities practically have not been subjected to non-destructive testing during the operation of the NPP, although they have also been important for the safe plant operation. Such facilities and components include as follows:supports and bearing structure of the reactor pressure vessel; core barrel; polar crane; refuelling machine; steam generators hydraulic snubbers; valves and pipelines; pipelines of the fire suppression system of the nuclear power unit; buried pipelines of the spray ponds.

The measures aimed at enlarging the scopes of inspection include:

For the purpose of extending the lifetime of the above facilities beyond their design life, they need to be subjected, in addition to the standard programmes (Fig. 23), to visual (VT) and penetrant (PT) testing every 10 years of operation.

Ultrasonic thickness measurement has to be applied on a regular basis to prevent corrosion damages and risk of thinning of walls (of pipelines and valves). The scope for inspection of the turbine hall equipment such as pipework, elbows, T-joints, and valves has grown several times by the end of the design service life as compared with the beginning of operation. For equipment where increased hardness has been reported after measuring of its mechanical properties, and in order to prevent further hardening under radiation conditions,regular implementing of the hardness testing method is necessitated. The specificities of the inspection of reactor internals are connected with the evaluation of the changes in the geometrical dimensions of the core barrel, on account of the expected swelling of metal under the effects of radiation.

Measures for increasing of the frequency of inspection

The periodicity of inspection of the facilities is determined in normative documents [e.g. 15, 16, 17]. These rules, however, provide only the general framework of the frequency of inspection, and do not cover the variety of different loads, the effects of the working environment and the respective metal wear after several decades of operation (30 years). The strength analyses found (see section 12 of this chapter) the necessity of raising the frequency of inspection in the critical areas of metal where enhanced stress has been registered (with values around the limit ones). Also, periodically, the development of defects has to be evaluated by methods of destruction mechanics, based on the predicted mechanical properties. In this case, the trend of development runs in two directions:

1) Increased frequency of inspection – this is necessitated especially for pipeline systems that are subjected to corrosion-erosion wear (see Table 2 – corrosion-erosion and erosion wear);

2) Use of diagnostic systems that monitor online certain parameters related to leaks. Lately, the "leak before break" concept based on acoustic emission method (see Chapter 2) has been more widely implemented.

Guidelines for the development of the inspection and diagnostic methods to achieve efficiency of the inspection. In terms of the practices implemented so far, the applied maintenance and repair system is sufficient for the timely detection of defects and tracking of their development. Nevertheless, it has to be pointed out that the testing method of traditional defectoscopy (VT, PT, ET, UT, and RT) prove insufficient for detection of defects in their early stages.

As has already described in Chapter 1, the operation of metal in equipment is mainly dependent on dislocation slips and movements of deformations in the localised areas of stress concentration. The inspection methods have low effectiveness as regards control of the stress-strain condition of equipment.

The analysis of the capabilities of the known inspection and diagnostics methods (VT, PT, ET, UT, RT) regarding the base metal of components and welded joints of equipment and structures permits identification of their main and significant deficiencies:

1) The greater number of these methods are not employed in the field of plastic deformations;

2) Inspection provides data about a restricted localised areas of a facility and is not suitable for monitoring of long and large size structures;

3) Changes in the structure of metal are not taken into account;

4) Inspection only takes place on the surface of the object, while assessing the in-depth layers of metal or welded joints is not possible;

5) Deriving of graded diagrams is required based on pre-made samples that do not reflect the actual condition of the equipment.

Preliminary preparation is required of the inspected surfaces of the respective objects for testing; It is difficult to determine the position of control sensors with regard to the direction of maximum stress and deformation that determine the reliability of the equipment. The problems that modern energy sector faces arise from ageing management of nuclear installations, namely:

1) For the assessment of the actual condition of metal, certain methods and tools are implemented (ultrasonic thickness measurement, thermal imaging control), which are not able to provide an early diagnosis of any developing imperfections;

2) There is no adequate scientific justification of the order of implementing of various methods and tools for destructive and non destructive examination;

3) There is no requirement to perform a 100% study of all ageing equipment assemblies in order to identify potentially hazardous areas;

4) The proposed strength assessment methodologies, as a rule, are based on the independent occurrence of corrosion, fatigue, and creep processes, although in practice these processes run simultaneously in different combinations;

5) The criteria for the limit condition of metal provided by the guideline documents (crack resistance, limitation of thinning of walls provoked by corrosion, fatigue wear limit, creep extension limit, etc.) are based on results of laboratory tests on samples that do not reflect the actual condition of the equipment.

