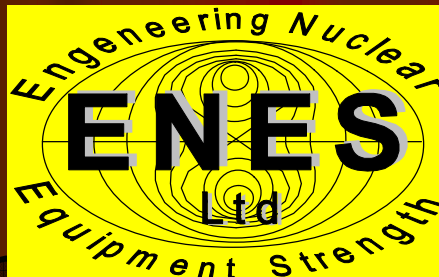


**International Atomic Energy Agency
WORKSHOP ON EROSION-CORROSION INCLUDING FLOW
ACCELERATED CORROSION AND ENVIRONMENTALLY ASSISTED
CRACKING ISSUES IN NUCLEAR POWER PLANTS
21-23 April 2009, Moscow, Russian Federation**

**Flow Accelerated Corrosion of Pipelines and
Equipment at Russian NPPs:
Problems and Solutions**



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STATUS OF THE PROBLEM

Flow accelerated corrosion (FAC) tends to cause local failures on NPP carbon steel piping and components.

A number of NPPs have started in-service wall thickness measurements on a regular basis following a severe accident at Surry Unit 2, USA, 1986.

Investigations identified the main factors which should be considered to predict FAC propagation by means of computer codes.

A severe accident at Japan's Mihama Unit 3 drew attention to this important problem again.

The above events occurring at western plants were comprehensively studied by Russian specialists with the IAEA and WANO technical support.

Examples of pipeline erosion-corrosion at NPPs worldwide



Ø18" elbow wall thickness decreased from 12.7 to 1.5 mm on feedwater pump inlet at Surry, 1986



FAC on Ø14" heater drain extraction line to high pressure heater (HPH) at Arkansas unit 2 (USA, 1986)



Main feedwater piping rupture at Loviisa-1, VVER, 465 MWe, 1990



FAC on Ø9" elbow of HPH drain line at Millstone unit 2 (USA, 1991)

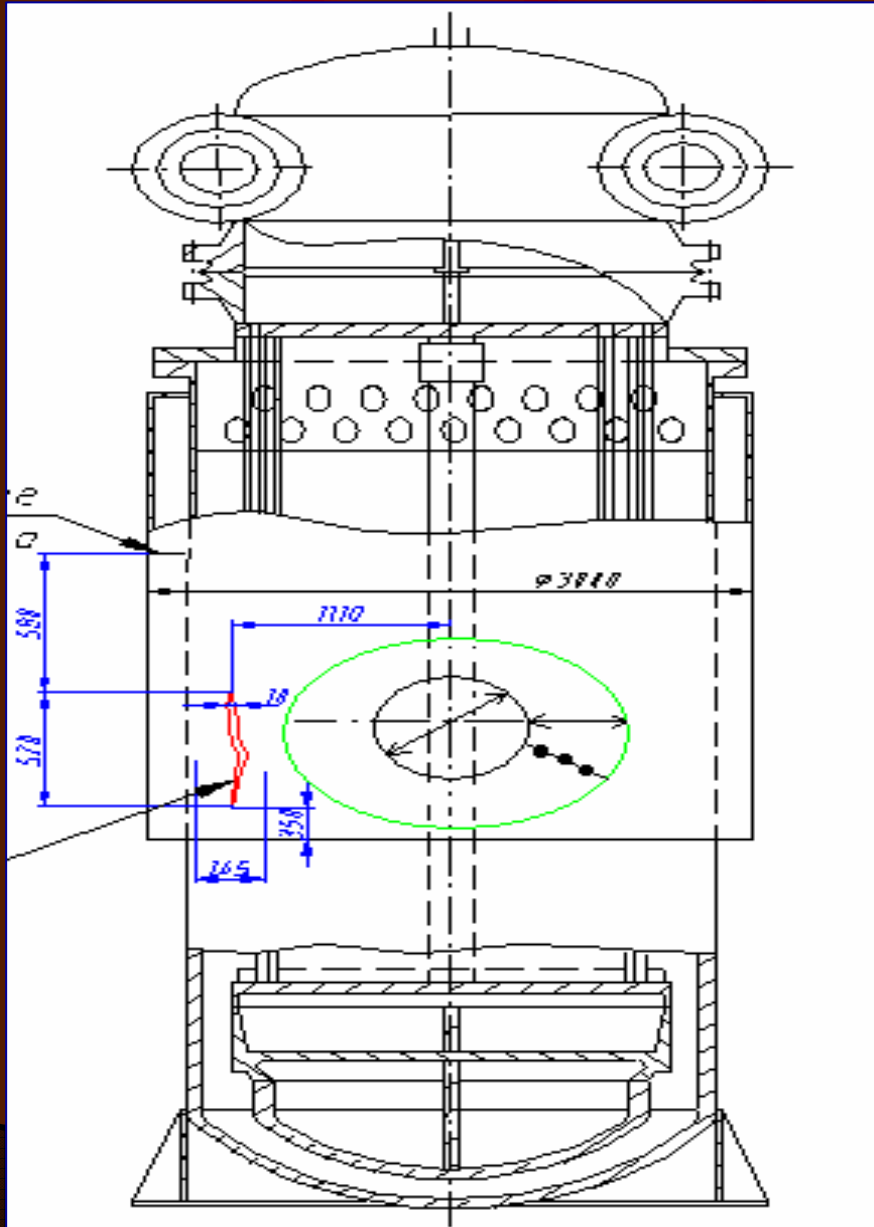


Wall thickness reduction from 10 to 1.5 mm on feedwater piping at Mihama unit 3, 2004



