NEW APPROACHES FOR FLOW-ACCELERATED CORROSION

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Introduction

Erosion-corrosion wear, or Flow Accelerated Corrosion (FAC), of equipment and pipelines is one of the main problems of NPPs operation. Erosion-corrosion wear is one of the widespread damaging mechanisms for equipment and pipelines manufactured from carbon steels. Malfunctions in Russian NPPs operation as a result of FAC occur on average 3 times per year.

Statistic data on metal wall thinning for typical elements (T-joints, bends, transitions, after fitting) of pipelines and equipment on WWER and RBMK NPPs

Only about 10% of the elements are subjected to the considerable wear (more than 20% of wall thinning) and are potentially dangerous to reach the critical unacceptable wall thinning.

A design margin set on metal wall thinning owing to foresee corrosion process is 1.2 mm on 30 years of operation – it is 0.04 mm per year. Actual rate of metals FAC wear can achieve 0.2-2.5 mm per year, that is dozens times more than the design margin on thinning.
Examples of the secondary circuit’s piping rupture due to FAC wear on different NPPs

- **USA**
  - AS “Sarpi”, 02.12.1986 г., блок № 2, 822 МВт
  - Отвод трубопровода подачи воды на ПН
    - Ø 457 мм
  - 12,7 мм → 1,5 мм

- **USA**
  - AS “Arkansas”, 04.1989 г., блок № 2, 1095 МВт
  - Трубопровод отбора греющего пара на ПВД
    - Ø 356 мм

- **Finland**
  - AS “Poviza”, 05.1990 г., блок № 1, 465 МВт
  - Основной трубопровод питательной воды

- **USA**
  - AS “Milsto”，11.1991 г., блок № 2, 863 МВт
  - Отвод трубопровода дренажа ПВД
    - Ø 222 мм

- **Japan**
  - AS “Mihama-3”, 08.2004 г., 826 МВт
  - 10,0 мм → 1,5 мм
  - Трубопровод питательной воды
    - Ø 550 мм

- **Russia**
  - Балаковская АЭС, 11.2004 г., Блок № 2, 1000 МВт
  - 8,0 мм → 1,5 мм
  - Трубопровод байпаса регулятора питательной воды
    - Ø 106x8 мм

*New Approaches for Flow-Accelerated Corrosion, M. Bakirov*
Example of the secondary circuit’s piping rupture due to FAC wear on Balakovo NPP, Unit 2 in 2004
Nature of the flow-accelerated corrosion

FAC nature consists in **mutual influence of three physical processes**:

- *corrosion* (chemical and electrochemical);
- *erosion* (mechanical destruction of the surface layer);
- *dilution* (for example of the oxide film).

Each process, even in a case of separate consideration, have not been completely studied until now.

A process of the corrosion in a considerable rate depends on metal chemical composition and water chemistry. Nevertheless, a required scope of input data from NPPs, concerning the above mentioned parameters, can not be collected in a sufficient scope which enables to carry out a comprehensive FAC analysis.

Erosion processes can be divided on cavitations erosion, abrasive erosion and “wind” erosion caused by a shearing stresses action on a metal-flow boundary.
Main factors and processes concerning FAC of the piping metal in a double-phased flow

**METAL**
- Metal properties
  - chemical composition (Cr, Mo)%;
  - wall thickness;
  - surface roughness
  - mechanical properties
  - residual stresses
- Water-chemical factor
  - temperature;
  - inter-phase distribution $K_d$;
  - pH (or inhibitor properties);
  - content of iron;
  - ion composition of water;
  - electroconductivity
- Properties of the corrosion products
  - density and porosity of the oxide layer;
  - atomic volume of the corrosion products;
  - constants, defining processes of formation and dilution of the magnetite.

