РОСАТОМ

Research and Development of Processing and Disposal of Solid Waste (Examination of Evaluation Technology for Integrity of Container during Storage of Highly Radioactive Solid Waste)

PROJECT OF DECOMMISSIONING AND CONTAMINATED WATER MANAGEMENT IN THE FY2020-2021 SUPPLEMENTARY BUDGET

Project Main Goals

ROSATOM

(i) Accumulation and studying in detail information related to the KURION/SARRY adsorption towers design features, operating history and results of preliminary investigations [see the slides: 3,4];

(ii) Development of corrosion occurrence review report based on Russian Side experience [see the slide: 5];

(iii) Implementation of adsorption towers ranking (related to the potential corrosion types, intensity, etc.) based on the accumulated data analysis;

(iv) Research Program Development for subsequent implementation of Corrosion experiments [see the slides: 6 - 12];

(v) Model samples manufacturing [see the slides: 11-12];

(vi) Preparation and implementation of Corrosion experiments (in accordance with the Research Program) [see the slides: 13 - 50];

(vii) Prediction Model development to predict possible development of the selected corrosion processes under the conditions of the 1F site for all of the types of KURION/SARRY adsorption towers [see the slides: 51 - 62];

(viii) Development of a forecast (using the Prediction Model) to describe the possible development of corrosion processes (under the storage conditions) for 50-year storage period [see the slides: 60,61];

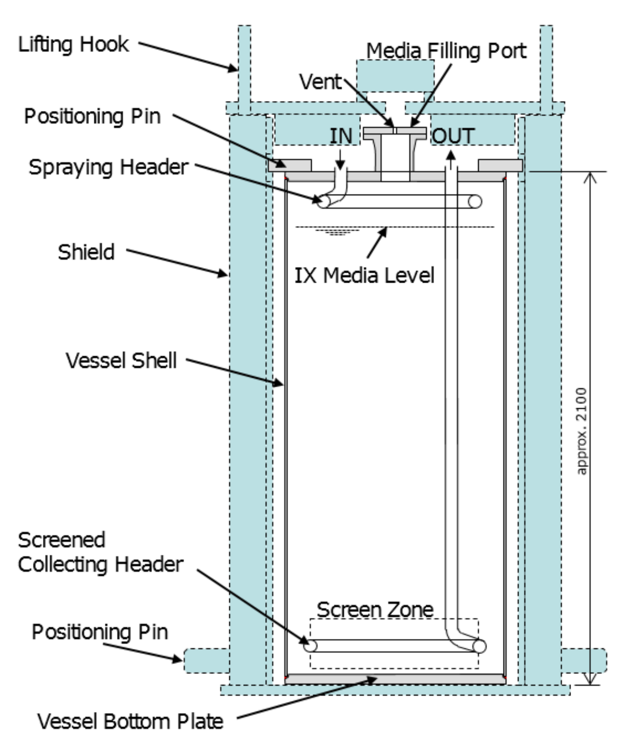
(ix) Development of Countermeasures set that can reduce the negative corrosion influence under the real storage conditions of the KURION/SARRY adsorption towers [see the slide: 63];

The main goal of the Project is to develop a Prediction Model for assessment of occurrence of Corrosion processes that can affect the KURION/SARRY adsorption towers integrity during their 50-year storage.

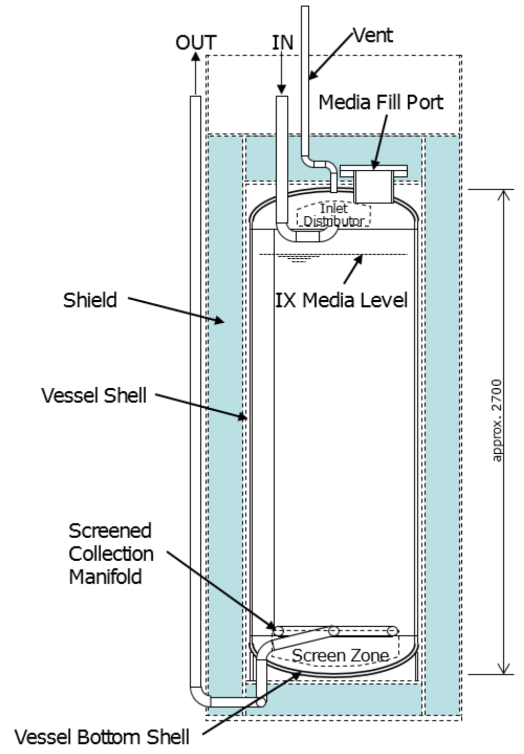
Results of preliminary Data accumulation and study (related to the KURION/SARRY design features as well as storage conditions) (1/2)

ROSATOM

Design conditions and storage conditions related to the KURION/SARRY adsorption towers:



KURION adsorption tower



SARRY adsorption tower

Storage conditions:

- **[Cl-] ~ 10 ppm;**
- **T ~ 20 ˚C.**

Temporary storage of the KURION adsorption towers

Storage of the SARRY adsorption towers

The following materials were selected for developing the Research Program related to Corrosion experiments implementation: steel – 316L; zeolite – Clinoptilolite.

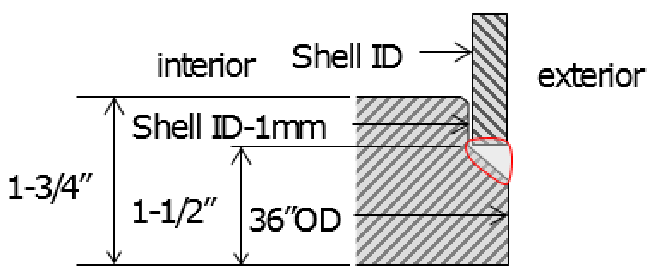
Results of preliminary Data accumulation and study (related to the KURION/SARRY design features as well as storage conditions) (2/2)

The following main requirements were formulated for Research Program Development:

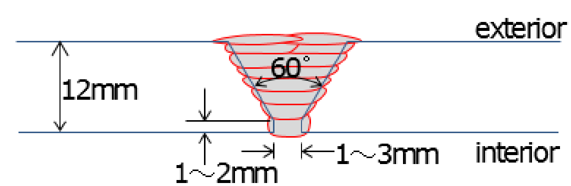
- **Specific activity of β/γ-containing components (^{90}Sr / ^{137}Cs) should be equal to ~ 10^8 Bq/g;**
- **Welded model samples should model as butt weld as O-like welded joint (to check the possibility of crevice corrosion development for KURION adsorption towers geometrical conditions);**
- **It is required to provide the following contact types for crevice corrosion experiments Implementation: Metal – Metal contact type, Metal – Non-metal contact type;**
- **Welding operations (when manufacturing the model samples) should be performed without additional thermal processing;**
- **The following details related to the welding conditions were taken into account:**

For KURION – Weld filler metal: ASME SFA-5.9 ER316LSi(Root pass)/ER316L(Subsequent pass); Carbon≦0.02 wt.%, δ-ferrite 9-11 wt.%. Welding conditions: Root pass : Gas Metal Arc Welding; Subsequent pass : Submerged Arc Welding.

For SARRY – Weld filler metal: WEL TIG 316L(Japanese welding rod), Carbon<0.02 wt.%, δ-ferrite 10-12 wt.%; Welding conditions: Root pass (root area formation):10～12kJ/cm, TIG welded in Argon atmosphere, Subsequent pass (formation of the remaining part of a weld): 10～15kJ/cm, TIG welded in Argon atmosphere (both side), not using backing plate



O-like welded joint of the KURION adsorption tower



Longitudinal welded joint of the SARRY adsorption tower

Report development on the Russian side's experience

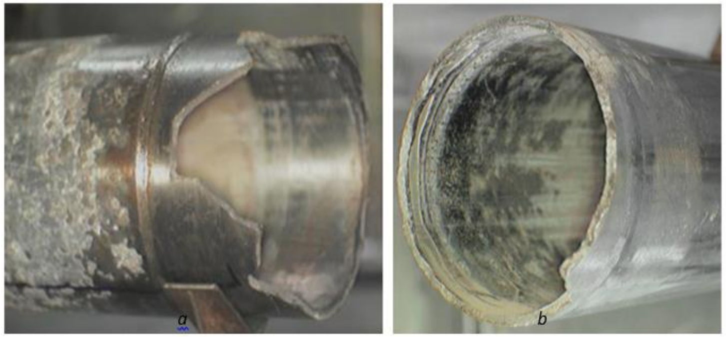
Report Content:

(a) Description of the Russian side's experience in the field of corrosion processes study;

The following corrosion mechanisms were considered:

- **Hydrogen cracking of Zr-containing alloys**
- **Stress corrosion cracking studies results**
- **Intergranular corrosion cracking**
- **Corrosion studies of structural and fuel materials**

(b) Application of Russian side's experience to consider the occurrence of the considered corrosion processes under the conditions of the KURION/SARRY storage



(a) **(b)**

External appearance of the RBMK's RPS channel in the zone of the process failure from the side of the adapter (a) and the pipe (b)

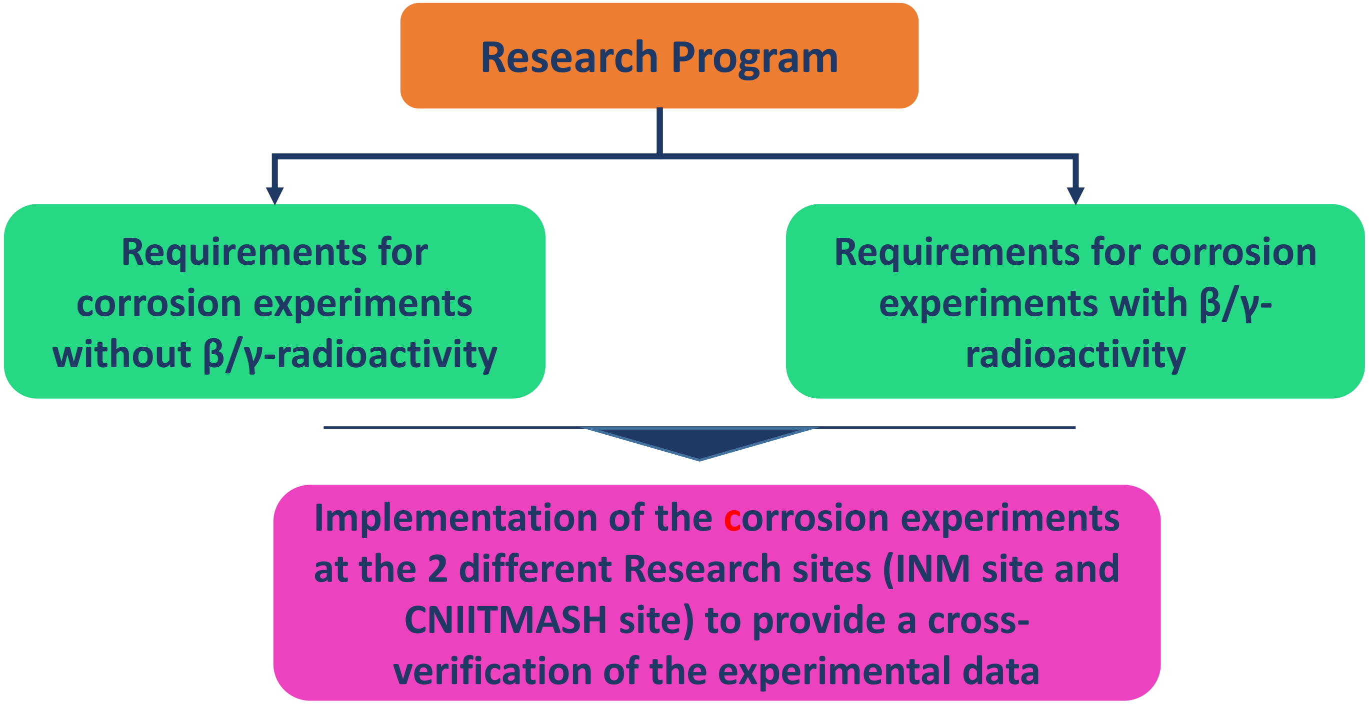
The following corrosion mechanisms were selected for the Research Program development:

- **Crevice corrosion;**
- **General(uniform) corrosion;**
- **Pitting corrosion;**
- **Intergranular corrosion;**
- **Stress corrosion cracking.**

Research Program Development

ROSATOM

The main purpose of Research Program is to select and assess the methods and equipment required for preparation and implementation of the experiments related to the accelerated occurrence of the selected corrosion processes. The scope of experiments (provided by Research Program) should be sufficient for further development of the Prediction Model as well as Countermeasures Plan.



The presence of β/γ-activity is provided by saturation of clinoptilolite with ^{90}Sr and ^{137}Cs

Research Program Development

INM's Scope of work

Type of corrosion	The state of the steel	Type of contact	Parameters of experiments				Type of the tower	Number of the samples	Control Methods to be used	Type of the sample
			T, °C	[Cl-], ppm	A, Bq/g	t, h/ σ_p	KURION/ SARRY			
1	2	3	4	5	6	7	8	9	10	11
General (uniform), Pitting	Homogeneous	-	25, 70	100, 10000, 29000	0, ~$4\cdot10^8$	1000, 2000, 3000, 5000	+ / + + - means consideration for certain tower type	48	Visual inspection, photo, gravimetry, Optical metallography, SEM/EDX	3-1
	Homogeneous	- ($E_{PR,P}$)	25, 70	100, 10000, 29000	0, ~$4\cdot10^8$	0, 1000, 5000	+ / +	36	$E_{PR,P}$= $E_{PR,P}$=f(Cl^-,A,t,D,T) before and after the 1000/5000-hour test	3-12
General (uniform), Pitting	With welded joint *)	-	25, 70	100, 10000, 29000	0, ~$4\cdot10^8$	1000, 2000, 3000, 5000	+ / +	48	Visual inspection, photo, gravimetry, Optical metallography, SEM/EDX	3-2
	With welded joint *)	- ($E_{PR,P}$)	25, 70	100, 10000, 29000	0, ~$4\cdot10^8$	0, 1000, 5000	+ / +	36	$E_{PR,P}$= $E_{PR,P}$=f(Cl^-,A,t,D,T) before and after the 1000/5000-hour test	3-13
Crevice	Homogeneous	M-NM (ASTM G78-01)	25, 70	100, 10000, 29000	0, ~$4\cdot10^8$	1000, 2000, 3000, 5000	+ / +	48	Visual inspection, photo, gravimetry, maximum depth of corrosion, Optical metallography, SEM/EDX	3-3 +2 sleeves
	Homogeneous	M-NM (ASTM G78-01) (ASTM G192-08)	25, 70	100, 10000, 29000	0, ~$4\cdot10^8$	0, 1000, 5000	+ / +	36	$E_{PR,CR}$= $E_{PR,CR}$=f(Cl^-,A,t,D,T) before and after the 1000/5000-hour test	3-10 +2 sleeves

Accepted Legend:
D: irradiation dose;
***): welded joint of steel AISI 316L;**
M-NM: metal-nonmetal

Research Program Development

INM's Scope of work

ROSATOM

Table continuation

Type of corrosion	The state of the steel	Type of contact	Parameters of experiments				Type of the tower KURION/ SARRY	Number of the samples	Control Methods to be used	Type of the sample
			T, °C	[Cl-], ppm	A, Bq/g	t, h/ σ_p				
1	2	3	4	5	6	7	8	9	10	11
Crevice	With welded joint *)	M-NM (ASTM G78-01)	25, 70	100, 10000, 29000	0, $\sim 4\cdot 10^8$	1000, 2000, 3000, 5000	+ / +	48	Visual inspection, photo, gravimetry, maximum depth of corrosion, optical metallography, SEM/EDX	3-4+2 sleeves
	With welded joint *)	M-NM (ASTM G78-01) (ASTM G192-08)	25, 70	100, 10000, 29000	0, $\sim 4\cdot 10^8$	0, 1000, 5000	+ / +	36	$E_{PR,CR}$= $E_{PR,CR}$=f(Cl^-,A,t,D,T) before and after the 1000/5000-hour test	3-11+2 sleeves
Crevice	With welded joint *)	M-M (ASTM G78-01)	25, 70	100, 10000, 29000	0, $\sim 4\cdot 10^8$	1000, 2000, 3000, 5000	+ / -	48	Visual inspection, photo, gravimetry, maximum depth of corrosion, optical metallography, SEM/EDX	3-4 + 3-7(3 mm)
	With welded joint **)	M-M	25, 70	100, 10000, 29000	0, $\sim 4\cdot 10^8$	1000, 2000, 3000, 5000	+ / +	48x2=96		3-6
Stress corrosion cracking	Homogeneous	-	25, 70	100, 10000, 29000	0, $\sim 4\cdot 10^8$	$\sigma_p=0{,}5\sigma_{0,2}$, $\sigma_p=0{,}75\sigma_{0,2}$, $\sigma_p=1{,}0\sigma_{0,2}$	+ / +	108	t_{cr}= f(Cl^-,A,t,T,D,σ)	3-14
Stress corrosion cracking	With welded joint *)	-	25, 70	100, 10000, 29000	0, $\sim 4\cdot 10^8$	$\sigma_p=0{,}5\sigma_{0,2}$, $\sigma_p=0{,}75\sigma_{0,2}$, $\sigma_p=1{,}0\sigma_{0,2}$	+ / +	108	t_{cr}= f(Cl^-,A,t,T,D,σ)	3-15

Accepted Legend:

***): welded joint of steel AISI 316L;**

****): welded joint of KURION adsorption tower;**

D: irradiation dose;

M-M: metal-metal;

M-NM: metal-nonmetal

INM's Additional Scope of work

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It is planned to consider the 3rd temperature (50 ˚C) for several types of studied corrosion processes in the conditions of absences of radioactivity. The absences of radioactivity will allow to show the required Arrhenius dependence as well as simplify the implementation of Additional scope of work.