Wall thickness reduction from 8 to 1.5 mm on feedwater bypass at Balakovo unit 2, 2004

Some Russian plants experienced FAC-induced local failures. However severe accidents were avoided by taking FAC prevention/mitigation actions in a timely manner



Erosion-corrosion failures of low pressure heater vessel at RBMK plant



PROBLEM SOLUTION AT RUSSIAN NPP (1)

A lot of investigations were completed or initiated by a number of organizations under the industry-wide integrated FAC prevention program at Russian NPPs. Some of the results of this activity are presented at this workshop.

VNIIAES processed and reviewed the results of pipeline wall thickness measurements at WWER and RBMK plants.

The above data were used to develop both PC codes aimed at reliable FAC prediction and regulatory documentation related to FAC control at WWER and RBMK plants.

In-service wall thickness control programs at NPPs were optimized based on the analysis of the above data. The studies of FAC initiation and propagation allowed to timely predict wall thinning prior to dangerous failures.

Internal/external operating experience exchange of among many similar NPPs facilitated early countermeasure program development at Russian NPPs.

PROBLEM SOLUTION AT RUSSIAN NPP (2)

The report highlights current ENES activity related to countermeasures aimed at preventing/mitigating FAC at Russian NPPs.

The results of the above activities are used at operating plants.

These results could also be applied both at plants under construction and similar foreign plants, including for PC codes, manuals, in-service inspection programs, and regulatory technical documentation.

Strength Calculations Performed by ENES (1)

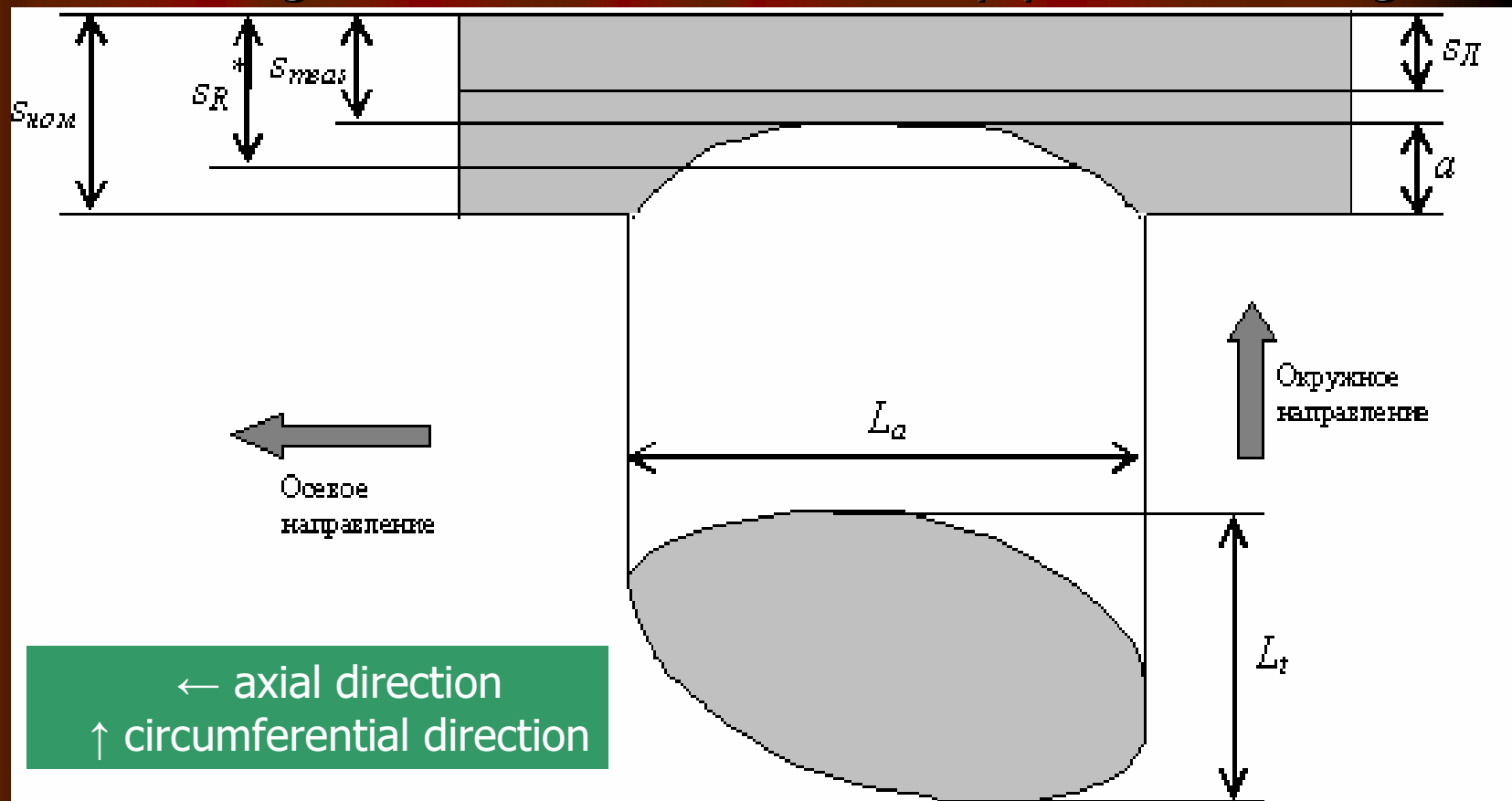
Development of Techniques to Determine Minimal Permissible Wall Thickness of Pipelines in Erosion-Corrosion Failure Zones
(Manual 0571-2006)