**Double-phase flow**
- Electrochemical corrosion
- Dilution of the magnetite
- Mass transfer

**Corrosion component**
- Metal properties
- Water-chemical factor
- Properties of the corrosion products

**Erosion component**
- Metal properties
Features of FAC physical-chemical processes in a single-phase and double-phase flows

<table>
<thead>
<tr>
<th>Single-phase flow (water)</th>
<th>Double-phase flow (wet steam)</th>
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<tbody>
<tr>
<td>$c = f(z)$</td>
<td>$c = f(z)$</td>
</tr>
<tr>
<td>$NH_3$, $N_2H_4$, $O_2$</td>
<td>$K_p &gt; 1$</td>
</tr>
<tr>
<td>$Fe^{2+}/Fe^{3+}$</td>
<td>$K = f(Re_e, Re_s)$</td>
</tr>
<tr>
<td>примесяи: NaCl...</td>
<td>$K &lt; 1$</td>
</tr>
<tr>
<td>$u_w(z)$</td>
<td>$\delta &lt; 300$ mm</td>
</tr>
<tr>
<td>$c_0$</td>
<td>$\delta &gt; 3$ mm</td>
</tr>
</tbody>
</table>

Metal, % (Cr, Mo, Cu)
Processes of the flow-accelerated corrosion

**Zone A** – laminar flow – very low rates of corrosion.

**Zone B** – turbulent flow – rates of metal mass losses are determined by a transfer of active components to the metal surface. Friction stress in this zone is insufficient to cause a destruction of the film on the metal surface.

**Zone C** – friction stress becomes such a big that the film moves off (eliminates) in some areas, and in that areas an intensive corrosion occurs. Metal mass losses become significant due to contact currents running between areas which are “naked” and covered by the film.

**Zone D** – elimination of the oxide film has a common character, therefore a portion of metal destruction caused by contact currents action becomes lower. However, the rate of metal mass losses is big because much more significant area of the “naked” metal is subjected to the action of the aggressive medium. In this zone turbulence rates and friction stress grow considerably and re-passivation of the metal surface is obstructed.

**Zone E** – an interval of speeds corresponding to the state when the film had been eliminated totally and metal re-passivation is impossible.

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Internal an external instability of FAC processes

All considered processes combined in a FAC term occur in conditions of internal and external instability. Internal instability is caused by existence of unsteady flows in pipelines and equipment when T-joints, bends, transitions, fittings, etc. are considered. In a figure below it is shown a picture of hydraulic modeling of a flow in a pipeline transition in a region of connection of two pipes with different diameters.

It is clearly seen a twist structure. However this picture reflects only a stationary case of the actual picture. In the reality such a twist is unstable in time. Amounts of the medium, which is being involved in a twist area, grow. The twist becomes unstable and blows down a part of the medium into the main flow. As a result, the twist area periodically moves along the pipe and results in vibration occurrence. Behind the twist area an after-trace occurs like the trace of a cylinder or sphere streamline. So, flows in equipment and pipelines elements are too instable.
Parameters defining FAC intensity

• Physical-chemical metal properties (content of chromium, cuprum, molybdenum).

• Thermal-hydraulic parameters of the working medium (temperature, speed).

• Water chemistry characteristics (pH value, concentrations of oxygen, amine).

• Geometry features (outside diameter of a pipe, wall thickness, constructive features: bend, T-joint, transition, fitting, etc.).

• Actual stressed state of a construction, physical-mechanical properties of the metal.

• Time of operation.

Due to the considerable scope of FAC experimental investigations, which have been carried out in recent years by chief NPP industry institutes in different countries (USA, France, Germany, Japan, Russia, etc.), effects of the above mentioned parameters on FAC intensity have been carefully studied as presented in slides below.
Influence of different parameters on FAC

Temperature influence

Flow speed influence
Influence of different parameters on FAC

**PH level influence**

Metal chemical composition influence (Dyreks’ formula):

\[ W_{EKI} = W_{EKI}^{\text{max}}/83 \text{Cr}^{0.89} \text{Cu}^{0.25} \text{Mo}^{0.2} \]

- Specific rate of material wear vs. pH at 40°C
  - \( p = 40 \text{ bar} \)
  - \( \theta = 180^\circ \text{C} \)
  - \( v = 39 \text{ m/s} \)
  - \( t = 200/400 \text{ h} \)
  - \( O_2\text{-cont.} \leq 5 \mu\text{g/kg} \)

- According to Resch:
  - \( \theta = 75^\circ \text{C} \)
  - \( v = 1.6 \text{ m/s} \)
  - \( t = 24 \text{ h} \)
  - \( O_2\text{-cont.} = 20 \mu\text{g/kg} \)