The scope of additional work is presented in the table form:

Type of Corrosion/Type of repassivation potential	Points of Time, h	Points of [Cl⁻], ppm	T, ˚C	Number of model samples to be used	The use of radioactivity
Pittting corrosion	0, 3000	1000, 5000, 20000	50	Type 3-1: 3 pcs, Type 3-2: 3 pcs,	Without use of radioactivity
Repassivation potential for pitting corrosion	0, 1000	1000, 5000, 20000	50	Type 3-12: 6 pcs, Type 3-13: 6 pcs	Without use of radioactivity
Crevice corrosion	0, 3000	1000, 5000, 20000	50	Type (3-3: 3 pcs + 3-4: 3 pcs) – contact «metal-nonmetal»+12 washers; Type (3-4: 3 pcs+ 3-7: 3 pcs) – contact «metal-metal»;	Without use of radioactivity
Repassivation potential for crevice corrosion	0, 1000	1000, 5000, 20000	50	Type 3-10: 6 pcs; Type (3-11: 6 pcs) - contact «metal-nonmetal». + 24 washers	Without use of radioactivity

Research Program Development

CNIITMASH's Scope of work

ROSATOM

Type of corrosion	State of the metal	Initial material	Number of the samples	a, mm length	b, mm width	c, mm thickness	Type of Drawing	Mode of experiment implementation
Pitting	Homogeneous	Steel sheet - 3 mm, steel 316L	60	50	20	3	3-1	t=20±1 °C (glass container)), the volume solution/sample surface ratio = 10:1. Duration is up to 72 hours Solution: 10% solution of $FeCl_3$
	Welded joint	Steel sheet - 10 mm, steel 316L, welding wire OK Autrod 316L + OK Flux10.92	60	50	20	3	3-2	
Crevice	Homogeneous	Steel sheet 3 mm, steel 316L	60	30	30	3	3-3	t=20±1/60±1 °C (glass container), the volume solution/sample surface ratio = 10:1. Duration is 30, 60, 90 days. [Cl^-] 10, 9505, 19 000 ppm
	Welded joint	Steel sheet - 10 mm, steel 316L, welding wire OK Autrod 316L + OK Flux10.92	60	30	30	3	3-4	
	Model tank	steel 316L	6	-	-	-	Model Tank as assembly	Solution is poured in the Model tank. t=20±1/60±1 °C. Duration 500 -3000 hours. [Cl^-] 10, 9505, 19 000 ppm
Intergranular	Homogeneous	Steel sheet - 3 mm, steel 316L	12	80	20	3	(80±0,5)x(20±0,5)x(3 ±0,2) mm	Preliminary heating up (650 °C, 1 hour). The boiling of solution with adding of the copper chips is implemented within the 8 hours. Z-like bend of the sample is used. Solution: It is planned to add the copper sulphate (50±0.1) g to (1000±3) cm^3 of water as well as small portions of sulfuric acid (250±3) cm^3

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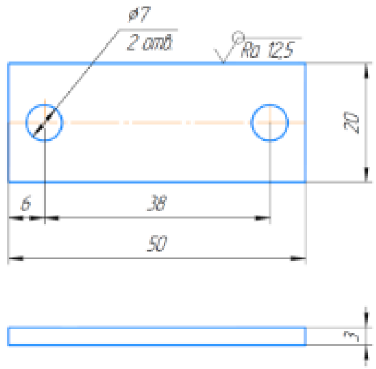
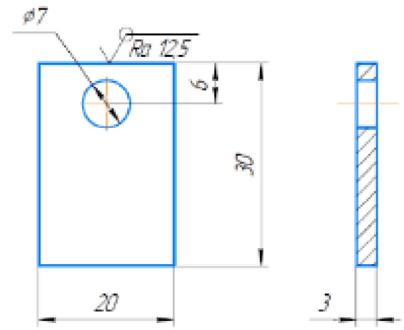
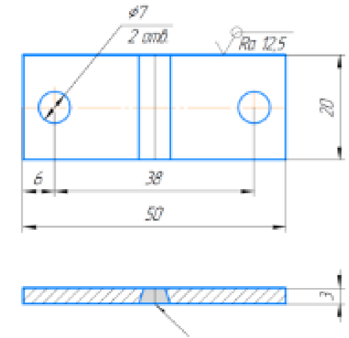
Type: 3-1 Steel 316 L
Related standard: GOST R 9.905-2007



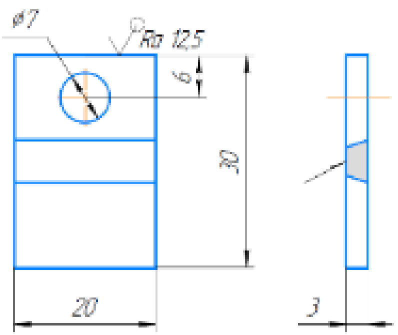
Type: 3-12 Steel 316 L
Related standard: GOST 9.912-88



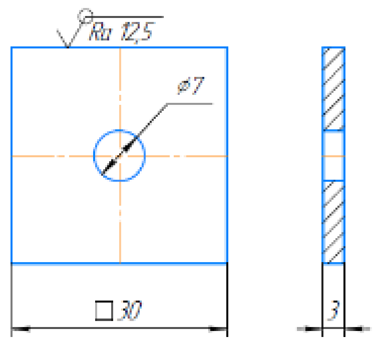
Type: 3-2 Steel 316 L
Related standard: GOST R 9.905-2007



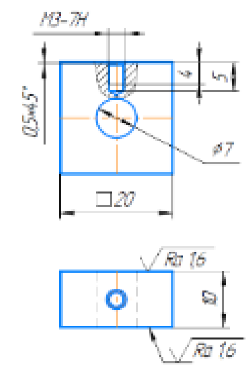
Type: 3-13 Steel 316 L
Related standard: GOST 9.912-88



Type: 3-3 Steel 316 L
Related standard: ASTM G 78-01



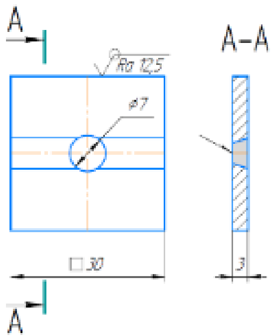
Type: 3-10 Steel 316 L
Related standard: ASTM G 192-08



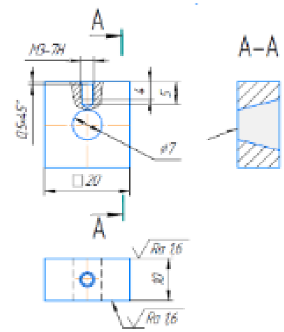
Research Program Development

Model Samples Description – Model Samples shape selection

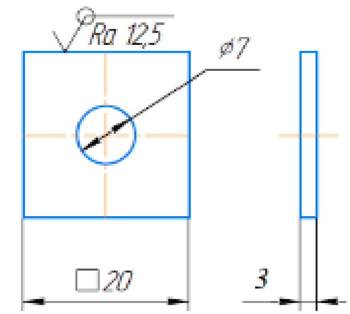
Type: 3-4 Steel 316 L
Related standard: ASTM G 78-01



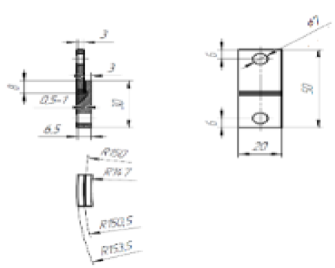
Type: 3-11 Steel 316 L
Related standard: ASTM G 192-08



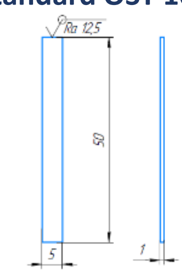
Type: 3-7 Steel 316 L
Related standard: ASTM G 78-01



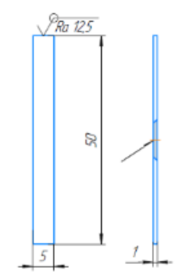
Type: 3-6 Steel 316 L
Related standard: GOST R 9/905-2007



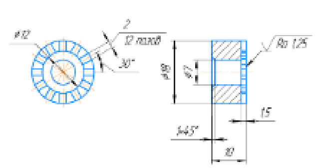
Type: 3-14 Steel 316 L
Related Standard OST 108.90101.79



Type: 3-15 Steel 316 L
Related Standard OST 108.90101.79



Crevice Washer

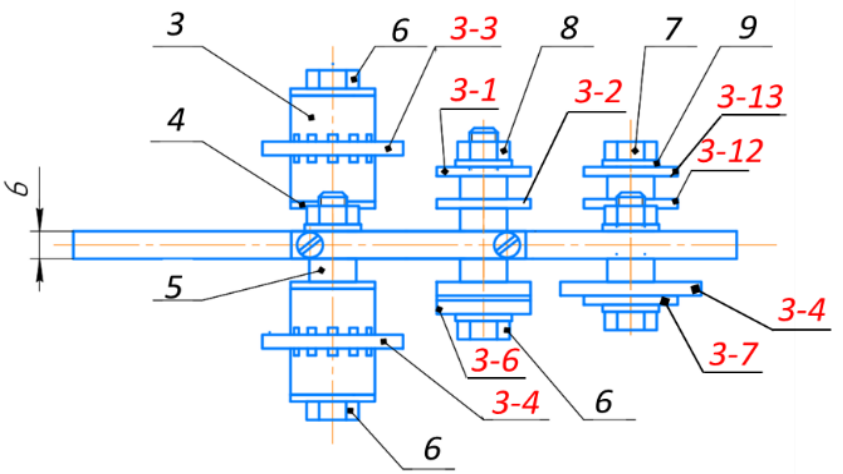


Corrosion Experiments Preparation

The selected scope of the experiments (see slides 7 - 9) implies the implementation of the hot experiments related to a certain set of the controlled parameters: t, h; T, ˚C; $[Cl]^-$ ppm; A Bq/g - **such a set of the controlled parameters is one experimental point.**

In order to optimize Hot Cell working volume filling it is planned to use the single assembly allowing to install all the required samples for each **experimental point**.

Uniform/Pitting corrosion	**Samples type 3-1, 3-2, 3-12, 3-13**
Crevice corrosion	**Samples type 3-3, 3-4, 3-10, 3-11, 3-7, 3-6 + Washers**
Stress corrosion cracking	**Samples type 3-14, 3-15**



1 -panel, 2- handle, 3- bushing (slot-forming device), 4, 9 - washer, 5 - high washer, 6, 7 - bolt, 8 - nut, 10 - screw, 12 - crucibles with samples type 3-10 and 3-11

The assembly related to the certain experimental point

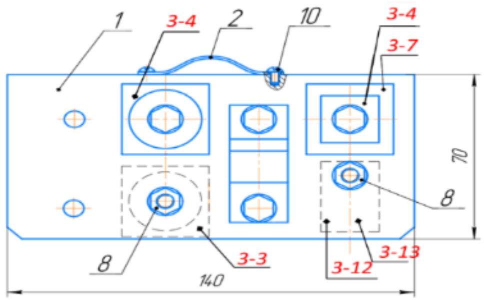
(t, T, $[Cl^-]$, A)

Corrosion Experiments Preparation

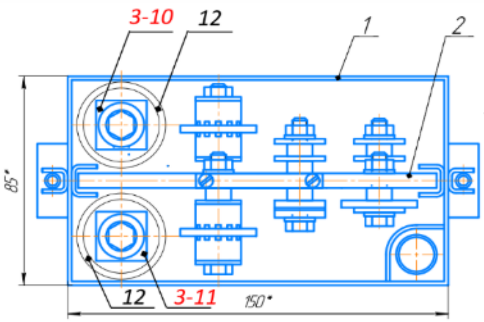
Description of Approach on Corrosion tests implementation

ROSATOM

Then each assembly is installed in the container



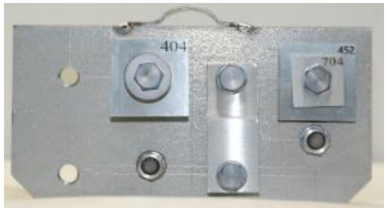
An overall view of a container with installed assembly for corrosion experiments



The cross-section of the assembly installed in the container

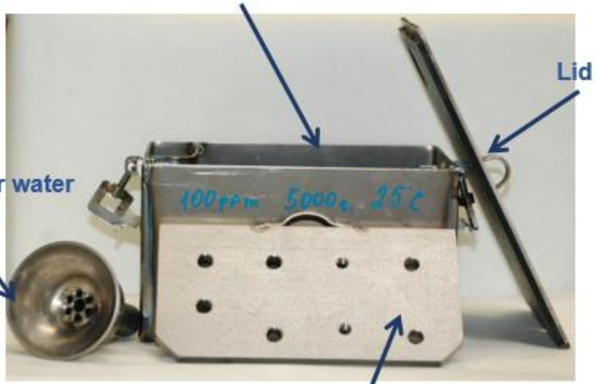
A scheme of samples installation inside the container

Panel with installed samples (top view)



Panel with installed samples (side view)

Container for corrosion tests with installed assembly

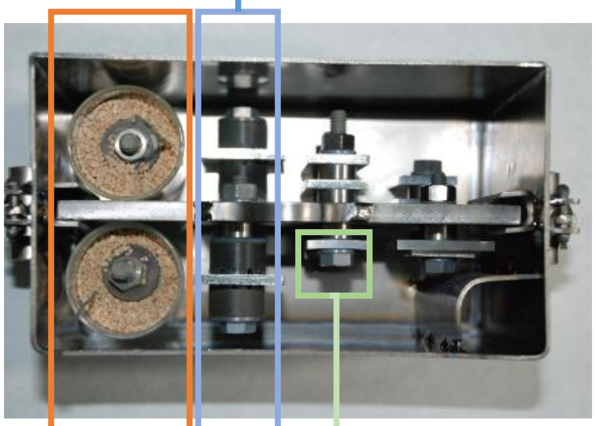


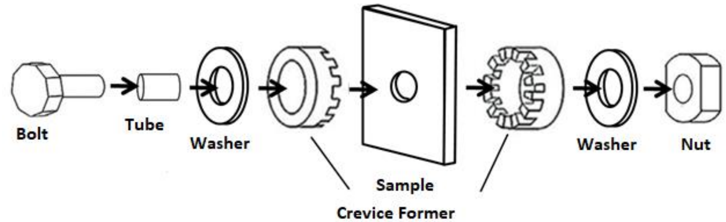
Corrosion Experiments Preparation

Details related to crevice corrosion

ROSATOM

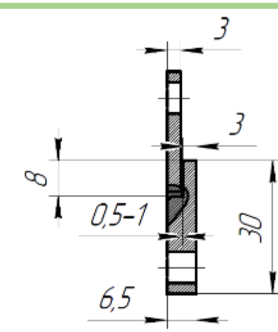
The scheme of crevice corrosion experiments implementation





Sample type 3-3, 3-4 assembling (multi-crevice experiment) in accordance with standard ASTM G-78

The surface roughness of the manufactured samples is equal to 1.6 µm (Ra=1.6 µm), Thus the studied crevice gap is equal to units of micrometer



Sample type 3-6

Despite the fact that the distance between two walls is in the shown range 0.5 -1 mm, there is the possibility of presence of the crevice gaps equal to tens of micrometer in areas located close to the welded joint. These areas are planned to be studied.

before adding zeolite after adding zeolite

Samples type 3-10, 3-11 for defining the repassivation potential of crevice corrosion

It is planned to implement the additional study (using the optical microscope) of the sample's surfaces in order to define that the measured value of repassivation potential is related to the considered gap

Corrosion Experiments Preparation

Samples weighting

Dimensions control

Electrochemical cell assembling

Sample type 3-3

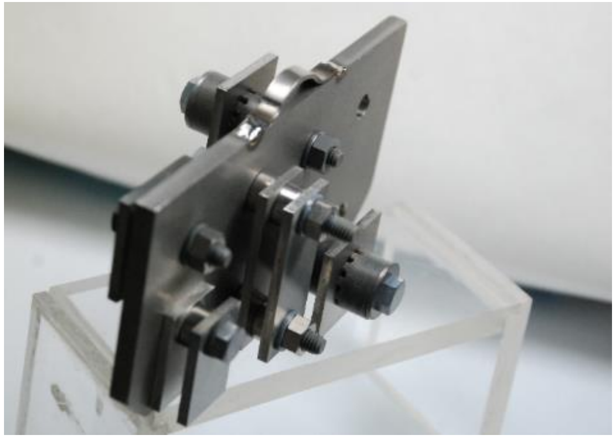
Samples type 3-4 + 3-7

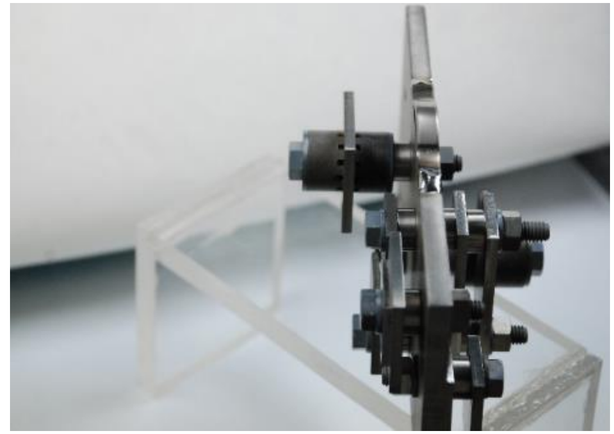
Sample type 3-12

Sample type 3-10

Samples assembling

Corrosion Experiments Preparation



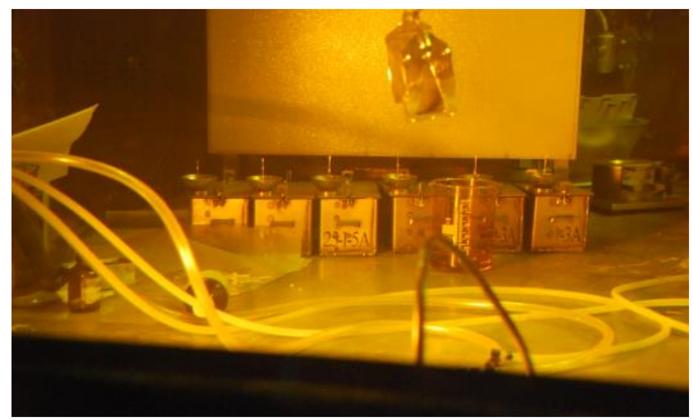


Samples are fixed on the panel

Container Filling (with zeolite) related to Repassivation Potential Measuring (crevice corrosion)