Permissible wall thickness is calculated based on the following initial data:

- in-service wall thickness measurement data
- technical specifications on the said piping
- operational loads affecting the said piping
- piping component manufacturer`s quality certificates

Strength Calculations Performed by ENES (2)

A diagram of local FAC-induced pipeline thinning



S_{R^*} , mm – calculated wall thickness

S_{meas} , mm – measured wall thickness

a , mm – depth of defect

$S_{л}$, mm – minimal wall thickness of pipeline

$S_{НОМ}$, mm – nominal wall thickness of pipeline

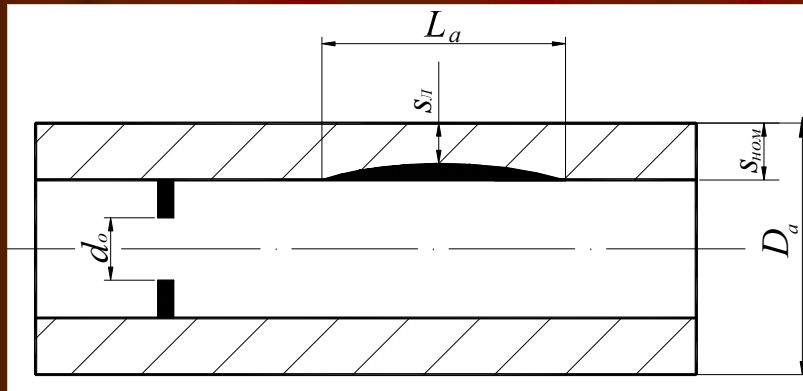
L_t , mm – local failure size in circumferential direction

L_a , mm – local failure size in axial direction

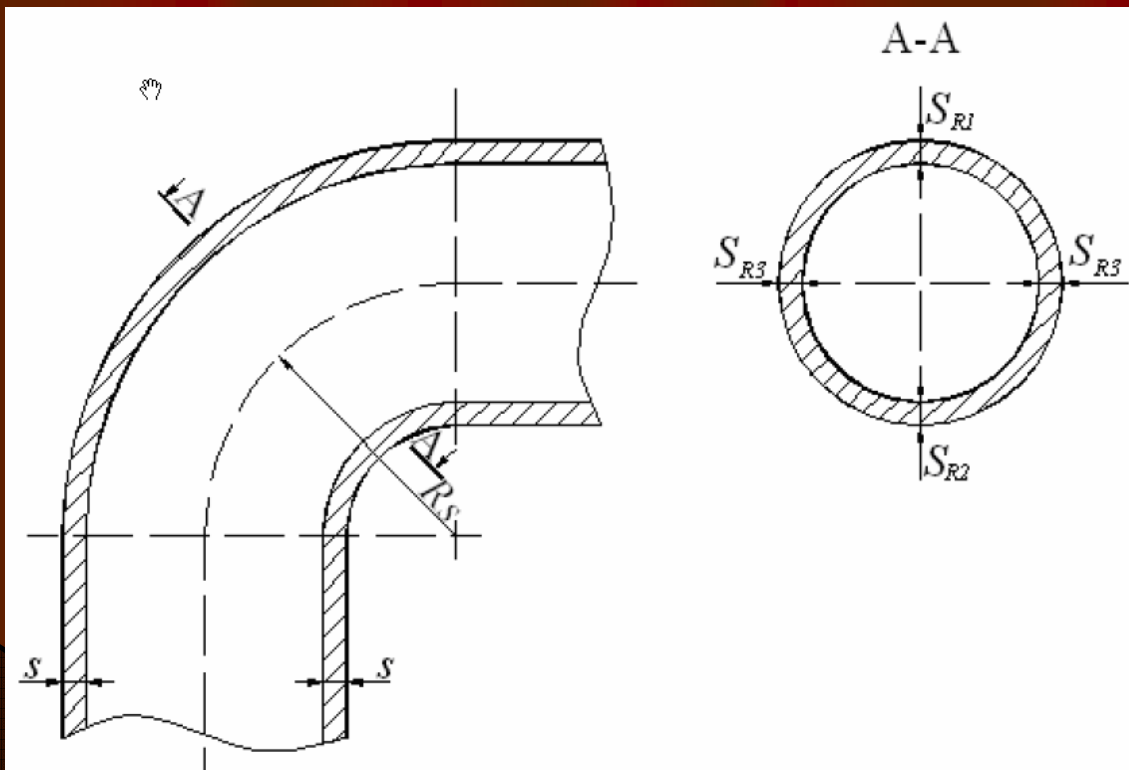
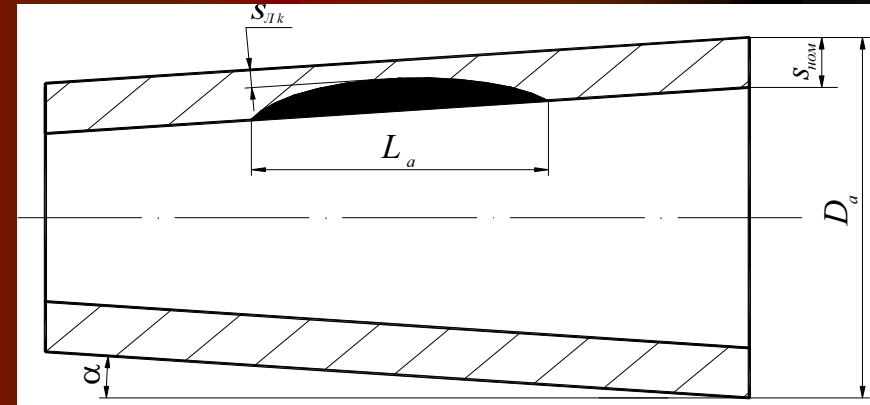
Strength Calculations Performed by ENES (3)