**Oxygen concentration influence**

- Specific rate of material wear vs. Oxygen content
  - \( p = 40 \text{ bar} \)
  - \( \theta = 120^\circ \text{C} \)
  - \( v = 35 \text{ m/s} \)
  - \( t = 200 \text{ h} \)
  - \( \text{pH} = 7 \)

- According to Resch:
  - \( \theta = 75^\circ \text{C} \)
  - \( v = 1.6 \text{ m/s} \)
  - \( t = 24 \text{ h} \)
  - \( \text{pH} = 7 \)

= converted values
Influence of elements’ geometry on FAC

- T-joints
- Bends, elbows
- Orifice, dents
- Fittings and input zones
Analysis of the Operational Inspection Programs acting on NPPs

Scopes and periodicity of FAC operational inspection on NPPs are set by “Typical programs of operational inspection of equipment and piping base metal and weld joints…” acting in nuclear industry. These programs differ for each type of the reactor assemblies.

NPPs operational experience shows the following:

- there are places which have not been included into the Program of the periodical operational inspection and where considerable rates of FAC wear exist;
- there is a redundant scope of the inspection in places with not significant FAC wear;
- there is no elements classification reflecting risk rates of FAC damaging, now operational inspection is to be done for all typical elements with the same periodicity, i.e. elements’ features are not considered;
- there is an imperfection in data collection and systematization system – necessity of creation of the common electronic data base exists;
- there is an insufficient analysis of periodical inspection results and no forecast of FAC dynamics are done.

**NPP have a very hard task to provide reliable in-time revealing of elements with extreme or non-accepted metal wall thinning.**
Technology of FAC operational inspection accepted on Russian NPPs

Current technology of FAC operational inspection of the equipment and piping requires to carry out point inspection of the wall thickness in accordance with Russian Codes PNAE G-7-031-91, and following disadvantages of that method are seen:

• preliminary trimming of the surface is required;
• discreteness of the point inspection – the method does not enable to obtain common picture of metal wear and to reveal reliably local zones of maximum thinning;
• the method does not provide reiteration and comparability of periodical inspection results;
• problem of dense corrosive deposits influence on inspection results have not been solved until now;
• influence of a human factor on inspection results.

The way to solve all mentioned problems is in using of automatic systems for periodical metal thickness inspection which enable to make complete scanning of the surface with computer form of results recording.

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Program for FAC problem resolving in NPP industry

Currently concern “Rosenergoatom” has developed a 4-years Program of works intended to improve normative documents and to optimize scopes and periodicity of FAC operational inspection of the secondary circuit equipment and piping of WWER-1000.

The Program aims implementation of the complex of activities used to prevent ruptures and to improve erosion-corrosion resistance of NPP equipment and piping.

Goal of the initiated work lies in elaboration of scientific – theoretical and methodological basis of physical – chemical and mathematics models, definition of technical solutions and method of diagnostics, forecast and control of the erosion-corrosion processes.

Also, it is very important to increase erosion-corrosion resistance of the metal, increase of reliability and safe operation of the power equipment of the secondary circuit of NPP with WWER by means of elements FAC monitoring.
Polygon for FAC Program implementation

Specialists of the Center of material science and lifetime in cooperation with NPP staff had executed on Balakovo NPP, Unit 3 the main algorithm of a design-experimental approach for the purpose of FAC problem solving, also inspection of NPP elements by use of modern equipment was carried out.

As a polygon for FAC works implementation there were chosen 4 one-type WWER-1000 units of Balakovo NPP. These units perfectly suit for FAC problems resolving due to the following factors:

• all units are of modern design, they are under operation for the long period (units were set in operation step-by-step with a period between sets of about 2 years). As a consequence, these units already have piping and equipment elements, being damaged by FAC mechanism;

• secondary circuit piping have single-type layouts, identical materials, thermal-hydro-dynamical parameters of the flow, water-chemistry parameters, etc.