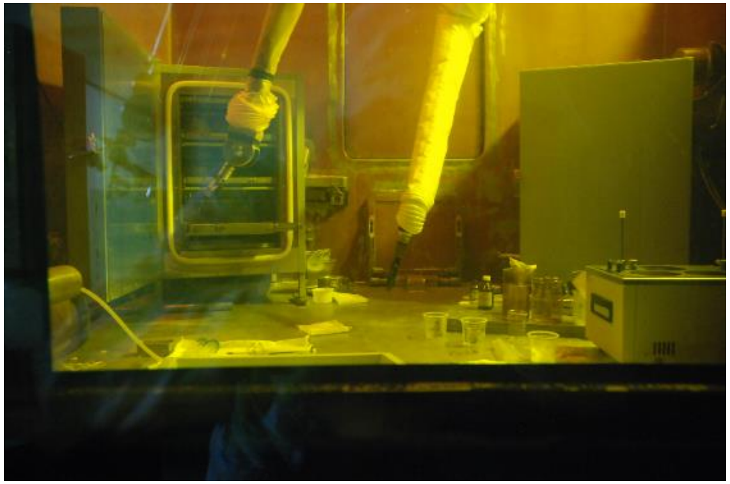
Installation of the samples inside the container

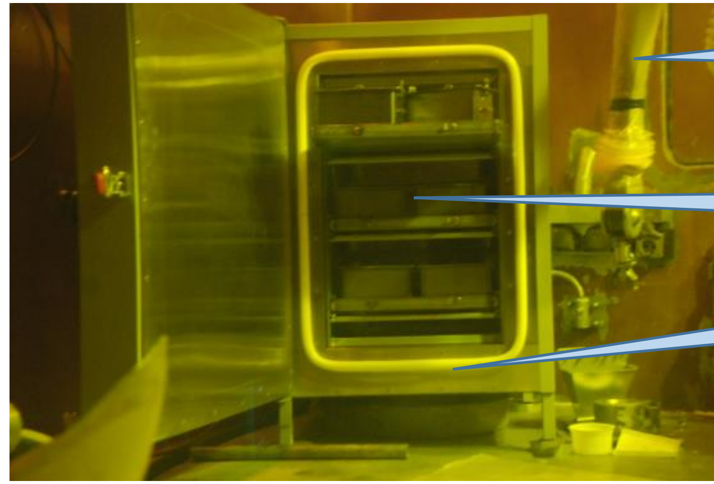
Container filling with Zeolite



Collection of the prepared container

Corrosion Experiments Preparation





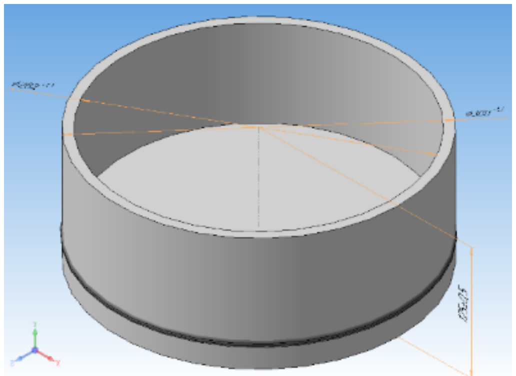
Hot Tests Implementation. Required set of the prepared containers and thermostatic equipment are installed inside the Hot Cell

Cold Tests Implementation. Required set of the prepared containers and thermostatic equipment are installed inside the Thermostatic Equipment

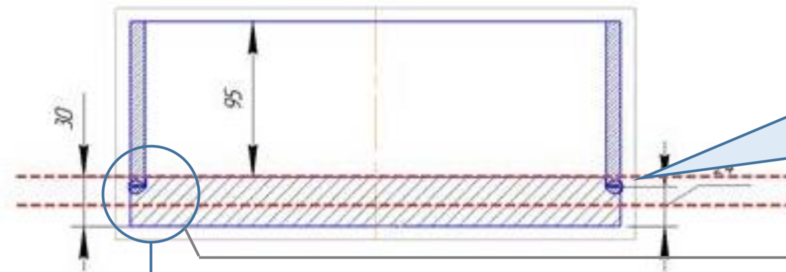
Corrosion Experiments Preparation

An Approach to Model Tanks Fragmentation

It is required to implement the Model Tanks fragmentation in order to provide the subsequent analysis of crevice corrosion occurrence. It is planned to implement preliminary analysis of the welded joint state using the microscope. In order to provide the access to the welded joint, the model tank is prepared in accordance with the following approach:



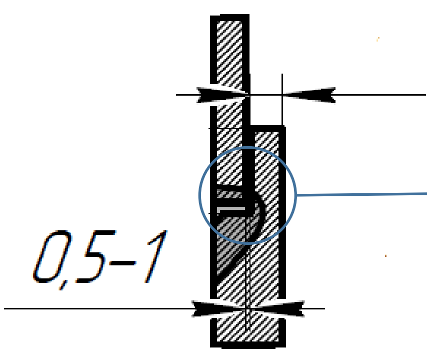
An overall view of the Model Tank



It is planned to use the optical microscope OLYMPUS SZ-61 that will provide the 5-20 times magnification

- A line showing the approach for preliminary cutting of the model tank to provide the visual control using the microscope. As a result, the areas for subsequent detailed metallographic control will be selected

An example of a view of surface state in the gap between the bottom and the shell



The technology of manufacturing of the model tanks doesn't exclude the presence of smaller gaps (gaps equal to tens of micrometer) in the areas close to the welded joint root (this fact will be defined after cutting the samples when corrosion tests are completed). Such areas are planned to be studied.

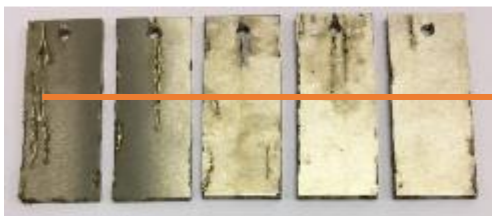
Experimental Results

CNIITMASH Site. Pitting corrosion (1/2)

Experiments related to the pitting corrosion (In accordance with Russian Standard GOST 9.912-89 – **equivalent of the Method A of ASTM G 48**). Experiments under the conservative conditions to assess the tendency of 316L steel to pitting corrosion.

Type of sample	Dimensions, mm	Number of the samples	Solution	Duration, h	Temperature, ˚C
Flat sample without welded joint	50x20x3	5	10% $FeCl_3 \cdot 6H_2O$	72	20±1
Flat sample with welded joint	50x20x3	5			

An overall view of the samples after the experiments

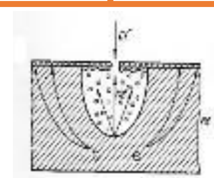


Front side

Opposite side

Samples before experiment

Samples without welded joint



Initially, obtained pittings are closed with «lids». Thus, when experiment had just been finished the samples surfaces look like «shiny steel»

shiny sample surfaces

Front side

Opposite side

Samples before experiment

Samples with welded joint

Experimental Results

CNIITMASH Site. Pitting corrosion (2/2)

Type of sample	Average rate of pitting corrosion, g/m^2h	Maximal depth of a pitting, mm
Flat sample without welded joint	3.3±0.4	1.7
Flat sample with welded joint	2.9±1.2	1.8

It should be noted, that it has been obtained that the areas of more extensive development of pitting corrosion are along the sample's ends surface as well as close to hole that in general corresponds to accepted standards. Crevice corrosion wasn't identified in the areas of contact with fluoroplastic thread (that provide the sample hanging), due to the fact that diameter of the fluoroplastic thread is much smaller then hole diameter.

General Tendency of AISI 316L steel to pitting corrosion has been identified.

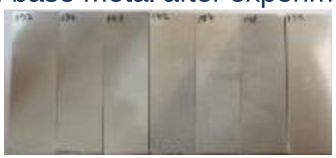
Experimental Results

CNIITMASH Site. Intergranular corrosion (IGC)

Experiments related to the Intergranular Corrosion (In accordance with Russian Standard GOST 6032-2017). GOST 6032-2017 has the following features compared with other standards (EN ISO 3651-2, ASTM A262:2014, JIS G0575:1999): preliminary heating – 650 ˚C during 60-min period, experiment duration – 8 hours, angle of sample bending – 90˚. Conditions: boiling water solution of $CuSO_4 \cdot 5H_2O$ (50±1g) and H_2SO_4 (250±3g) with presence of metallic Cu; Duration of boiling ~ 8 hours.

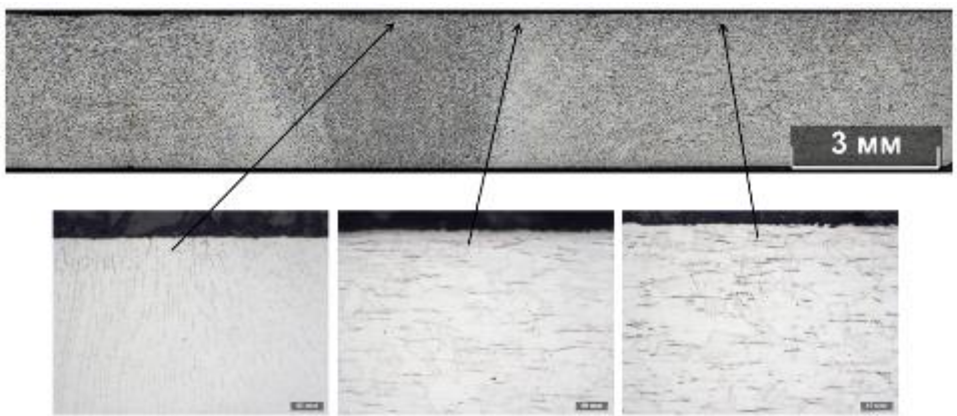
The state of base metal after experiment is finished

The state of weld metal after the experiment is finished



Non-welded Samples before the experiment

Welded Samples before the experiment



Microstructure of the weld metal

Microstructure of the HAZ material

Microstructure of the base material

The boundaries of austenitic grains were not destroyed after the IGC experiments are finished. Based on these results, it was concluded that the weld metal of heat-affected zone (HAZ) and the base metal don't have tendency to IGC.

Tendency of the studied metal to intergranular corrosion hasn't been identified

Experimental Results

CNIITMASH. Crevice corrosion (in accordance with ASTM G 78) (1/4)

ROSATOM

Experiments related to the crevice corrosion (In accordance with Standard ASTM G 78).

Type of sample	Dimensions, mm	Number of the samples	Solution	Duration, d	Depth of washer's groove (h), mm	Temperature, ˚C
Flat sample without welded joint	30x30x3	54	1 – [Cl$^-$] = 10 ppm 2 - [Cl$^-$] = 9500 ppm 3 - [Cl$^-$] = 19 000 ppm	90	0.2/0.3/0.5	25±5/60±2
Flat sample with welded joint	30x30x3	54				

Area of crevice corrosion, S mm^2

Temperature, ˚C	25			60		
[Cl-], ppm	10	9500	19000	10	9500	19000
h = 0.2 mm	0.00	26.50	40.75	0.75	16.62	38.00
h = 0.3 mm	0.00	33.20	71.50	0.00	6.25	32.00
h = 0.5 mm	0.00	15.25	47.00	0.00	0.00	27.00

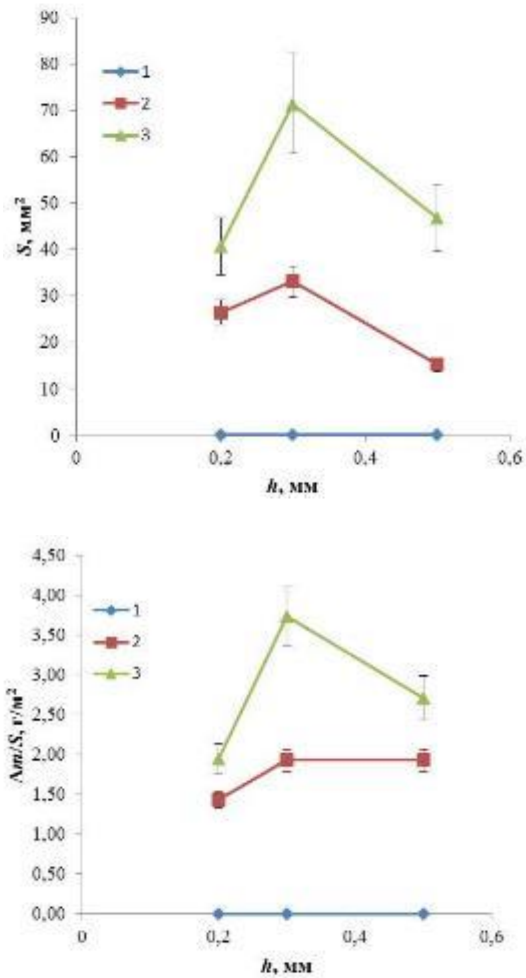
Mass loss per surface area of sample, Δm/S g/mm^2

Temperature, ˚C	25			60		
[Cl-], ppm	10	9500	19000	10	9500	19000
h = 0.2 mm	0.00	1.44	1.94	0.74	1.50	3.29
h = 0.3 mm	0.00	1.93	3.74	0.00	0.86	2.16
h = 0.5 mm	0.00	1.93	2.72	0.00	0.00	1.94

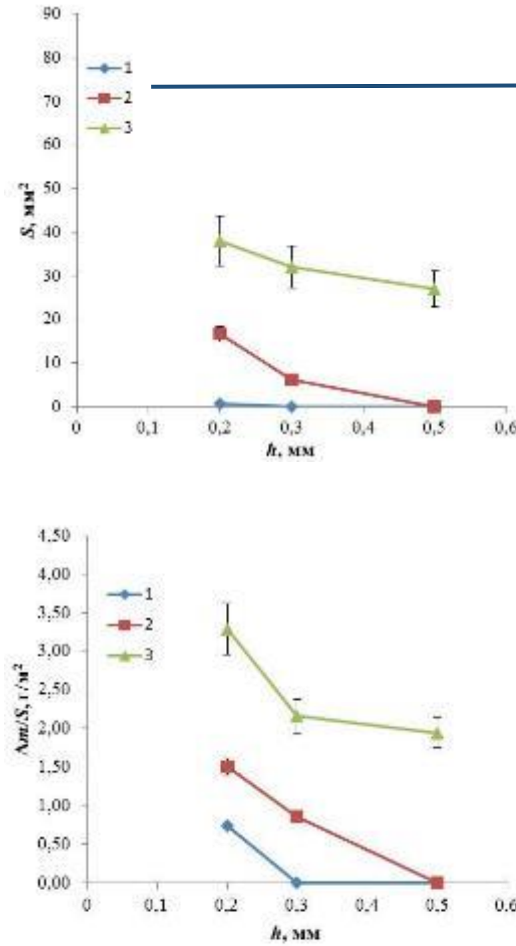
Experimental Results

CNIITMASH. Crevice corrosion (in accordance with ASTM G 78) (2/4)

1 – [Cl-] = 10 ppm;
2 - [Cl-] = 9 500 ppm;
3 - [Cl-] = 19 000 ppm



(a) For T = 25 ˚C



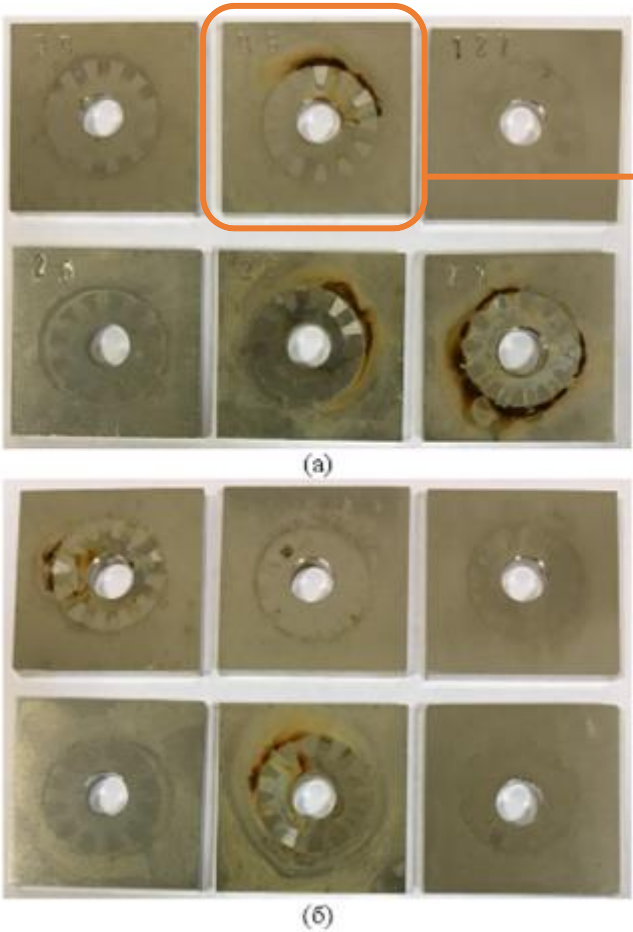
(a) For T = 60 ˚C

Graphical interpretation of the dependencies of S mm^2 (surface of crevice corrosion foci) and Δm/s g/mm^2 (mass loss)