The following pipeline failures could occur:

Rectilinear section



Tapered-curvature section with FAC damage

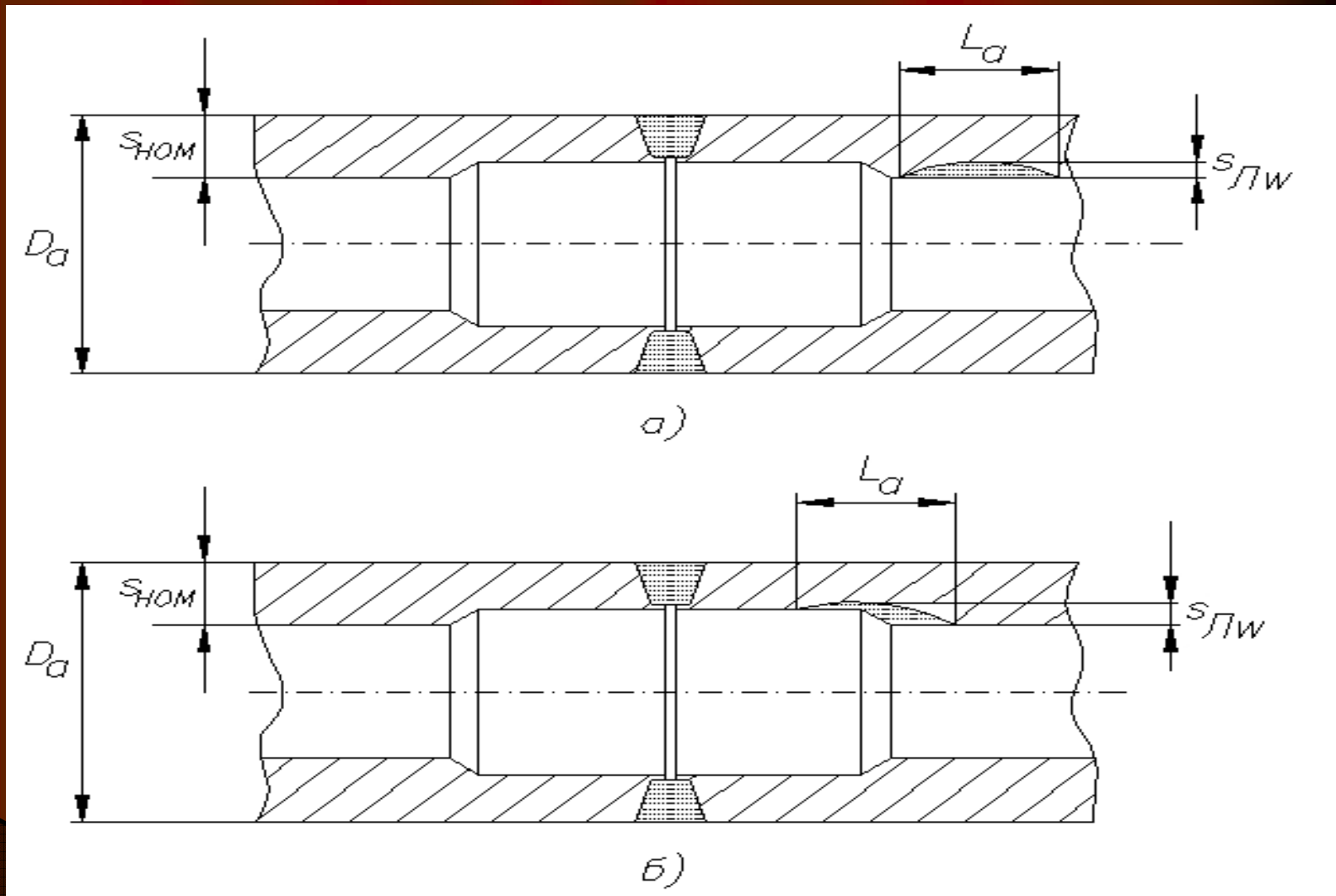


Schematic of elbow

Strength Calculations Performed by ENES (4)