• there is a possibility in the frames of this work to collect all the necessary data regarding the really operating NPP elements.
A new design-experimental approach for perfection of FAC wear inspection on NPPs

Accepted design-experimental approach includes implementation of the following stages:

1. **Elements classification concerning risk rates of FAC damaging.**
2. **Elaboration and application on NPPs of new methods and equipment of the operational inspection.**
3. **Elaboration of a design-experimental procedure for FAC rates definition.**
4. **Verifying stress calculation for determination of the minimum acceptable wall thinning levels.**
5. **Actions intended for increase of FAC resistance of NPP equipment.**

On a first stage of the work it was carried out an enlarged collection and analysis of initial data used for the consequent design-experimental substantiation of the pipelines operational reliability.

It was analysed about 1500 elements of the secondary circuit piping and for the inspection were chosen 30 zones after the throttling, regulating and transition elements.

Chosen elements were subjected to intensive FAC wear during operation and are the most critical from the point of potential rupture as a result of critical metal wall thinning.
Concept of works for FAC, proposed by CMSLM

History of the problem

Fulfilled scope of works

- Actions implemented on NPPs
- Developed Type Programs for FAC inspection
- Developed normative documentation
- Application of new methods and devices for inspection

Elaboration of the Comprehensive Program of FAC actions

NPPs maintenance

- Scopes of the operational inspection
- Periodicity of the operational inspection
- Methods and devices for the operational inspection
- Elaboration of engineer approaches for FAC rates forecast

Improvement of the normative base

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1. Elements classification concerning risk rates of FAC damaging

- Collection of the input data on NPP
  - Certificate, passport, design data
  - Layouts, construction features
  - Results of the periodical operational inspection
  - Water chemistry data

- Creation of the electronic data base for input data systematization
- Collection of missing initial data and their integration into the common electronic data base

Input data array

- Elaboration and realization of an algorithm for the comprehensive analysis of the secondary circuit elements

Elements ranging on groups depending on rates of FAC risk wear

Elaboration of the Operational Inspection Program
1.1. Analysis of operational parameters of the secondary circuit elements

Operational parameters (pressure, temperature, steam quality, medium discharge, water chemistry parameters, etc.) and design features of the secondary circuit elements taking into account the known dependencies of a definite parameter influence on FAC rates provide a possibility to define groups of elements considering their location in the secondary circuit which operate in the worst conditions favourable for the intensive FAC wear processes.
1.2 Collection and analysis of input data

Example of a piping layout

Certificate data on a chemical composition and mechanical properties of a metal
1.3 Database of pipelines layouts

Трубопроводы отсоса паровоздушной смеси из ПП. Черт. Б-802877 Св. ф. 160908

Трубопроводы дренажей из короба ПВД №1 Черт Б - 802801 Сб.

Table:

<table>
<thead>
<tr>
<th>№с. шланг</th>
<th>DнмхмS</th>
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Diagram:
2. Elaboration and application on NPPs of new methods and equipment of the operational inspection

Center of material science and lifetime in cooperation with “Special scientific engineering” company (Ukraine) had elaborated and manufactured an improved Electro-Magnetic-Acoustic (EMA) tester for wall thinning measurements which enables to make continuous scanning of the measured surface.

**Advantages (compared to traditional US-testers):**

- Enables to perform continuous scanning of the surface and to obtain 3D-shape of FAC wear;
- Excludes gaps of local wall thinning;
- Inspection process without preliminary surface preparing;
- The device has PC-form of inspection results records;
- Lubrication or contact fluid is not necessary.

Systematic inaccuracy of EMA-tester measurements is less than ± 0,2 mm. Comparison of metal wall thickness results measured by EMA-tester and traditional US-tester shows results coincidence.

*At present time the Center has a bank of real test samples with different shapes of FAC wear, which have been cut off on different NPPs for a replacement.*
2.1. An example of 3D-shape of the metal wear of feed water piping

Application of the modern equipment of operational inspection on NPP with continuous scanning enables to exclude local wall thinning, to improve reliability of inspection results, to provide record of inspection data in automatic mode and facilitates incorporation of inspection results to the common data base. Proposed form of inspection data record allows to compare results of the periodical operational inspection, to asses dynamics of FAC wear progress during different operational periods. 3D-shape of FAC wear surface can be used as initial data for verifying stress analysis defining minimum allowable wall thickness levels.