Experimental Results

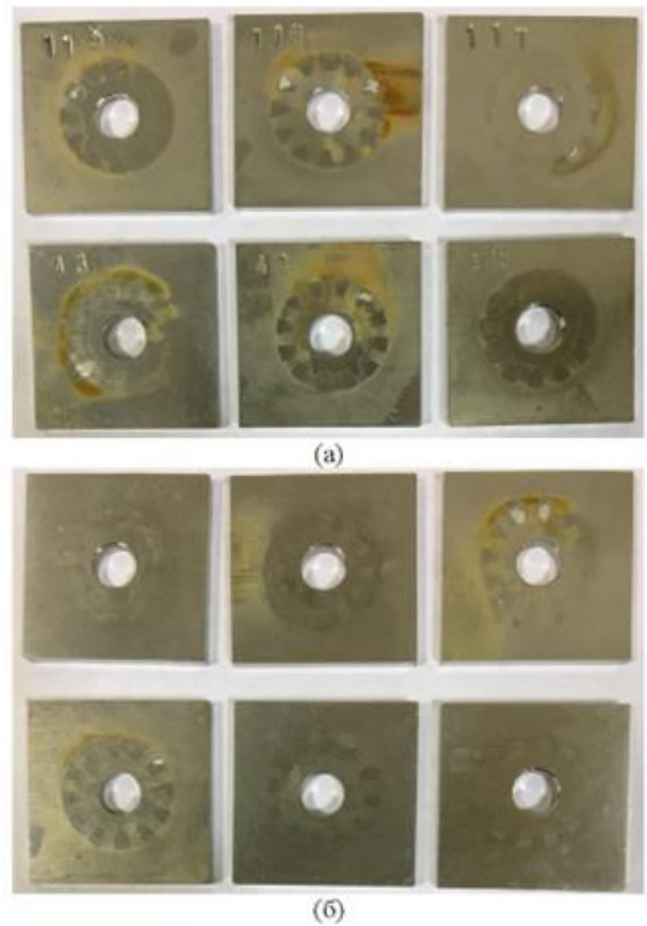
CNIITMASH. Crevice corrosion (in accordance with ASTM G 78) (3/4)

Overall view of some samples after completion of the crevice corrosion experiments:



Sample № 98 will be considered in detail on slide № 26

(a) Front side, (b) Opposite side
Solution: 3, t = 60 ˚C
Washer's groove 0.2 mm

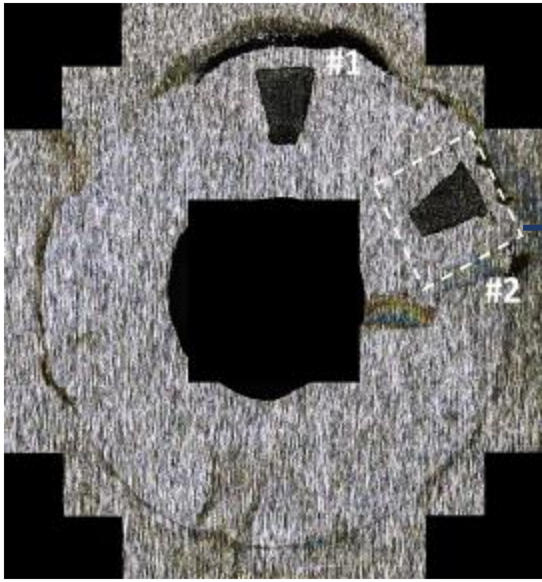


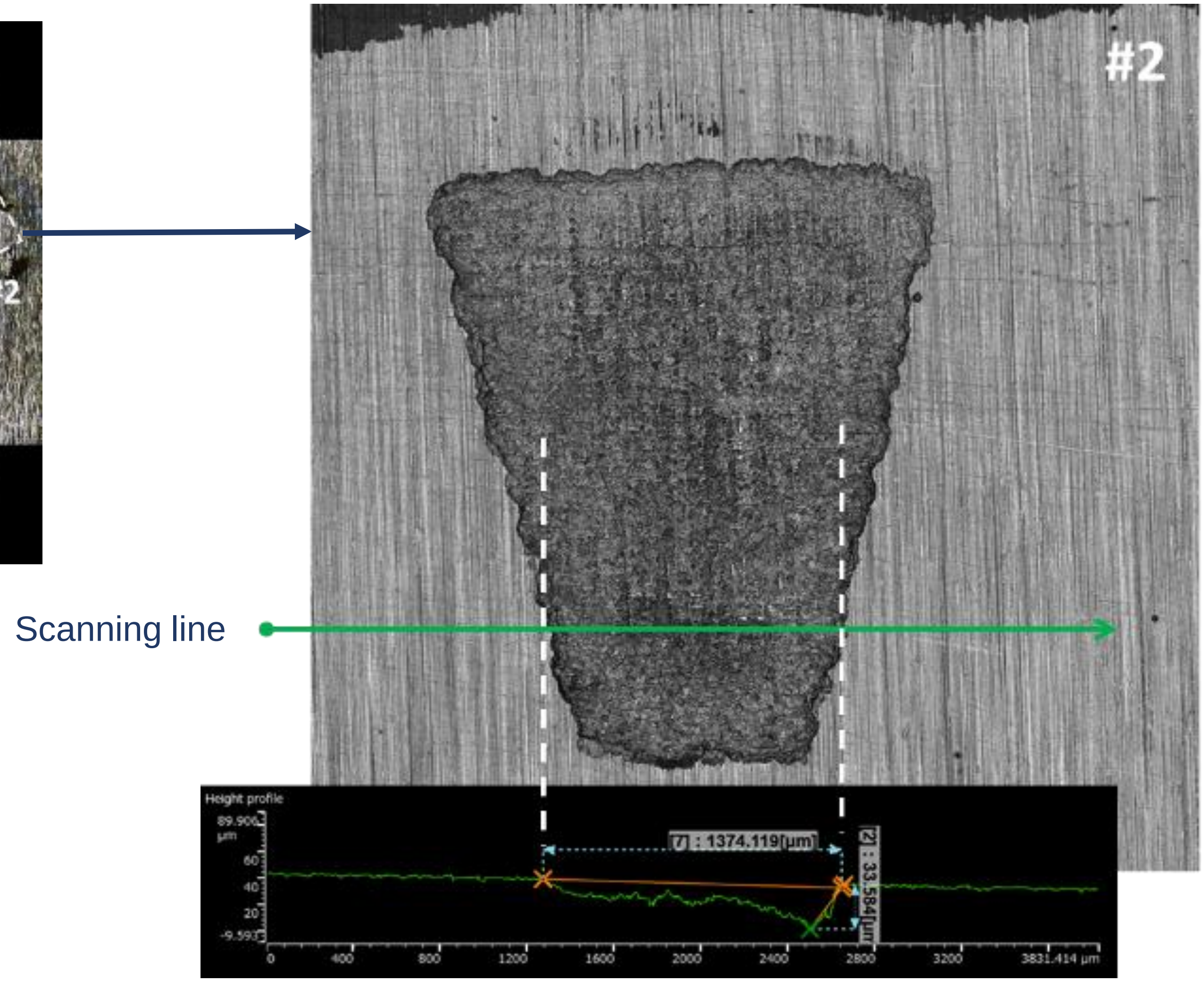
(a) Front side, (b) Opposite side
Solution: 2, t = 25 ˚C
Washer's groove 0.2 mm

Preliminary Experimental Results

CNIITMASH. Crevice corrosion (An example of analysis) (4/4)

Study of the sample № 98:





$D_{cr,max}$ = 33.6 µm

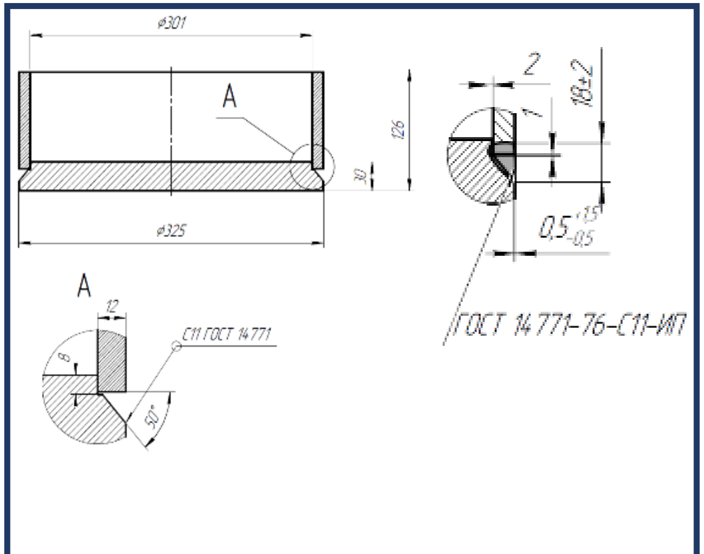
Dcr,max Is the maximal depth of crevice corrosion

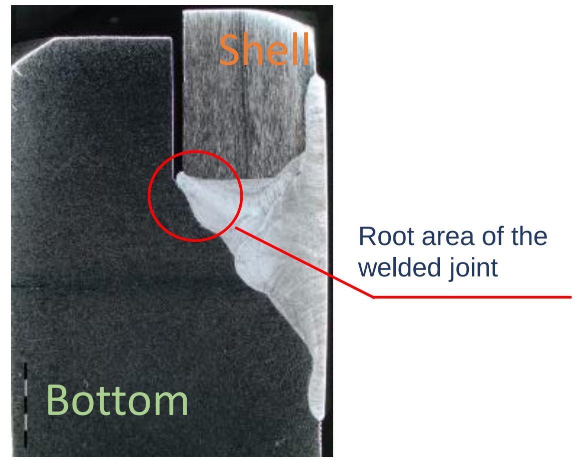
Experimental Results

CNIITMASH. Crevice Corrosion. Model Tanks (1/4)

Use of Automatic welding method led to appearance of a defect called «incomplete welding». After that, additional Model Tank was manufactured (using the Manual Welding Method) in order to avoid such a defect, thus Model Tank with/without incomplete welding defect were analyzed.

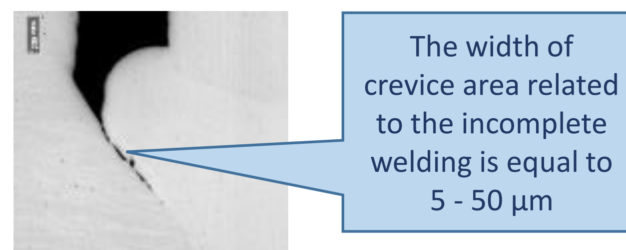
A scheme of the manufactured Model Tanks:





Prepared metallographic Specimen

Model Tank	Conditions of an experiment
Model Tank 1	T = 25±5 ˚C, [Cl-] = 10 ppm;
Model Tank 2	T = 25±5 ˚C, [Cl-] = 9 500 ppm;
Model Tank 3	T = 25±5 ˚C, [Cl-] = 19 000 ppm;
Model Tank 4	T = 60±2 ˚C, [Cl-] = 10 ppm;
Model Tank 5	T = 60±2 ˚C, [Cl-] = 9 500 ppm;
Model Tank 6	T = 60±2 ˚C, [Cl-] = 19 000 ppm;



An example of incomplete welding. Model Tank 6

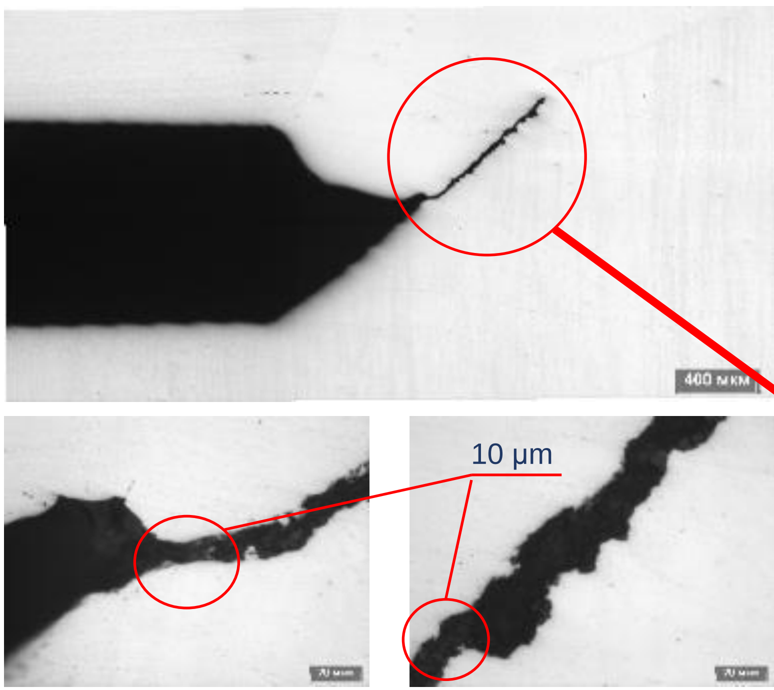
10-µm-like defects (in the root area of the welded joint) are most interesting areas from the point of view of crevice corrosion development.

Experimental Results

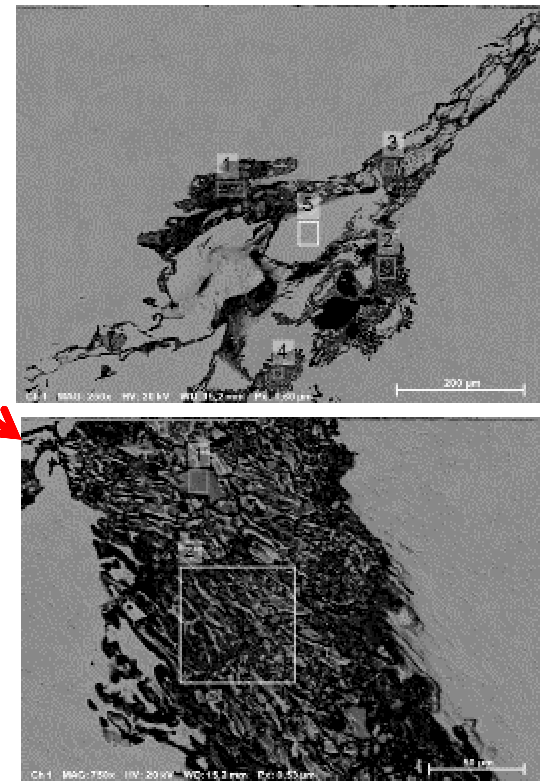
CNIITMASH. Crevice corrosion. Model Tanks. Example of crevice Corrosion formation (2/4)

ROSATOM

Analysis of the crevice corrosion development in case of presence of the defect (incomplete welding). Model Tank №6 - [Cl-] = 19 000 ppm. T = 60 ˚C, t = 3000 hours.



The presence of etched areas inside the defect related to the incomplete welding



Normalized mass concentration [%]

Spectrum	O	Al	Si	Cr	Mn	Fe	Ni	Mo
1	22,07	1,82	3,12	23,38	2,52	27,52	3,25	16,32
2	22,54	2,18		22,90	0,80	33,66	2,59	15,32
3	23,30	2,01	3,72	19,59	7,80	27,31	2,08	14,19
4	20,25	0,82		23,21	0,71	36,06	2,02	16,92
5			0,66	18,21	1,52	66,46	10,71	2,45

Normalized mass concentration [%]

Spectrum	O	Al	Si	Ca	Cr	Mn	Fe	Ni	Mo
1	28,85		1,08		23,19		24,17	1,77	20,95
2	21,71	0,86	0,51	0,48	22,82	0,67	38,27	2,59	12,09

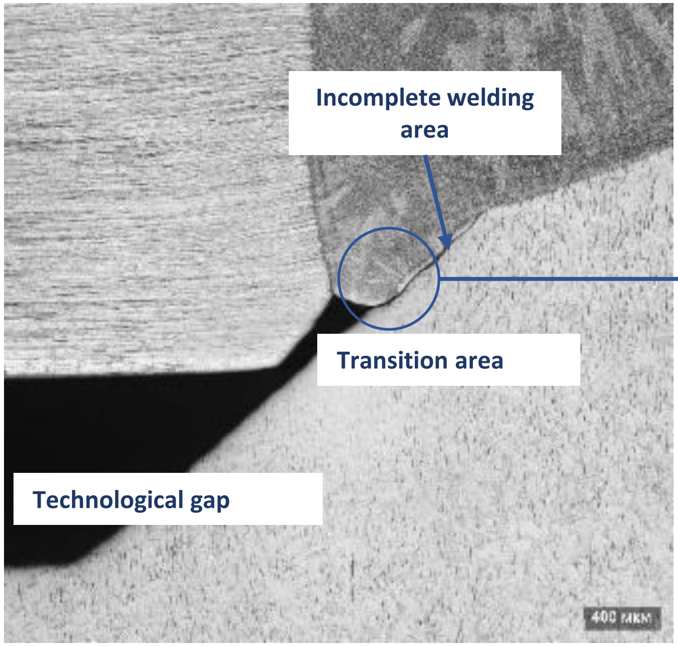
SEM+EDS

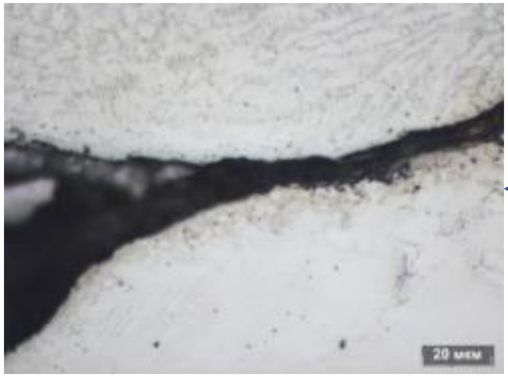
In the crevice gap of defect there is a selective Fe dissolution (Fe goes into solution in the form of ions and forms a corrosion product already at the exit of the crevice gap) as well as enrichment of the surface with elements that are more stable under these conditions (Cr, Mo) due to their greater tendency to transition to a passive state, which confirms the strengthened occurrence of crevice corrosion (anodic dissolution). The presence of Si is explained by the fact that the root area of the welded joint was created using a Si-containing ER316LSi welding wire. Al, Si, Mn, Ca can get into the defect area from the flux OK FLUX 10.92 (Flux OK FLUX 10.92 - Neutral agglomerated chromocompensating flux used in welding).