Schematic of local joint failure

- a) local failure outside bored joint
- b) local failure in bored joint



Strength Calculations Performed by ENES (5)

Minimal wall thickness of pipeline section under inner pressure is calculated in two stages.

The first stage includes determination of calculated wall thickness S_R^* and permissible wall thickness S_R

Minimal permissible wall thickness S is calculated as part of S_R at the second stage in case of local wall thinning.

$S_{\text{л}} = S_R$ in case of uniform wall thinning.

Strength Calculations Performed by ENES (6)

Calculation of S_R^*

The following formulation is used for joints, pipe sections downstream of restrictors and rectilinear sections

$$S_{Rw}^* = \frac{pD_a}{2[\sigma] + p} \cdot \frac{1}{\varphi_w}$$

$$\varphi_w = 1$$

in case of rectilinear sections joints outside bored areas and pipe sections downstream of restrictors

In other cases

$$\varphi_w$$

is selected according to table depending on joint type, pipe diameter and thickness

The following formulation is used for conical joints

$$S_{Rk}^* = \frac{pD_a / \cos(\alpha)}{2[\sigma] + p}$$

Wall thickness of outside elbow sections under inner pressure is calculated using the following equation

$$S_{R1}^*$$

$$S_{R1}^* = S_R^* \cdot Y_1 \cdot K_1$$

where

$$S_R^* = \frac{pD_a}{2[\sigma] + p}$$

Y_1 - shape factor
 K_1 - end factor

Strength Calculations Performed by ENES (7)

Calculation of permissible wall thickness S_R

$$s_R = \max \{s_R^* + 0,2; 0,5s_{HOM} + 0,2\}$$

Calculation of minimal wall thickness S_{II}

The following equation is used
if two conditions below are valid

$$\beta_0 = \left[\frac{1 - \exp\left(\frac{-L_a L_t}{4 R s_R}\right)}{1 - \exp\left(\frac{-2 L_t}{\sqrt{R s_R}}\right)} \right]^{0,5}$$

$$s_{HOM} < L_a < 8\sqrt{R s_R} \quad \text{and} \quad s_{HOM} < L_t < 0,25\pi D_a$$

$$s_{II} = \beta_0 s_R \quad \text{if} \quad 0,3 < \beta_0 < 1$$

$$s_{II} = s_R \quad \text{if} \quad \beta_0 \geq 1$$

$$s_{II} = \beta_0 s_R \quad \text{if} \quad \beta_0 \leq 0,3$$

Permissible corrosion thinning of plant component walls during the lifetime exceed 30 years