Increasing the operating life of nuclear facilities sees increased number of defects due to the natural ageing of metals. This implies development of the metal inspection activities along the following lines:

Application of inspection methods associated with establishing of critical zones of elevated concentration of stresses;

Use of the diagnostic systems installed on NPP facilities. The diagnostic systems are based on passive control methods where the equipment is operable and no surface preconditioning is required. Thermal imaging of mechanical and electrical equipment is applied, and also the acoustic emission method and the magnetic method (metal magnetic memory).The trend currently observed is one of transition from traditional defectoscopy to technical diagnostics that employs a comprehensive approach:

1) Determination of defects parameters using traditional inspection methods - VT, PT, UT, ET, RT. 2) Development and implementation of an electronic database for the inspection results;

3) Assessment of the distribution of internal (residual) stresses by using the methods of acoustic emission and metal magnetic memory;

4) Determining the actual structural and mechanical characteristics of metal through the kinetic hardness method;

5) The methods of inspection have to cover the critical areas found in irreplaceable equipment, as identified after measurements, testing or after strength analyses;

6) Development and approbation of a software that calculates the minimal acceptable thickness based on the physically measured results for pipelines subjected to erosion-corrosion wear.

Categorisation of inspection is acceptable for the purpose of NPP facilities and components control and for achieving of the required effectiveness [18]. The purpose of categorisation is to unify the requirements for inspection of the individual facilities taking into account their condition and importance for safe operation:

1) Inspection category 1 should be applied to facilities of the safety systems and the systems important to safety, in which critical areas have been identified. The specific activities in this case are related to shortening the intervals between the individual inspections, application of a set of inspection methods using qualified methodologies, use of diagnostic systems for the localisation and control of

leaks, strict control of the load cycles under all regimes, preparation of new strength calculations, etc. After evaluation of the inspection results compliance, the brittle fracture toughness has to be assessed.

2) Inspection category 2 should be applied to facilities for which no critical areas have been found. The inspection activities in this case should follow normative requirements (or consider the current sate in the NPP), while the compliance assessment has to follow the norms.

3) Inspection category 3 should be applied to determine the general mechanical and structural condition of the object (facility) and its supports, the integrity of the structure, corrosion-erosion wear and deposits, etc.

The process of inspection categorisation shall include, as a minimum, information regarding:

1) The classification level of the facilities in terms of the safe operation of the nuclear power plant;
2) Data of defects in the metal of the facilities;
3) Any identified effective degradation mechanisms.

Table 6 provides an example of a potential allocation of the inspection categories with regard to the different facilities.

Table 6. Suggestion for the categorisation of inspection

Classification as per level of importance of the facilities/ Presence of critical areas	Facilities of the safety systems	Facilities of the systems important to safety, primary circuit	Facilities of the secondary circuit	Auxiliary facilities
Critical areas have been identified by the strength analyses; in-service inspection defects	Category 1 as per the testing method, includes VT I PT, ET, UT		Category 1 VT I PT I UT (thickness measurement)	Category 2 VT II PT II UT (thickness measurement)
Critical areas have been identified by the strength analyses; no defects	VT I PT, ET, UT		VT II/III PT UT (thickness measurement)	VT III
No critical areas have been found.	VT II PT, ET, UT			
Loading mechanism	Radiation loading	Erosion, corrosion. Stress corrosion	Erosion, corrosion, general thinning of	Wear, corrosion deposits.

	Thermo-hydraulic loads		walls	

The approach described demonstrate that the scope and periodicity of inspection can be identified not only based on the normative requirements, but also on the evaluations performed of the stress-strain state of facilities and assessment of the influence of the working environment, Fig. 50.