Experimental Results

CNIITMASH. Model Tanks. Features of crevice Corrosion formation (3/4)

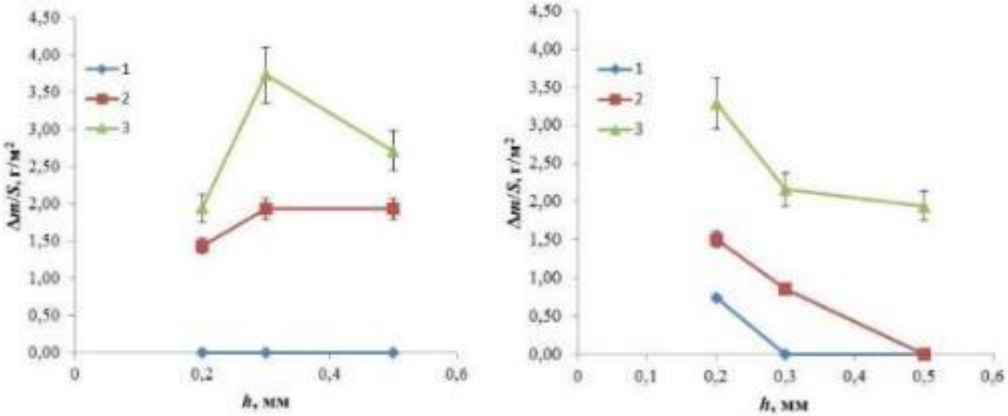
Development of crevice corrosion depends not only on the defect width but also it depends on its configuration (presence of transition area).





Model Tank № 4 ([Cl$^-$] =10 ppm, T = 60 ˚C, t = 3000 h)

The influence of transition area is also modelled by using the varied value of washer's groove depth (h):



The dependence of mass loss ($\Delta m/S$) from the value h under the following conditions: T = 25˚C (left side) and 60˚C (right side): 1 - [Cl$^-$] = 10 ppm; 2 - [Cl$^-$] = 9500 ppm; 3 - [Cl$^-$] = 19000 ppm. Duration : 90 days (in accordance with ASTM G 78).

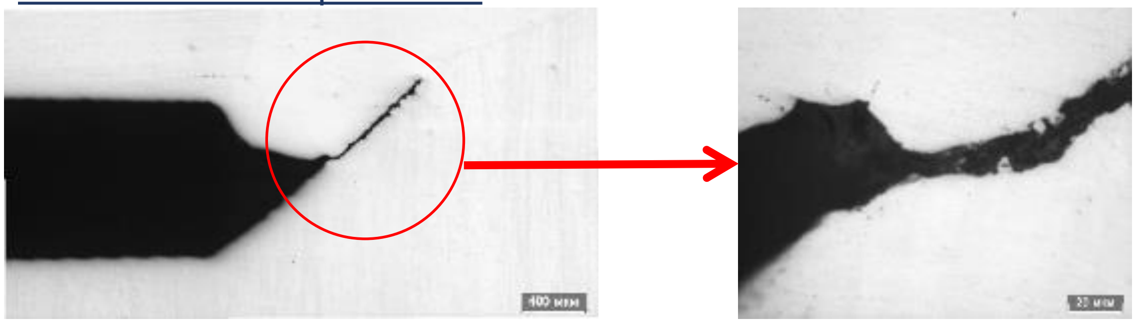
The overall view of the samples tested under the following conditions: [Cl$^-$] = 10 ppm, T = 60 ˚C

Experimental Results

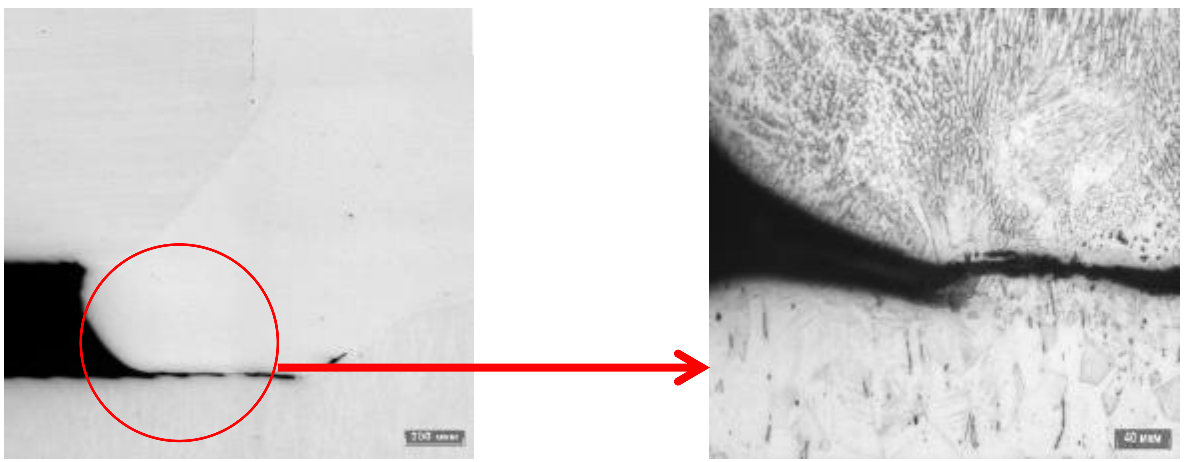
CNIITMASH. Model Tanks. Features of crevice Corrosion formation (4/4)

Development of crevice corrosion depends not only on the defect width but also it depends on its configuration. An example of crevice corrosion presence/absence inside the same Model Tank. **Model Tank 6. Sample 6: [Cl^-] = 19 000 ppm. T = 60 ˚C, t = 3000 hours**:

Crevice corrosion presence:



Crevice corrosion absence:

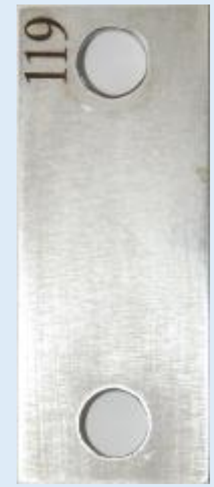
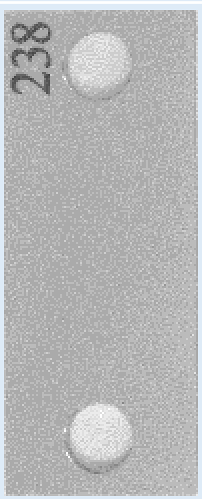
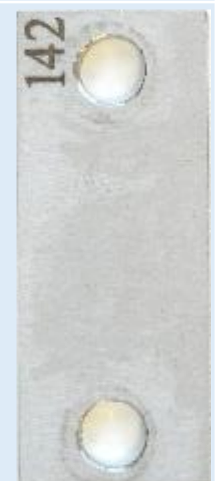
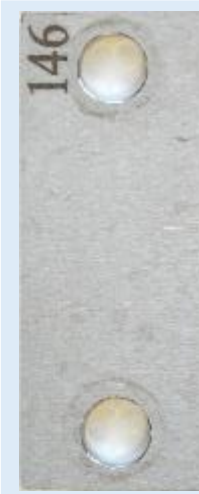


The presence of transition area (width = 0,1 – 0,3 mm) located between technological gap and a gap formed by incomplete welding has quite a significant impact on crevice corrosion intensity. This finding has a good corresponding with results obtained during the experiments described in the item (a) in case of using the washer’s groove equal to 0.2 mm. The process of crevice corrosion formation in the incomplete welding area is a stochastic one (in spite of same conditions, crevice corrosion could/couldn’t be formed in the considered areas).

Experimental Results

INM. Uniform/Pitting Corrosion. Examples of Samples appearance

ROSATOM

t, h	Before test	70 °C without radiation			70 °C with radiation		
		100 ppm	10 000 ppm	29 000 ppm	100 ppm	10 000 ppm	29 000 ppm
1000-1200							
1728-2064							

Experimental Results

INM. Uniform/Pitting Corrosion

Pitting corrosion without radiation								
t, h	D, MGy	T, °C	25			70		
		$[Cl^-]$, ppm	100	10000	29000	100	10000	29000
1100-1200	0	Metal	No*	No	No	No	No	No
		Welded joint	No	No	No	No	No	No
2000-2064	0	Metal	No	No	No	No	No	No
		Welded joint	No	No	No	No	No	No
3024	0	Metal	No	No	No	No	No	No
		Welded joint	No	No	No	No	No	No
4056-4152	0	Metal	No	No	No	No	No	No
		Welded joint	No	No	No	No	No	No
* - No = no pitting corrosion								

Experimental Results

INM. Uniform/Pitting Corrosion

Pitting corrosion with radiation								
t, h	D, MGy	T, °C	25			70		
		[Cl$^-$], ppm	100	10000	29000	100	10000	29000
1000	~0.87	Metal	No*	No	No	No	No	No
		Welded joint	No	No	No	No	No	No
1728-2000	~1.5--~1.7	Metal	No	No	No	No	No	No
		Welded joint	No	No	No	No	No	No
3024	~2.6	Metal	No	No	No	No	No	No
		Welded joint	No	No	No	No	No	No
4056-4152	~3.6	Metal	No	No	No	No	No	+**
		Welded joint	No	No	No	No	No	+**

* - No = no pitting corrosion,
** - + = Pitting observed

Experimental Results

INM. Crevice Corrosion. Results for experiments without radiation

ROSATOM

Crevice corrosion without radiation (in µm)									
t, h	D, MGy	Material	T, °C	25 °C			70 °C		
			[Cl$^-$], ppm	100	10000	29000	100	10000	29000
1100-1200	0	Metal	Metal/nonmetal	No*	7.6…11.3	31.7..58.6	No	29.0…33.2	12.5…38.6
		Welding	Metal/nonmetal	No	No	15.4	No	15.4…25.3	22.6…42.0
		Metal	Metal/metal	No	No	No	7.3	No	18.4
2000-2064	0	Metal	Metal/nonmetal	No	9.3…10.6	16.6…17.5	No	14.4…15.0	148.3…173.4
		Welding	Metal/nonmetal	No	4.6…7.7	7.4…17.0	No	29.1	35.2
		Metal	Metal/metal	No	No	No	No	No	+ (n.d)**
3024	0	Metal	Metal/nonmetal	No	5.6…15.6	15.6…18.2	2.1	31.6…56.0	34.9…77.0
		Welding	Metal/nonmetal	No	9.8…23.9	5.4…10.6	No	17.2	22.8
		Metal	Metal/metal	No	No	No	7.1	No	22.9
4152	0	Metal	Metal/nonmetal	No	11.3	7.4…26.2	3.7	31.6…56.0	87.8…160.0
		Welding	Metal/nonmetal	No	7.6	5.6…7.4	+ (n.d)	21.4…30.4	24.4
		Metal	Metal/metal	No	No	No	No	No	+ (n.d)

* - No = no crevice corrosion,

** - + (n.d.) = crevice corrosion observed (depth of crevice corrosion no dementing)

Experimental Results

INM. Crevice Corrosion. Results of experiments with radiation

Crevice corrosion with radiation (in µm)									
t, h	D, MGy	Material	T, °C	25 °C			70 °C		
			[Cl⁻], ppm	100	10000	29000	100	10000	29000
1000	~0.87	Metal	Metal/nonmetal	No*	11.2…23.7	23.7…61.9	No	9.9…69.7	19.9…30.7
		Welding	Metal/nonmetal	No	8….26.7	17.4….58.3	No	12.3..28.9	12.7…41.3
		Metal	Metal/metal	No	No	No	No	No	+ (n.d)**
1728-2000	~1.5-~1.7	Metal	Metal/nonmetal	No	9.9…14.3	21.4…77.7	No	19.1…24.2	10.0…19.0
		Welding	Metal/nonmetal	No	8.0…13.9	10.7…19.3	No	21.0…27.1	28.4…46.1
		Metal	Metal/metal	No	5.1	4.2	No	No	2.6
3048	~2.6	Metal	Metal/nonmetal	26.6	12.7…70.0	17.8…35.6	No	18.0…31.5	73.9…90.9
		Welding	Metal/nonmetal	11.1	11.2…50.8	10.6…15.0	No	36.2…41.4	10.5…16.4
		Metal	Metal/metal	No	No	No	No	No	7.6
4056-4152	~3.6	Metal	Metal/nonmetal	No	15.8…37.7	17.6…22.8	No	20.0…59.8	44.1…87.9
		Welding	Metal/nonmetal	No	8.5…19.0	9.0	No	10,6…25.4	29.0…45.9
		Metal	Metal/metal	No	+ (n.d)**	+ (n.d)**	No	+ (n.d)**	+ (n.d)**

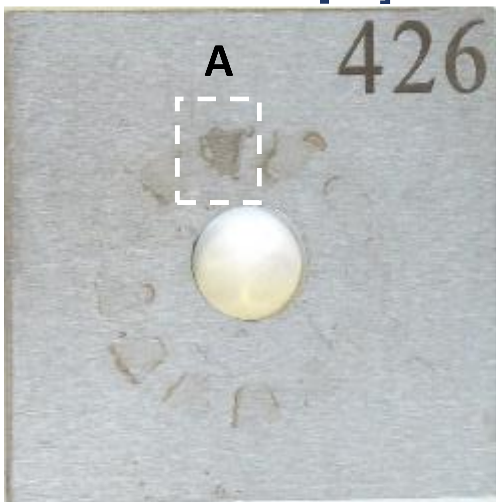
* - No = no crevice corrosion,

** - + (n.d.) = crevice corrosion observed (depth of crevice corrosion no dementing)

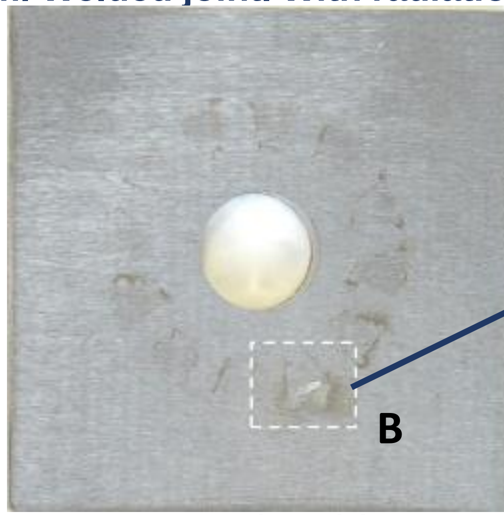
Experimental Results

INM. Crevice Corrosion. Example of implemented analysis (1/2)

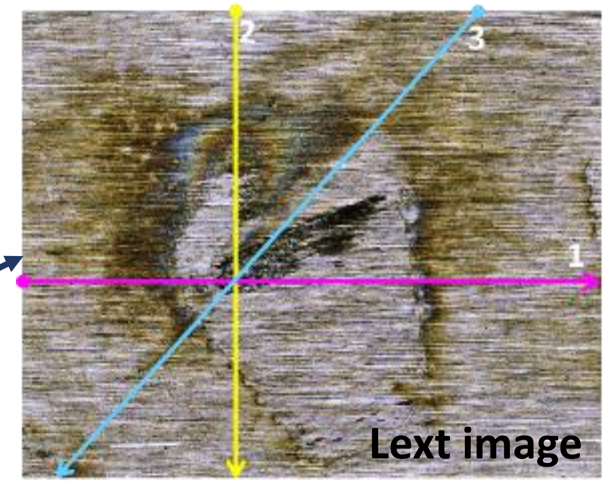
T = 25 ˚C. t = 2000 h. [Cl-] = 100 ppm. Welded joint. With radiation



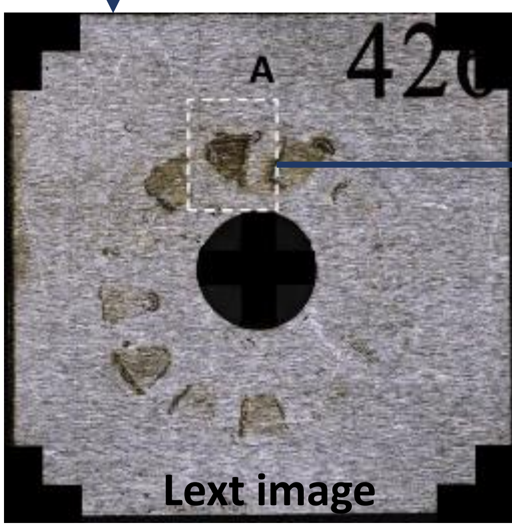
Front side



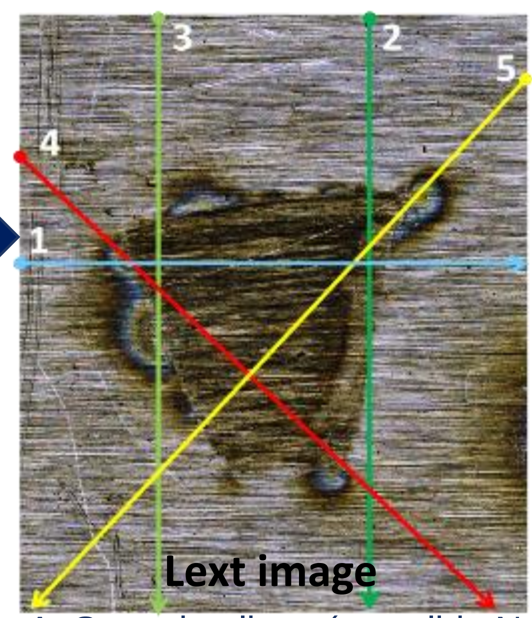
Opposite side



Area B Scanning lines



Front side

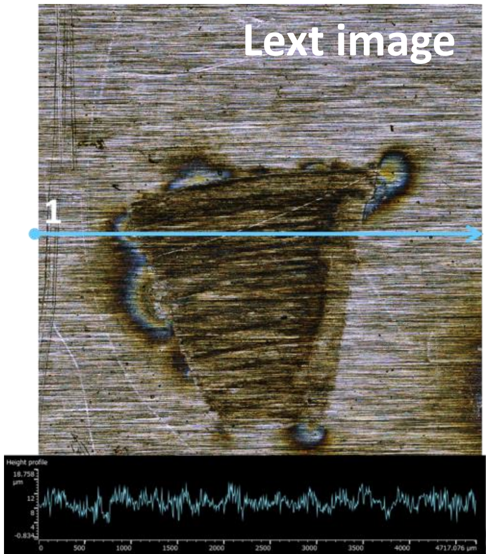


Area A, Scanning lines (see slide No37)