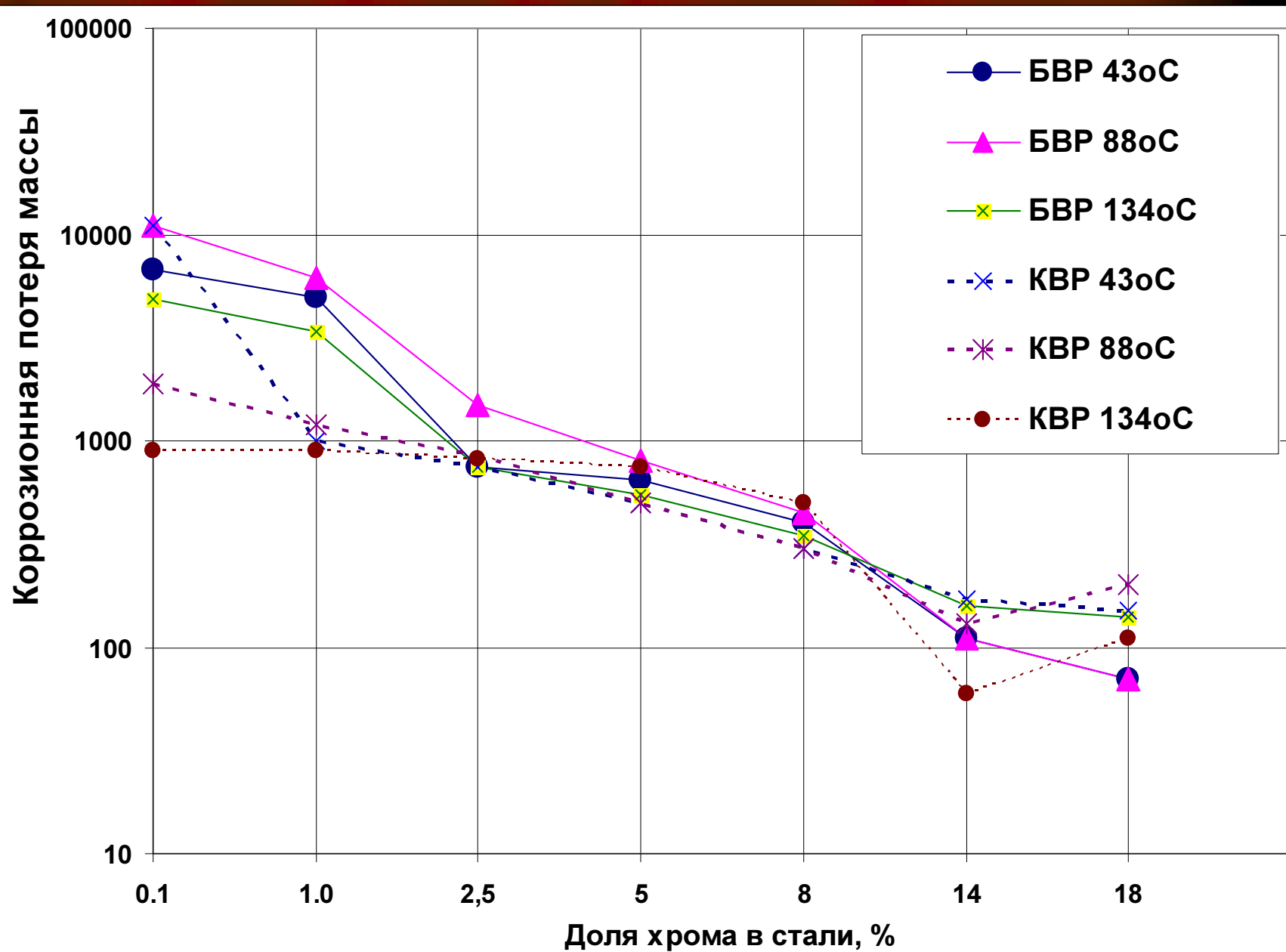
Manual of strength calculation for equipment and pipelines of nuclear power installations (PNAE G-7-002-86) specifies permissible corrosion wear of structural materials «C2» during 30 years of plant operation. ENES calculated «C2» values for some new plants with design lifetime above 30 years (Tianwan NPP, WWER-1500, LAES-2) based on corrosion resistance of structural material, chemistry control and other plant peculiarities.

In 2008, ENES analyzed plant component corrosion behavior for Leningrad NPP-2 with 60 years lifetime, including components of primary system, secondary side and auxiliary systems.

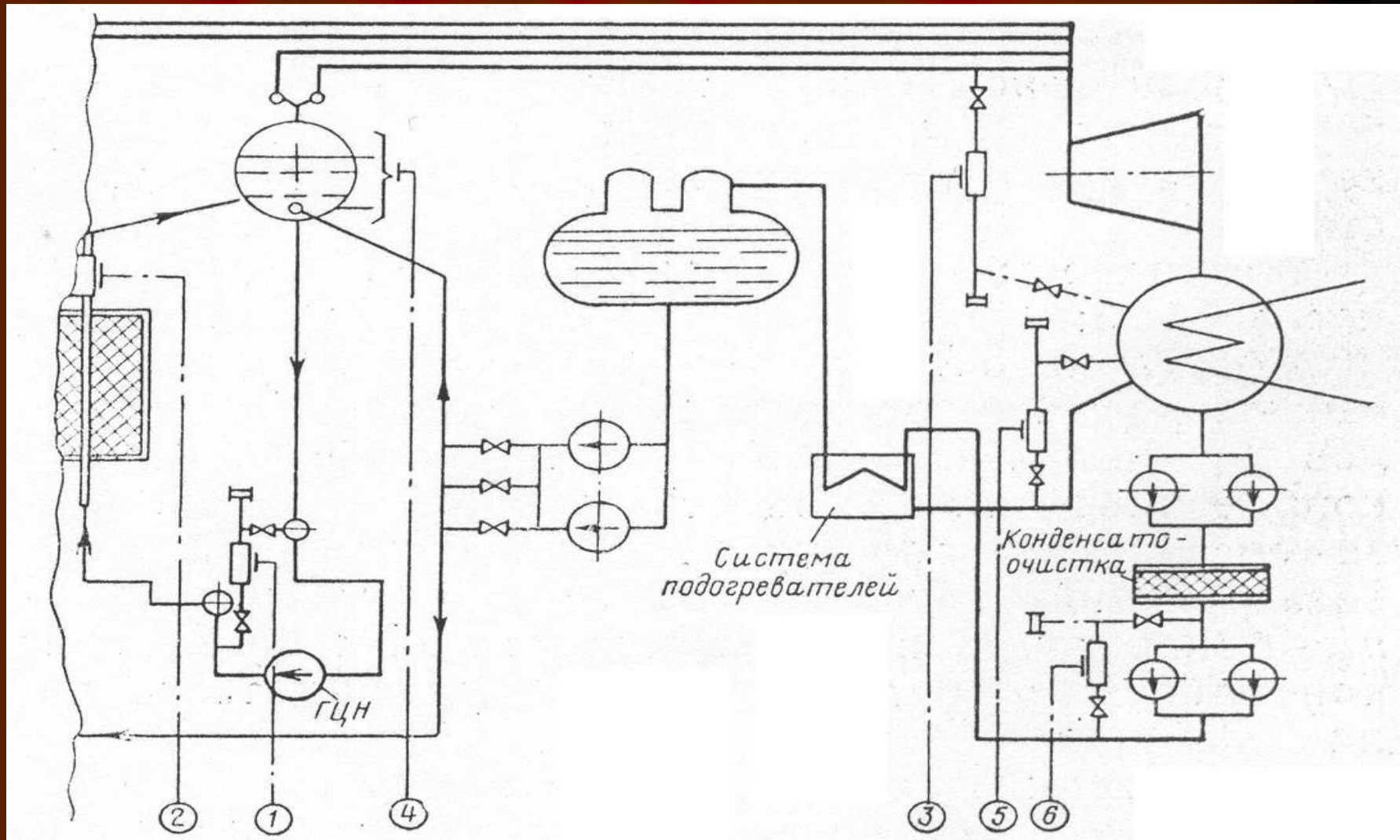
In most cases the calculated C₂ values do not exceed maximum permissible values of generalized corrosion wear specified by PNAE G-7-002-86.