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2.1. (continuation) An example of 3D-shape of the metal wear of feed water piping

Piping after a transition 400x500, steel 15GS, bore 530x28

3D-shape of FAC wear surface
Flat topogram of FAC wear surface
2.2. Inspection of the elements’ actual stressed state on NPP by use of magnetic methods

In parallel with wall thickness measurements there was carried out an inspection of the actual stressed state for 30 elements. Stressed state was measured since residual stresses are one of causes of intensive FAC wear processes. Stressed state was measured by use of magnetic structure tester. Obtained stresses in the element metal allow to precise FAC zones with maximum wear.
2.2. (continuation) Inspection of the elements’ actual stressed state on NPP by use of magnetic methods

Change of metal properties and structure of the secondary circuit pipelines is stipulated by a thermal-force action of operational loads, equipment and piping operational modes, technology of assembling and mounting, etc. Evaluations of the stressed-deformed state, determination of the actual mechanical properties, residual stresses are necessary for making the verifying stress calculations in the most critical zones subjected to the intensive FAC wear for the purpose of elements’ bearing ability confirmation.

- Change of the metal structure due to action of cyclic, static loads, residual mounting (welding) stresses.
- Cumulative operational damaging of the metal.

- Decrease of cyclic strength characteristics as a result of fatigue damages of the metal structure.
- Increase of a number of dislocations and appearance of other discontinuities in the metal structure.
- Deformation of the crystal lattice.
- Change of magnetic characteristics, coercive force growth.
- Change of mechanical characteristics of the metal short-time strength.

- Magnetic methods for the measurement of a gradient of a residual magnetizing force and the method for the measurement of a spectral density of Barkgauzen magnetic noises.
- Non-destructive methods of inspection of the metal mechanical properties by use of the kinetic indentation diagram.

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2.3 Inspection of the metal mechanical properties by use of the kinetic indentation method

Kinetic indentation method

Diagram of the ball indentation
Inspection of residual stresses and magnetic properties

Пример распределения давления

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2.3 (continuation) MINITEST – portable kinetic hardness tester

General view of the device

Features:
- performing hardness tests of metals
- allow to perform both static and dynamic tests
- registration of indentation diagram
- express estimation of mechanical properties of metals
- can be used both at laboratory and at plant conditions
3. Elaboration of a design-experimental procedure for FAC rates definition

For elaboration of the Procedure for FAC rates definition two approaches should be used: 3D-modelling of flow hydrodynamics and neuron network planning.

3.1. 3D-modelling of flow hydrodynamics

For determination of the thermo-hydrodynamic parameters of the flow including definition of flow rates and flow energies are used standard finite element programs for thermal-hydro-gasdynamic calculations (for example, ANSYS/CFX-5.x, FLUID). Results of hydrodynamic modeling are also used for optimization of inspection zones.
3.2. Neuron network planning for making forecast of FAC process dynamics during NPP operation

For the purpose of making forecast of FAC process dynamics the most perspective way lies in using a technology of neuron networks: input data for the analysis are hydrodynamic modeling results, electronic data base and results of expert operational inspection of wall thinning in the “worse” places.

By use of neuron networks technology it is easy to investigate a dependence of forecasted value from independent variables. For example, taking parameters of the working medium (pH, T, composition), metal, flow as initial data and information from data base enables to use neuron networks for making forecast of metal wall thinning in a definite zone and FAC process progress. One more advantage of neuron networks lies in the fact that building of neuron-structure model happens during a process of network self-training without human participation.

Neuron networks methods have a number of advantages compared to the methods of mathematical statistics and technical analysis which are being traditionally used for making forecasts. Neuron networks analysis does not assumes any restrictions to the character of input data (parameters).
3.2. (continuation) Neuron network planning for making forecast of FAC process dynamics during NPP operation

As input data it could be taken both indicators of the given temporary row and data of other parameters dynamics while other methods consider only values of the row to be forecasted.

Application of the neuron networks does not implies any restrictions on a character of the investigated parameters, as a consequence, instability of the considered processes is not a problem at all. The most valuable property of the neuron networks is their ability to solve successfully the tasks in which definition of analytical dependencies between input and output data is obstructed or furthermore is impossible. Neuron networks are capable to find optimum affecting indicators concerning the studied task and give a possibility to build optimum forecast (prediction) strategy for the considered row (parameter). Moreover, that strategy can be adaptive to the given situation and can also change if the situation changes.