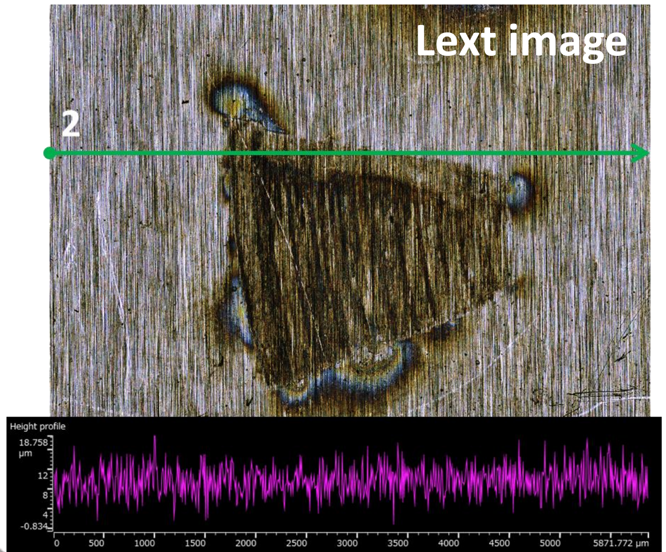
Experimental Results

INM. Crevice Corrosion. Example of implemented analysis (2/2)

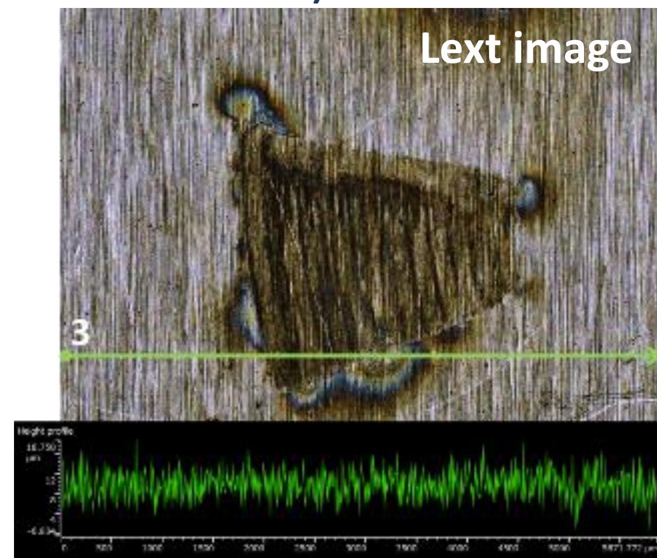
Sample No 426. **Welded joint. T = 25 ˚C. t = 2000 h. [Cl-] = 100 ppm. With radiation. Area A. Profiles in accordance with the selected scanning lines** **(Dcr,max - the maximum depth of crevice corrosion)**



Dcr,max = 0 µm

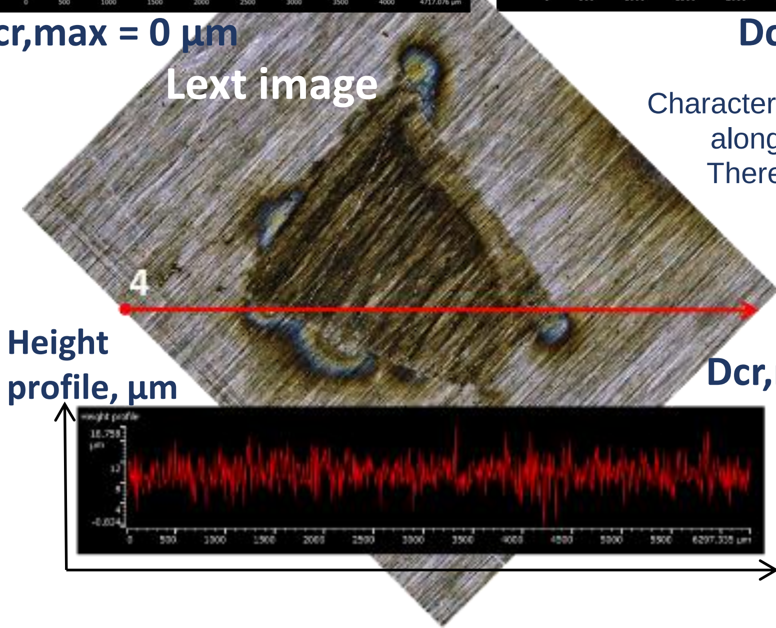


Dcr,max = 0 µm

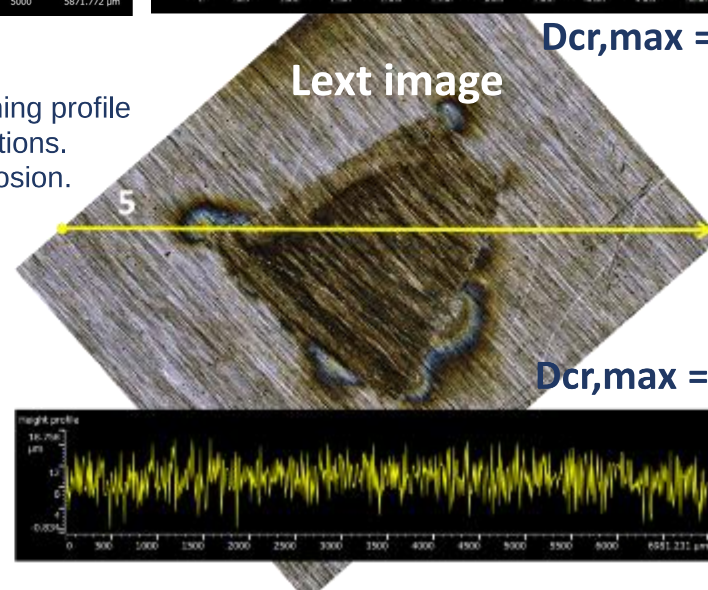


Dcr,max = 0 µm

Characteristic types of scanning profile along lines in any directions. There is no crevice corrosion.



Dcr,max = 0 µm



Dcr,max = 0 µm

Experimental Results

INM. Crevice Corrosion. Samples type 3-6 made of fragmented Model Tanks.

Example of the Implemented study (1/4)

ROSATOM

Before test

70 °C, with radiation

[Cl-] 100 ppm

[Cl-] 10 000 ppm

[Cl-] 29 000 ppm

Preliminary Experimental Results

INM. Crevice Corrosion. Samples type 3-6 made of fragmented Model Tanks. Example of the Implemented study (2/4)

Sample № 623, T = 70 °C, [Cl-] = 29 000 ppm, t = 3048 h, without radiation

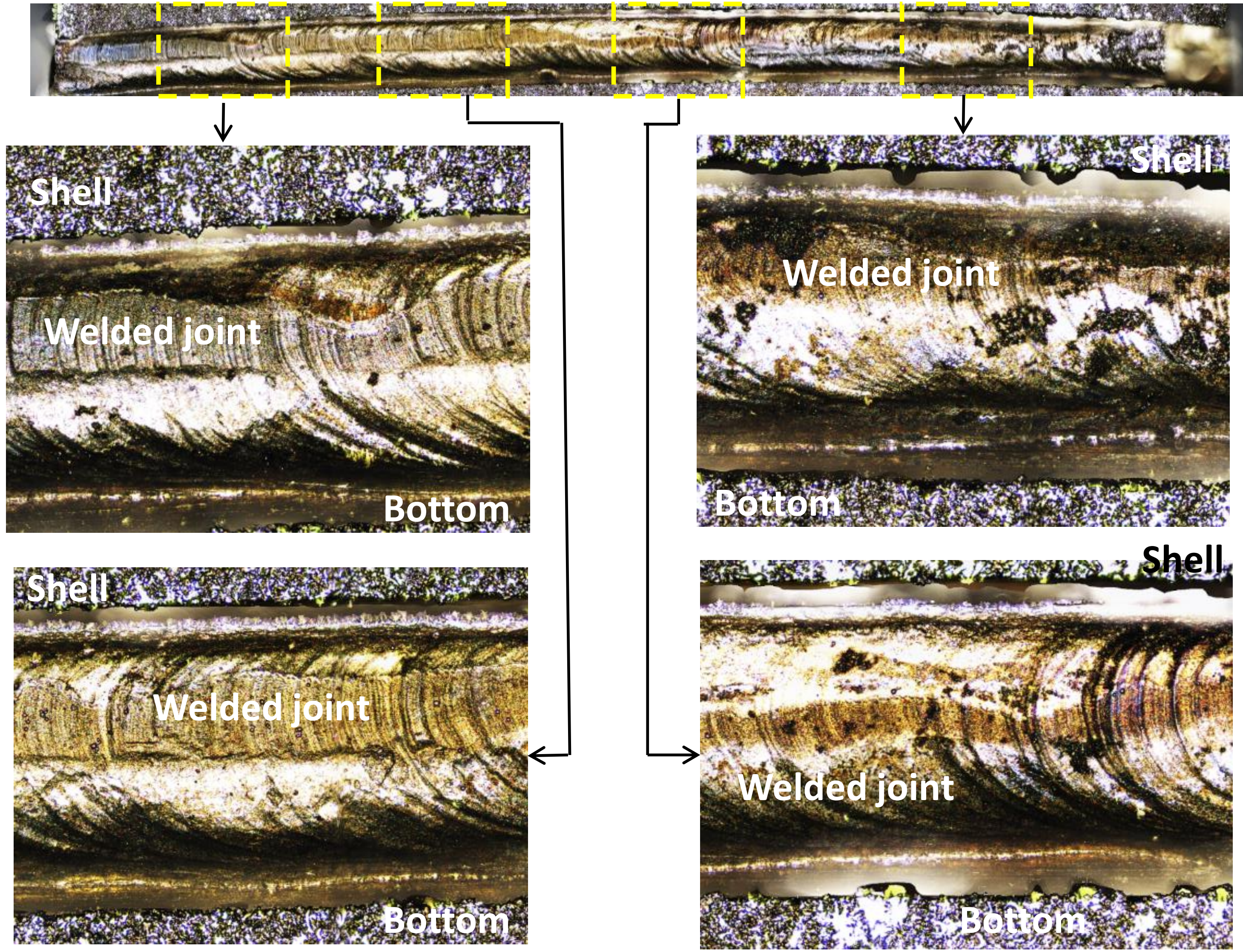
Lext* investigation

Refer to the lower left photo on p. 40

In the gap between Shell and Bottom, crevices and corrosion products haven't been indicated.

*Lext – Laser confocal scanning microscope OLYMPUS LEXT OLS5000

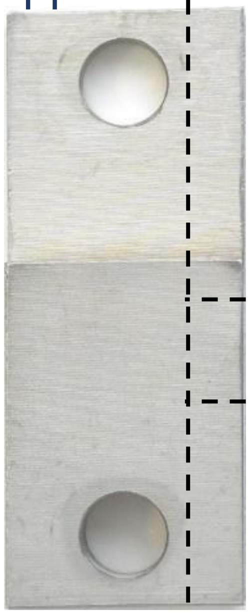
Appearance



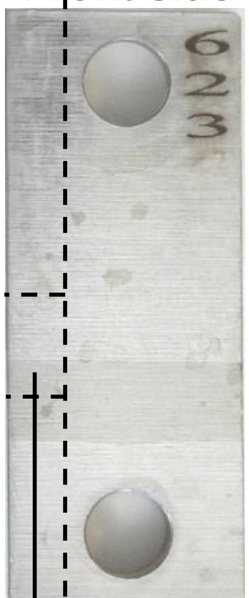
Preliminary Experimental Results

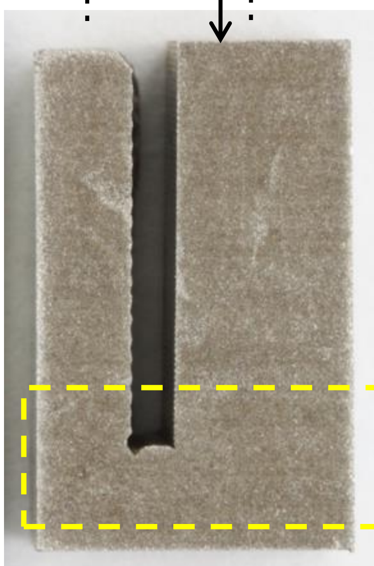
INM. Crevice Corrosion. Samples type 3-6 made of fragmented Model Tanks. Example of the Implemented study (3/4)

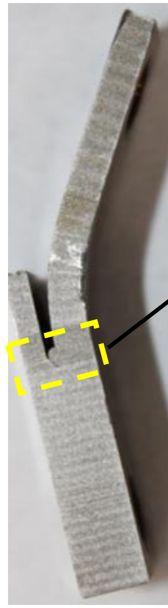
Opposite side



Front side



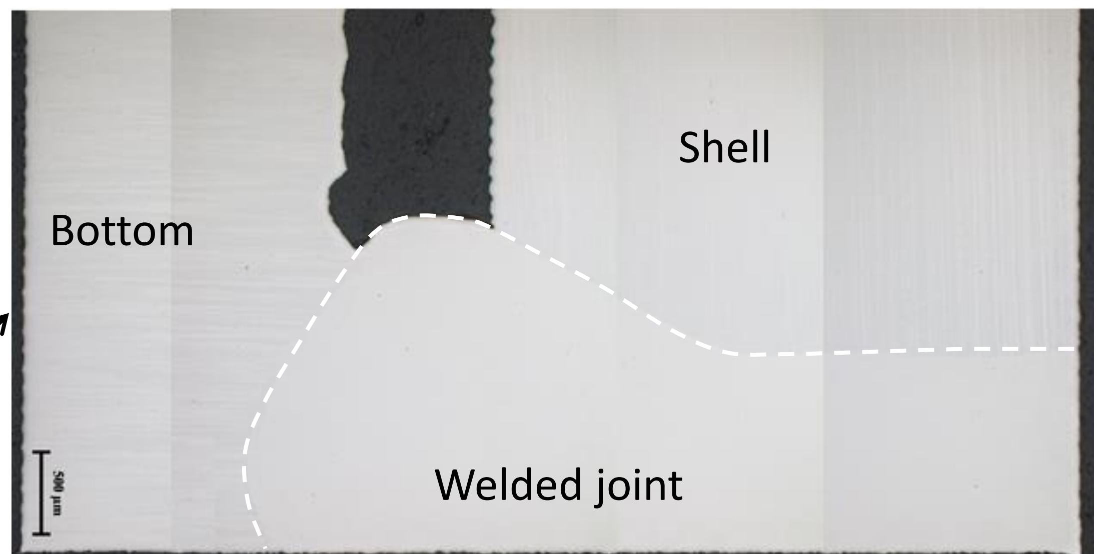




A sample for study using Lext

Welded joint's metal is fused with shell/bottom metall. Crevices/Corrosion products haven't been identified.