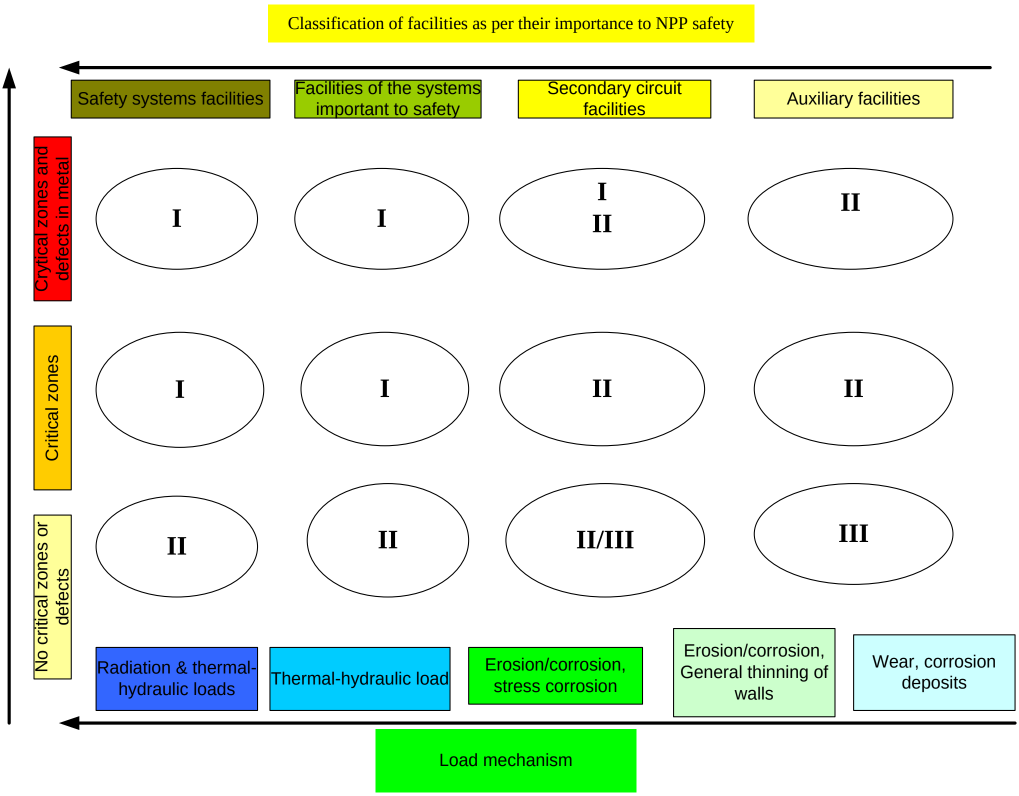


Fig. 50. Categorisation of inspection according to the importance of facilities for the safe plant operation and the loading mechanisms

REFERENCES

1. R.Krivanek, J. Fiedler, Main corrective measures in an early phase of nuclear power plants preparation for safe long term operation, Nuclear Engineering and Design Journal, 316 (2017)
2. OAO OKB Gidropress, General programme for comprehensive assessment of the actual condition and assessment of the residual lifetime of SSGs at Kozloduy NPP, within the design range of OAO OKB Gidropress (Russia, 2012)
3. OAO OKB Gidropress, Report on the results from the comprehensive assessment of the actual condition and assessment of the residual lifetime of equipment and pipelines of the reactor unit at Kozloduy NPP, within the design range of OAO OKB Gidropress (Russia, 2013)
4. IAEA, IEAE Safety Standards Series, NS-G-2.12 (Vienna)
5. Ostrejkovskii Ageing of the materials in nuclear industry (Moscow, 2002)
6. M. Georgiev, Crack resistance of metals under static load (Sofia, 2005)
7. Akiyoshi Nomoto, Understanding on the Mechanisms of Irradiation Embrittlement of RPV Steels and Development of Embrittlement Correlation Method, Central Research Institute of Electric Power Industry (Japan, 2014)
8. PNAE G 7-002-86 Equipment and pipelines strength analysis norms for nuclear power plant (Russia, 1986)
9. Unified procedure for integrity and lifetime assessment of components and piping in VVER NPPs during operation Verlife, IEAE, 2010; Nulife 2014, Project RER 4030;
10. JA Collins Failure of materials in mechanical design: analysis, prediction, prevention (1993)
11. W. Feodosiev, Resistance of the materials (Moscow, „Nauka", 1986)
12. V.T.Vlasov, A.A.Dubov Physical Base of the metal magnetic memory method, ZAO Tisso Publishing House (Moscow, 2004)
13. Galya Dimova, Assessment of non destructive and destructive testing activities for NPP's safety, Technical meeting of NDT cluster (Sofia, 2015)
14. Methodology for Qualification of Non-destructive testing, IAEA, Vienna
15.ATPE-9-03 Typical program for control of base and weld metal of NPP's equipment and pipelines, WWER 1000 (Russia, 2003)
16.NP 084-15 General Provisions for Installation and Operation of Emergency Power Supply Systems for Nuclear Power Plant (Russia, 2015)
17. ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components (2013)
18. Galya Dimova, Significance of NDT for LTO of units, type VVER 1000, Kozloduy NPP, Sozopol, www.ndt.net (2016)

19. Galya Dimova, Ageing management in NPP. Effectiveness of the methods for control, examination and monitoring in relation to mechanisms of degradation of mechanical properties, 13-th National Congress on Theoretical and Applied Mechanics, 2017, MATEC Web of Conference, № 05015
20. Galya Dimova, Comparison of the embrittlement methods for metal of reactor pressure vessels, magazine Science News of NTS, ISSN 1310-3946 (2017)