For the multi-layer neuron networks it was strictly mathematically proved that they can perform any real continuous vector function via any real continuous vector argument. It means, that multi-layer neuron networks can be used to solve any task of functions building including forecast functions.

Neuron network analysis was successfully realized in works of SG tubes lifetime forecast (see a figure).
3.3. Electronic data base for an estimation of a residual lifetime of NPPs’ power equipment
3.4. Profits gained from the design-experimental approach implementation for FAC modeling

Design-experimental approach for FAC processes modeling gives a base for creation of a soft for FAC rates calculation in a single-phase and double-phase flows.

To verify an certify FAC soft it is used existing electronic data base as well as experimental tests on a FAC test-bench in accordance with specially elaborated program of experiments with variation of different parameters effecting on FAC rates.

*Implementation of the above mentioned works enables to elaborate and certify a procedure of design-experimental substantiation of zones, scopes and periodicity of the operational inspection of NPP piping and equipment.*
4. Verifying stress calculation for determination of the minimum acceptable wall thinning levels

Existing in Russia normative documents for the stress calculation of the minimum acceptable wall thinning of the elements with FAC wear consider only uniform wear shapes and do not consider the real shape of FAC wear.

Real shape of FAC wear can be obtained by use of modern equipment realizing the method of continuous scanning which allows to receive general picture of FAC wear as well as real shapes of local zones of wall thinning. A new stress calculation is intended to receive allowable geometrical shapes of wall thinning as well as wear depth. Relationships between the real shape of the defect and its depth enable to define a current condition of the element from the point of its further reliable operation and to forecast its residual lifetime.

On a figure it is performed an example of lifetime curves building for definition of the residual lifetime of the element considering the real wear shapes: zone I – supercritical condition, zone II – non-critical condition.
5. Actions intended for increase of FAC resistance of NPP equipment

As the actions intended for increase of erosion-corrosion resistance of NPP equipment the following actions can be outlined:

- elaboration of recommendations for choosing of the chemical composition of the materials used for manufacturing of NPP piping and equipment: definition of the minimum allowable contents of alloying elements in carbon steels;
- applying on NPP a technology of universal protective coating placing (thickness up to 0.02 mm) on the internal surface of the metal for the purpose of increase the wear resistance and lifetime of elements operation;
- passivation of piping and equipment inner surface by means of protective films creation.

An example of the universal protective coating technology work
Commercial proposals

Taking into account the accumulated considerable experience in FAC field Center of Material Science and Lifetime is able to carry out the flowing works in the frame of lifetime management of NPPs’ power equipment and pipelines manufactured from carbon steels:

- **elaboration and certification of the procedure of design-experimental substantiation of zones, scopes and periodicity of the NPP elements operational inspection**;
- **elaboration and certification a new Regulatory Document of stress calculation for definition of the minimum acceptable wall thickness levels considering real wear shape, FAC rates and inaccuracy of devices for wall thickness measurements**;
- **improving the current Regulatory Documents and correcting of the Typical programs of operational inspection – optimization of zones, scopes and periodicity of the inspection**;
- **elaboration of recommendations for operational lifetime prolongation of the WWER second circuit’s elements by means of increasing of erosion-corrosion resistance of new and operating energetic equipment and of the equipment, beyond the design lifetime**;
Commercial proposals (continuation)

- improving of safe and uninterrupted work of the power unit due to in-time prediction of the most damaged elements behavior from point of view of erosion-corrosion effects and determination of lifetime for the equipment, operating in the conditions of increased thermal-mechanical and hydro-dynamical loads, which cause intensive erosion-corrosion wear of the metal;
- creation of a system for monitoring of erosion-corrosion conditions of the secondary circuit elements of WWER power units;
- optimization and effectiveness increasing of diagnostic and preventive regulations, inspection methods of erosion-corrosion state definition and prevention of emergency situations and unplanned shutdowns occurrence as a result of damaging of NPPs’ working elements metal;
- creation of the normative base for data collection, diagnostic and monitoring of the second circuit's equipment and pipelines of WWER power unit.
- giving the recommendations to the main designer for making a new improved design of NPP.