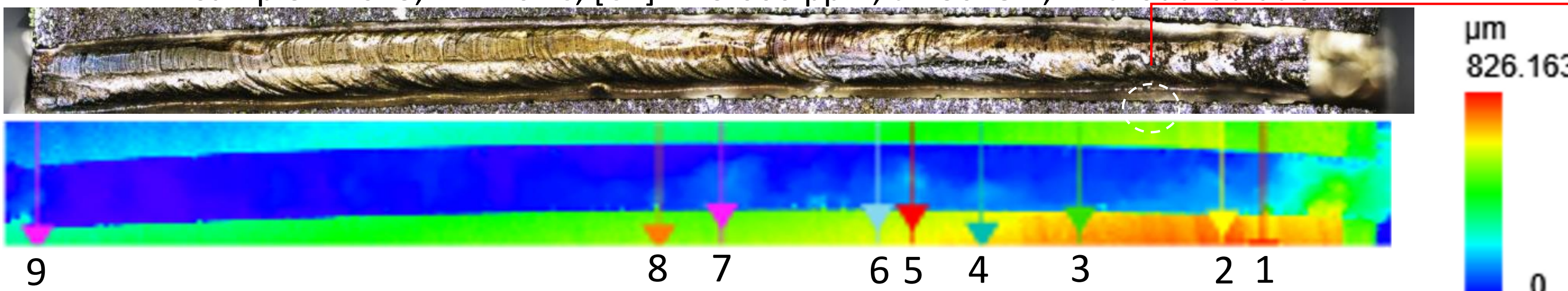
Refer to the lower left photo



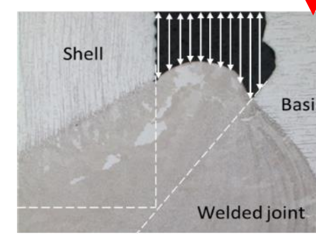
Preliminary Experimental Results

INM. Crevice Corrosion. Samples type 3-6 made of fragmented Model Tanks. Example of the Implemented study (4/4)

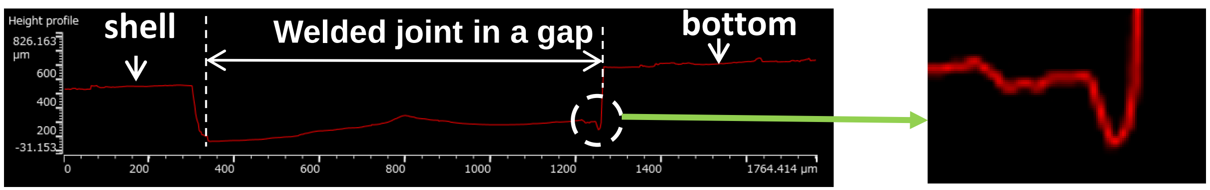
A sample № 623, T = 70 °C, [Cl-] = 29 000 ppm, t = 3048 h, without radiation



Scanning the profiles has been implemented by using the confocal laser microscope in order to define the presence of epy beginning of areas of incomplete welding as well as presence of crevice corrosion (enlarged views of profiles of the zones that are close to boundaries between welded joint and bottom parts):

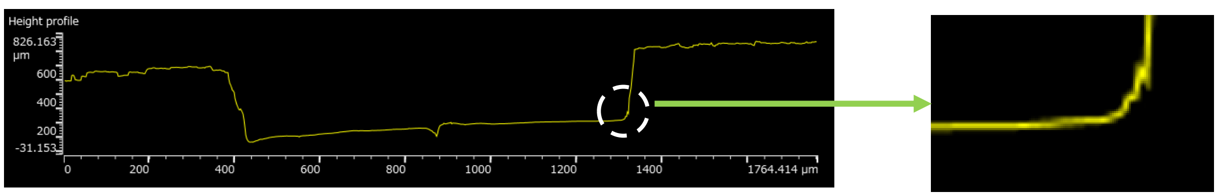


1



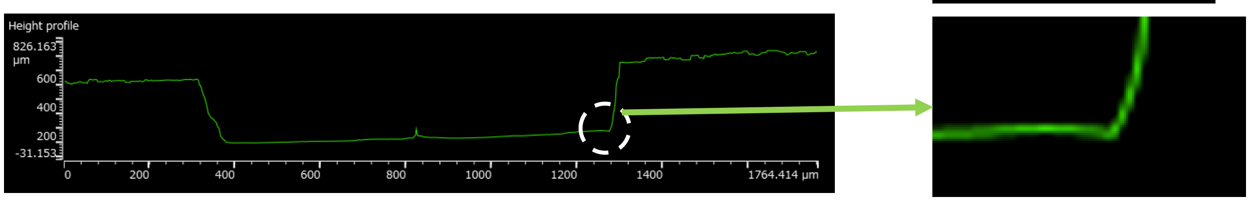
a zone with biggest (but not significant) changes of a scanning profile end. The beginning of an area of incomplete welding and presence of crevice corrosion in it hasn't been identified.

2



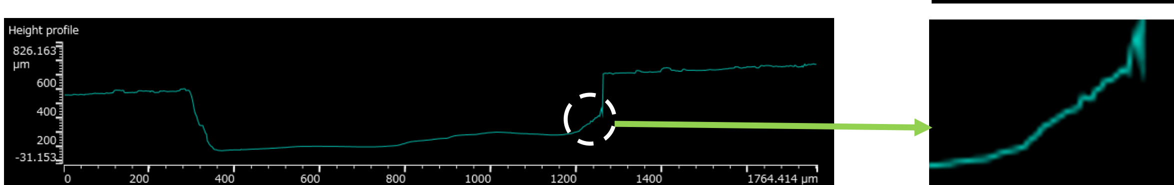
a line of transition from welded joint to bottom side has quite a smooth profile. The beginning of an area of incomplete welding and presence of crevice corrosion in it hasn't been identified.

3



a line of transition from welded joint to bottom side has quite a smooth profile. The beginning of an area of incomplete welding and presence of crevice corrosion in it hasn't been identified.

4

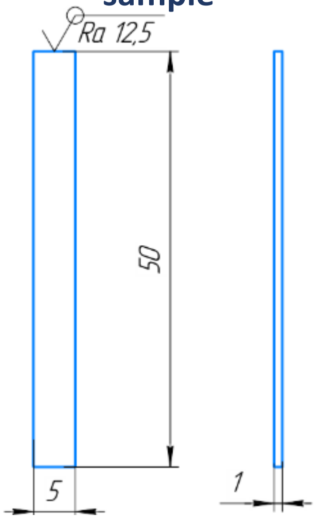


this scanning line transits to tilted plane of the bottom side. The beginning of an area of incomplete welding and presence of crevice corrosion in it hasn't been identified.

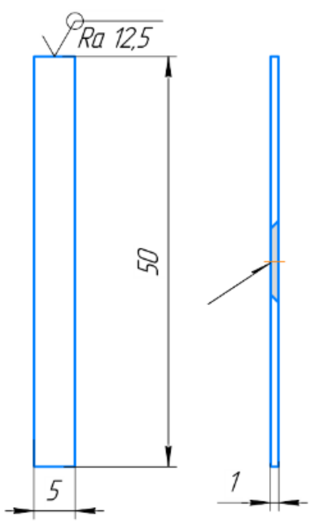
Experimental Results

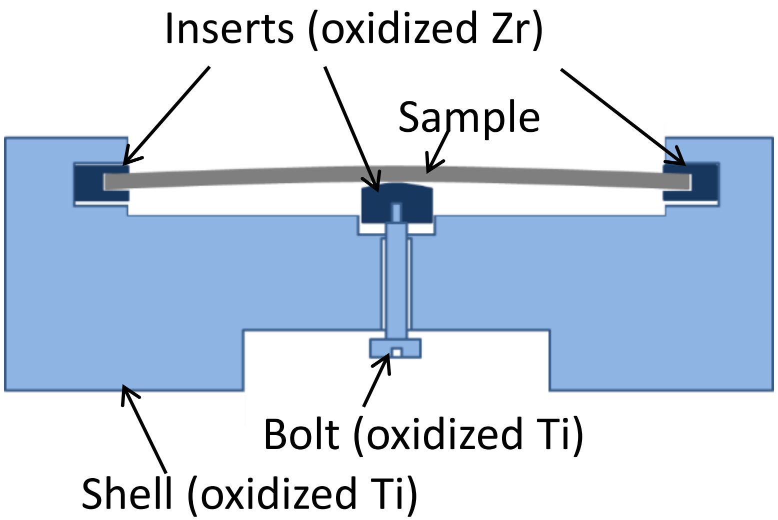
INM. Stress Corrosion cracking (1/6)

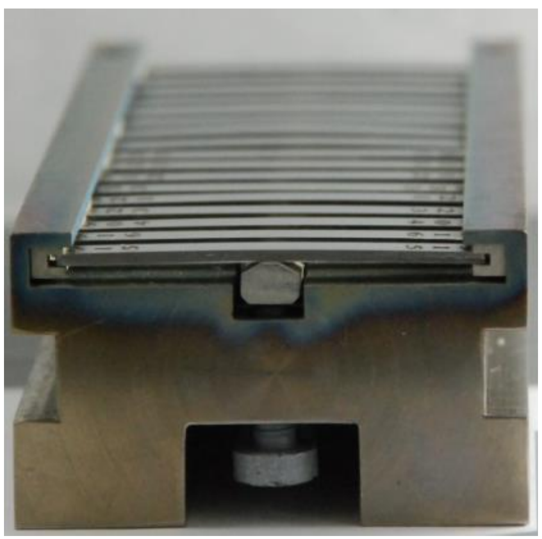
Homogeneous sample



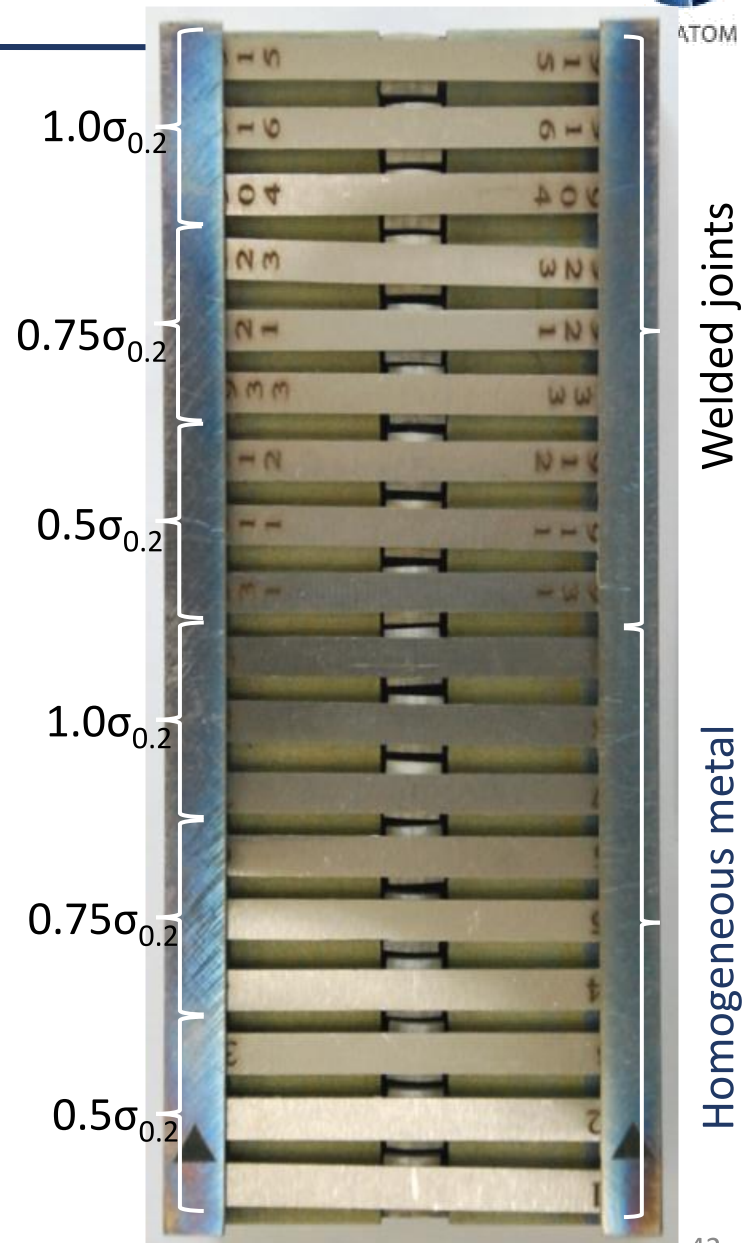
Welded joint sample







SCC installation as an assembly



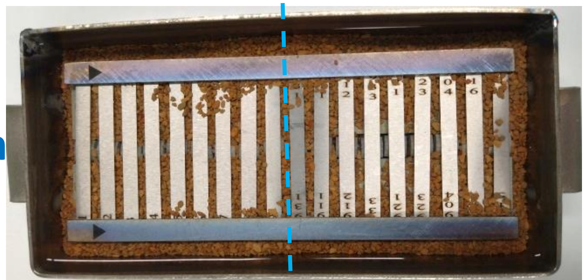
Experimental Results

INM. Stress Corrosion cracking (2/6)

25 ºC Without Radiation

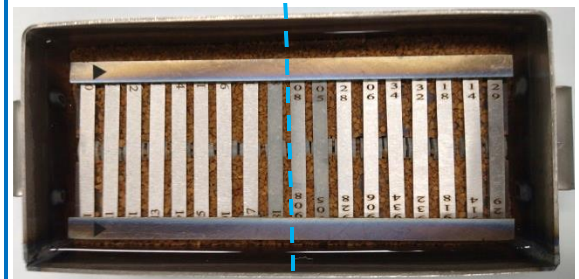
1000 h

[Cl⁻]=100 ppm



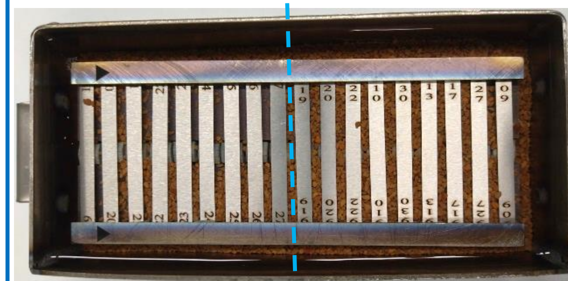
Homogeneous | Welded

[Cl⁻]=10 000 ppm



Homogeneous | Welded

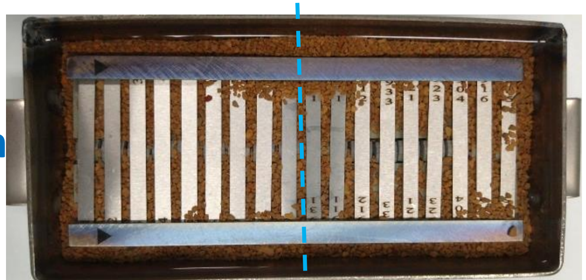
[Cl⁻]=29 000 ppm



Homogeneous | Welded

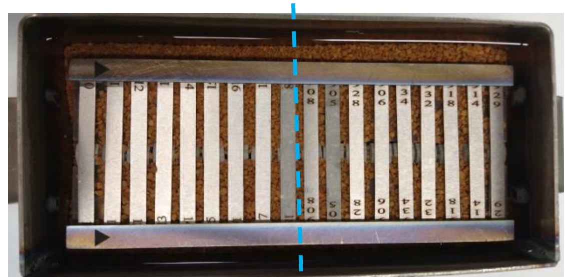
2000 h

[Cl⁻]=100 ppm



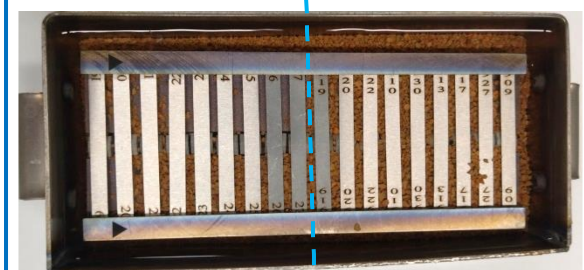
Homogeneous | Welded

[Cl⁻]=10 000 ppm



Homogeneous | Welded

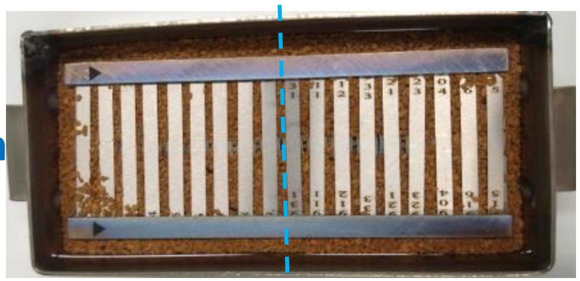
[Cl⁻]=29 000 ppm



Homogeneous | Welded

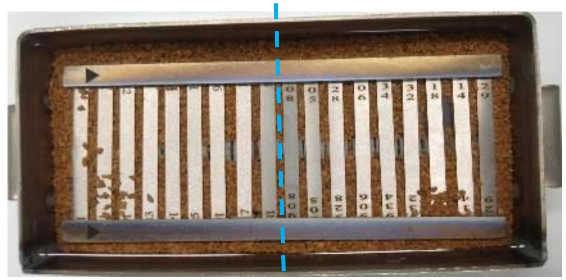
3000 h

[Cl⁻]=100 ppm



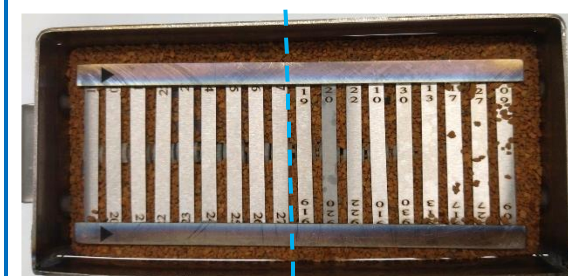
Homogeneous | Welded

[Cl⁻]=10 000 ppm



Homogeneous | Welded

[Cl⁻]=29 000 ppm



Homogeneous | Welded

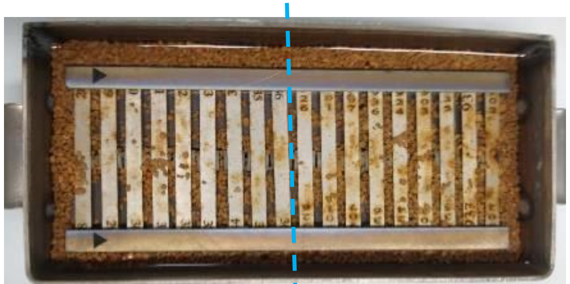
Experimental Results

INM. Stress Corrosion cracking (3/6)