Proper selection of structural materials and chemistry control were recommended for some piping in steam-water cycle and auxiliary systems to reduce corrosion wear of carbon steels.

Corrosion rate versus chromium content in carbon steel



Corrosion specimen testing in primary/secondary systems at RBMK plants



**1 – reactor water; 2 – steam-water mixture; 3 – saturated steam;
4 – steam drum; 5 – heater drains, 6 – condensate**

Corrosion specimen testing at VVER plants

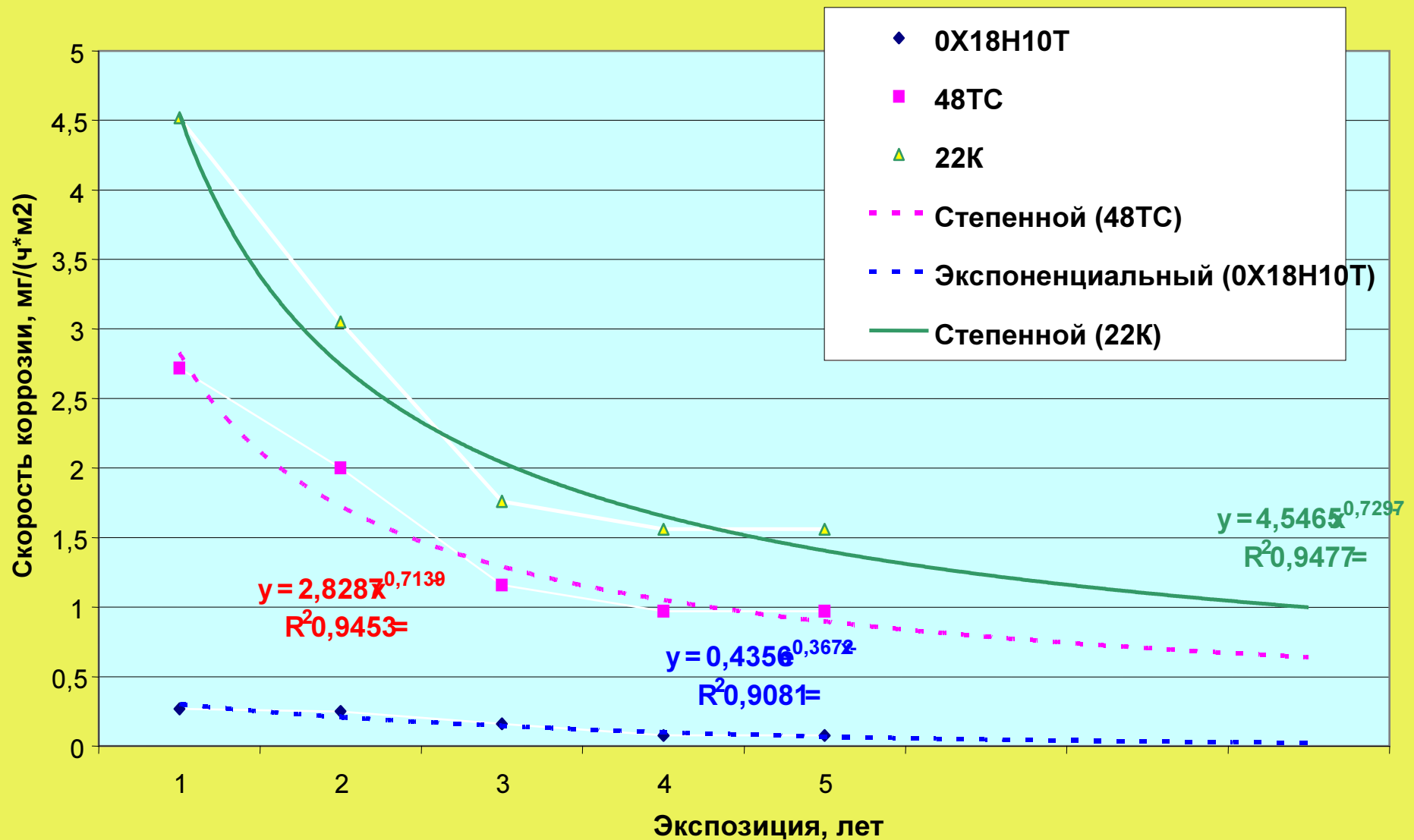
Kola NPP uses corrosion specimen testing on a regular basis. Results of these investigations in primary system were used to implement hydrazine water chemistry.

Results of corrosion specimen test in secondary system were used to substantiate ODA injection.

Corrosion tests of coolant-material compatibility were performed prior to water chemistry optimization in nuclear plant primary, secondary and auxiliary systems.

Corrosion specimen testing in VVER primary system

Расчет скорости коррозии стальных образцов в водной фазе
компенсатора давления блока №2 Кольской АЭС



Water Chemistry Improvements Aimed at FAC Mitigation

CORROSION TESTS AT DIFFERENT WATER CHEMISTRIES

- corrosion tests aimed at water chemistry control improvements at Zaporizhe NPP, Kalinin NPP, Balakovo NPP, Kola NPP
- material-environmental compatibility tests at Kozloduy NPP to ensure morpholine water chemistry implementation
- material-environmental compatibility tests to substantiate ethanolamine water chemistry implementation at Bohunice NPP
- material-environmental compatibility tests at EREC for lithium hydroxide injection
- in-service corrosion control by means of specimens

OCTADECYLAMINE INJECTION INTO SECONDARY COOLANT AT KOLA NPP

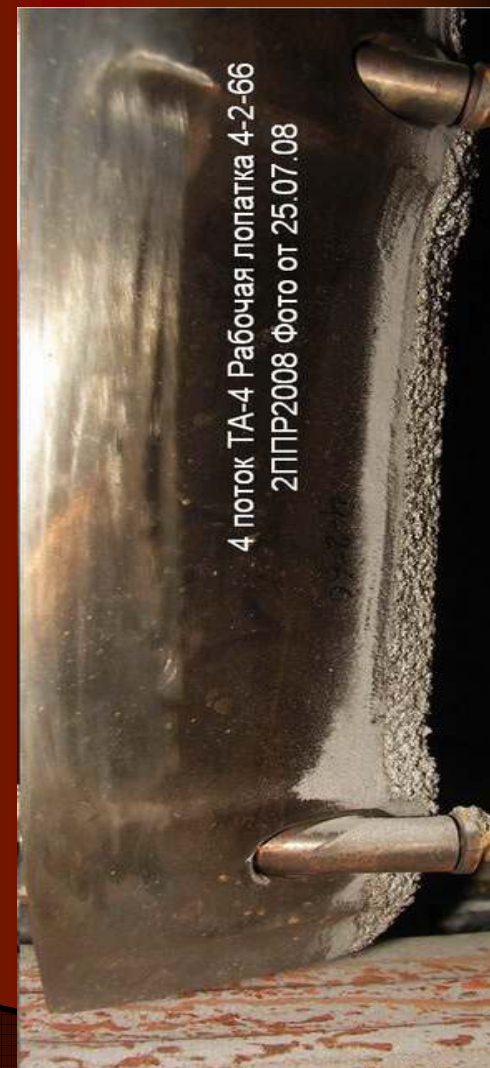


CHEMISTRY CONTROL CRITERIA

- 1. FAC minimization of equipment and piping of steam-water cycle**
- 2. Minimization of deposition and concentration of corrosion active impurities on heat-transfer surfaces**
- 3. Providing design technological parameters of equipment operation**

Octadecylamine (ODA) injection into secondary coolant was implemented at Kola NPP to meet the above requirements

ODA injection reduced corrosion product deposition on surfaces



Results of recent ODA injection into secondary coolant at Kola NPP

Optimization of ODA content in steam-water cycle
FAC mitigation according to plant in-service inspection data

Reduction of local and generalized corrosion

Protection of equipment and piping of steam-water cycle from atmospheric corrosion during outages

Reduction of corrosion failures in tube bundles of steam generators

Stabilization of corrosion product deposition on surfaces of steam generators from secondary side

CONCLUSIONS

Erosion-corrosion is an important problem for most nuclear power plants, especially for plants that will be operated for a longer lifetime.

Proper selection of structural materials and chemistry control are effective options to mitigate erosion-corrosion process at power plants

Even a negligible chromium content increase in carbon steel could significantly reduce erosion-corrosion rate

Some water chemistry improvements implemented at some power plants turned out to be effective to reduce erosion-corrosion