70 °C Without Radiation

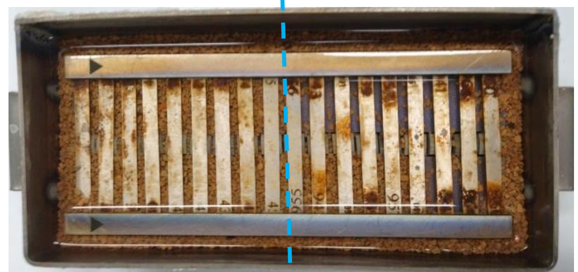
1000 h

$[Cl^-]$=100 ppm



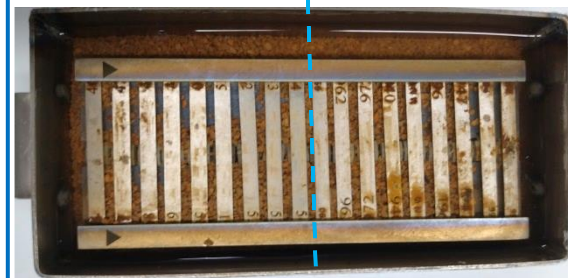
Homogeneous | Welded

$[Cl^-]$=10 000 ppm



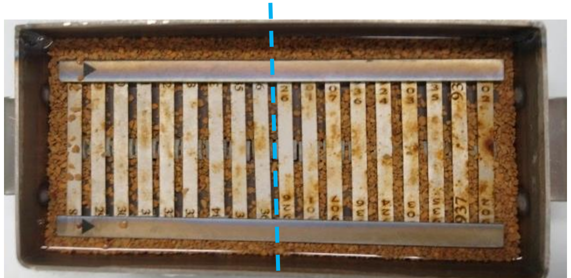
Homogeneous | Welded

$[Cl^-]$=29 000 ppm

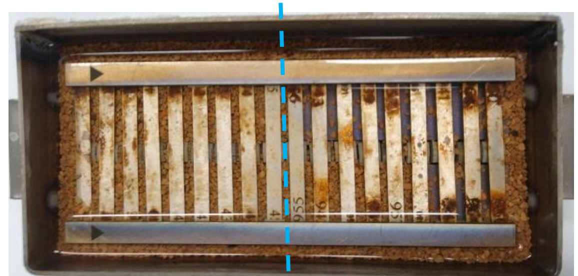


Homogeneous | Welded

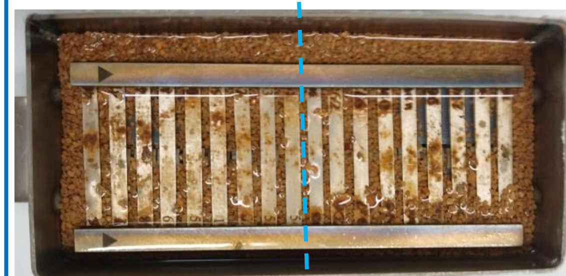
2000 h



Homogeneous | Welded

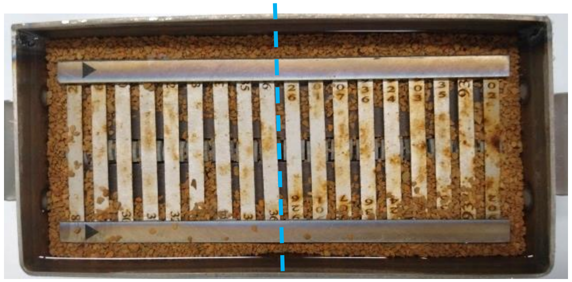


Homogeneous | Welded

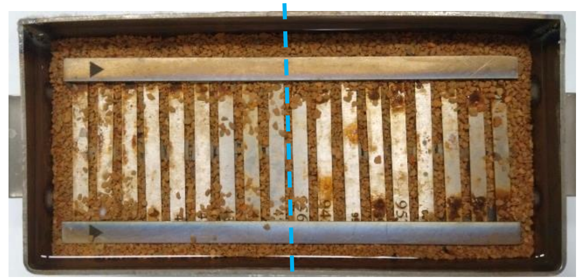


Homogeneous | Welded

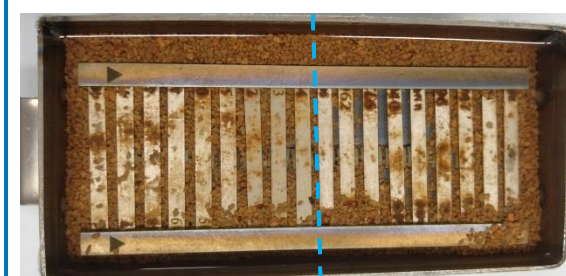
3000 h



Homogeneous | Welded



Homogeneous | Welded

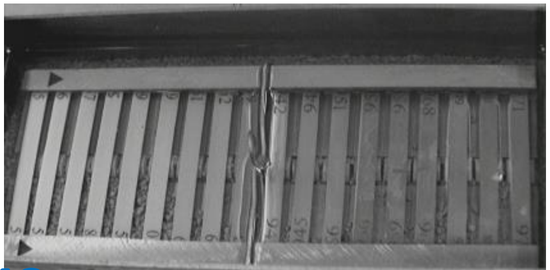
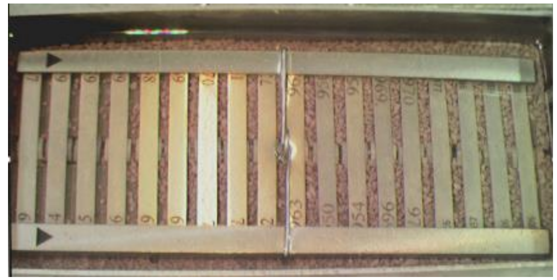
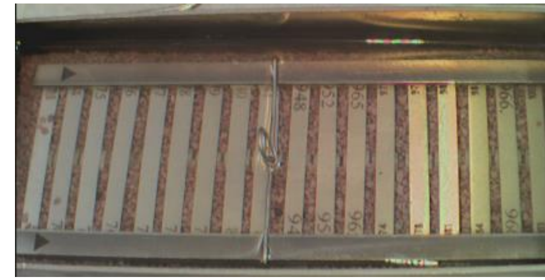
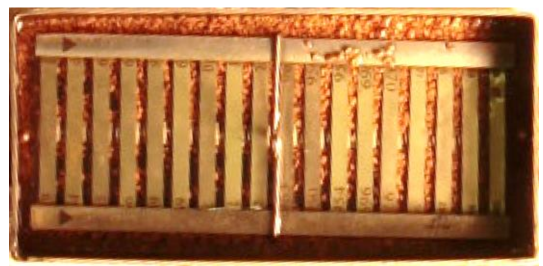
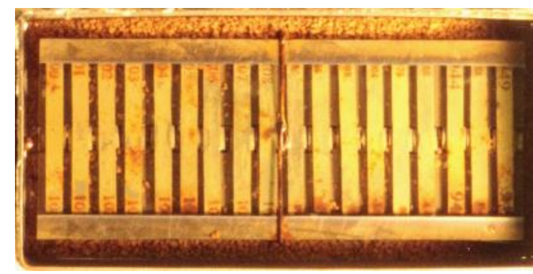
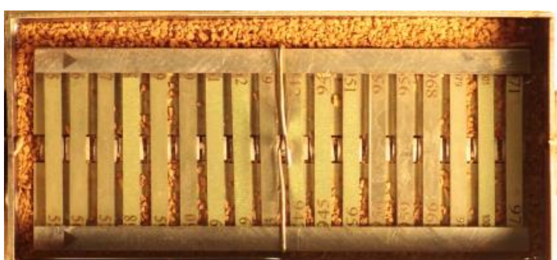
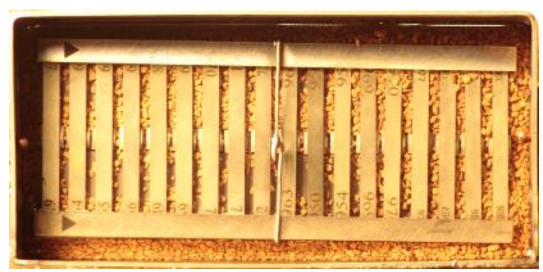
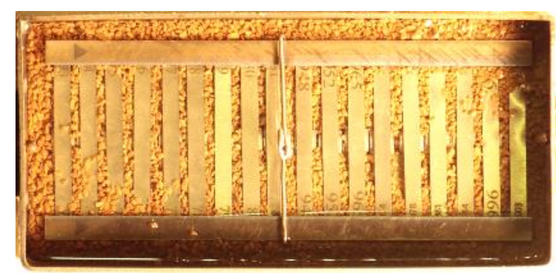


Homogeneous | Welded

Experimental Results

INM. Stress Corrosion cracking (4/6)

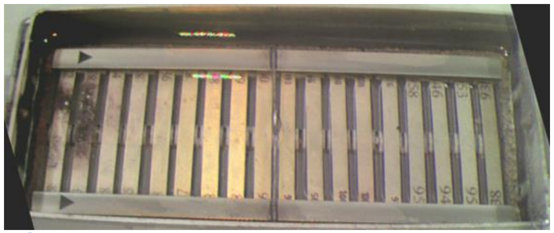
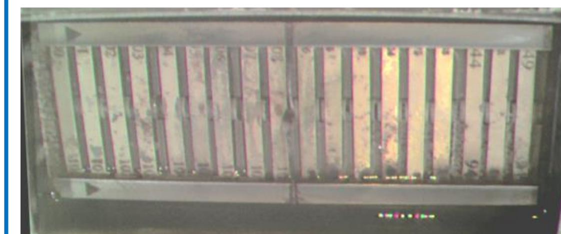
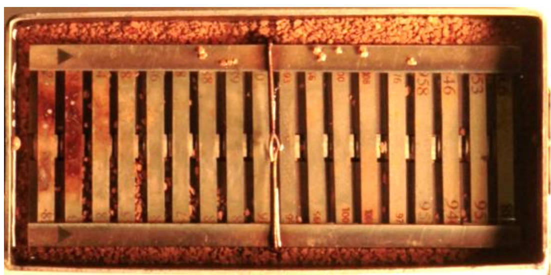
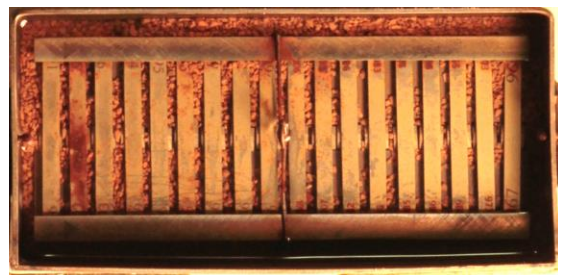
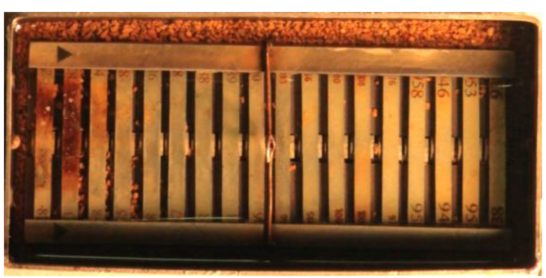
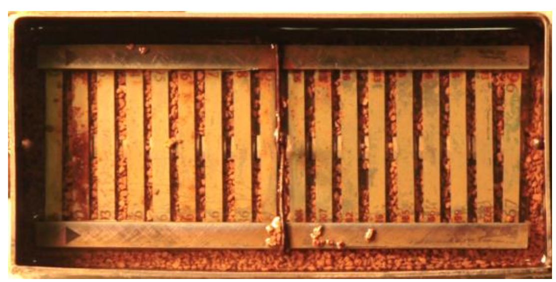
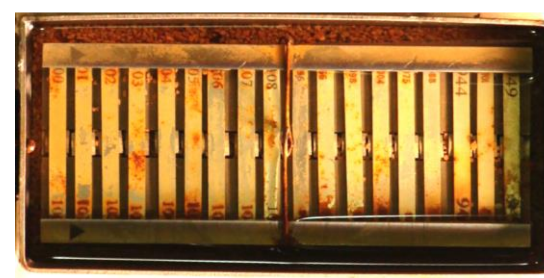
25 °C with radiation

	$[Cl^-]$=100 ppm	$[Cl^-]$=10 000 ppm	$[Cl^-]$=29 000 ppm
1000 h, ~0.87 MGy	 Homogeneous Welded	 Homogeneous Welded	 Homogeneous Welded
2000 h, ~1.7 MGy	 Homogeneous Welded	 Homogeneous Welded	 Homogeneous Welded
3000 h, ~2.5 MGy	 Homogeneous Welded	 Homogeneous Welded	 Homogeneous Welded

Experimental Results

INM. Stress Corrosion cracking (5/6)

70 °C with radition

	$[Cl^-]$=100 ppm	$[Cl^-]$=10 000 ppm	$[Cl^-]$=29 000 ppm
1000 h, ~0.87 MGy	 Homogeneous Welded	 Homogeneous Welded	 Homogeneous Welded
2000 h, ~1.7 MGy	 Homogeneous Welded	 Homogeneous Welded	 Homogeneous Welded
3000 h, ~2.5 MGy	 Homogeneous Welded	 Homogeneous Welded	 Homogeneous Welded

Experimental Results

INM Stress Corrosion cracking (6/6)

Stress corrosion cracking without radiation

t, h	D, MGy	Material \ T, ºC / [Cl-], ppm	25			70		
			100	10000	29000	100	10000	29000
1000	0	Homogeneous metal	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
		Welded joint	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
2000	0	Homogeneous metal	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
		Welded joint	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
3000	0	Homogeneous metal	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
		Welded joint	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
4000-5000	0	Homogeneous metal	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
		Welded joint	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC

Stress corrosion cracking with radiation

t, h	D, MGy	Material \ T, ºC / [Cl-], ppm	25			70		
			100	10000	29000	100	10000	29000
1000	~0.87	Homogeneous metal	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
		Welded joint	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
2000	~1.7	Homogeneous metal	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
		Welded joint	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
3000	~2.5	Homogeneous metal	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
		Welded joint	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
4000-5000	~3.4-4.25	Homogeneous metal	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC
		Welded joint	No SCC	No SCC	No SCC	No SCC	No SCC	No SCC

Corrosion Experiments Implementation
CNIITMASH's Side. Main Findings

Type of Corrosion	Type of Samples	Experimental Conditions	Main Findings of the Experiments
Crevice corrosion	Model Tanks	Six Model Tanks were manufactured to implement the crevice corrosion experiment under the following conditions: T = 25±5/ 60±2 ˚C, [Cl^-] = 10/9 500/19 000 ppm, duration 3000 h.	The use of the selected process on automatic welding led to presence of a defect of «Incomplete Welding». The width of crevice of incomplete welding area is in the following range 5 – 50 µm. Crevice corrosion development is happened not in the technological gap that is equal to 0.8 – 1 mm (a gap between bottom part and shell part of the Model Tank) but in the zone of incomplete welding. Herewith, the presence of transition area (width = 0.1 – 0.3 mm) located between technological gap and a gap formed by incomplete welding has quite a significant impact on crevice corrosion intensity. This finding has a good corresponding with results obtained during the experiments described on the slide 49 (crevice corrosion) in case of using the washer's groove equal to 0.2 mm. The process of crevice corrosion formation in the incomplete welding area is a stochastic one (in spite of same conditions, crevice corrosion could/couldn't be formed in the considered areas).
Intergranular corrosion (IGC)	Plate-like samples: (80±0.5mm)x(20 ±0.5mm)x(3±0.2 mm). Welded/non-welded samples.	Experiments were implemented under the following conservative conditions: preliminary heating – 650 ˚C during 60-min period, experiment duration – 8 hours, angle of sample bending – 90˚. Conditions: boiling water solution of $CuSO_4 \cdot 5H_2O$ (50±1g) and H_2SO_4 (250±3g) with presence of metallic Cu; Duration of boiling ~ 8 hours	In accordance with obtained experimental data, the general tendency of steel AISI 316L to IGC hasn't been identified.

Corrosion Experiments Implementation

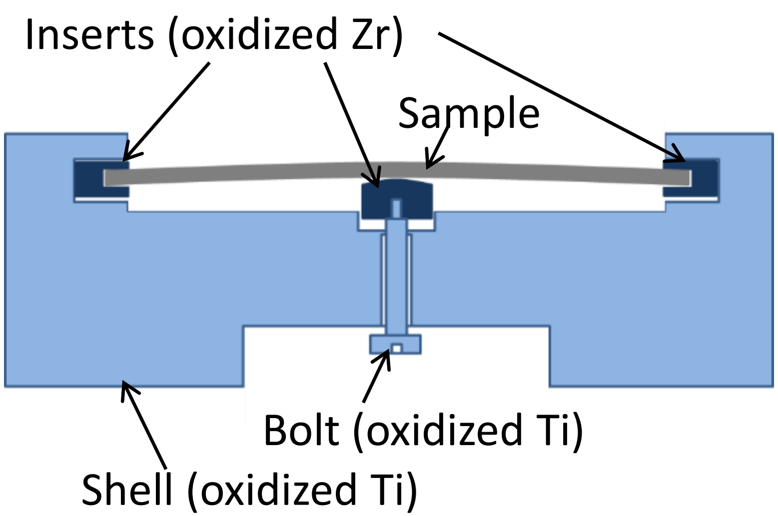
INM's Side. Main Findings (1/2)

Type of Corrosion	Type of Samples	Experimental Conditions	Main Findings of the Experiments
General(Uniform)/ pitting corrosion	Homogeneous metal – Sample 3-1, 3-12; Welded Sample – Sample 3-2, 3-13.	Experiments were implemented under the following conditions: [Cl^-] = 100, 10 000, 29 000 ppm, T = 25, 50, 70 ˚C; Duration – 1000/2000/3000/5000 h, samples: welded/non-welded, with/without radiation.	General corrosion hasn't been identified. Pitting corrosion development has been identified for experiments that have been implemented under the following conditions: - Experimental duration is more than 4000 hours; - [Cl^-] = 29 000 ppm.
Crevice corrosion	Homogeneous metal – Sample 3-3, 3-10; Welded Sample – Sample 3-4, 3-11, 3-7, 3-6.	Crevice corrosion experiments have been implemented under the following conditions: [Cl^-] = 100, 10 000, 29 000 ppm, T = 25, 50, 70 ˚C; Duration – 1000/2000/3000/5000 h	- The surface of crevice corrosion Development increases as the value of [Cl^-] increases; - The pH value has the quite high extent of influence on crevice corrosion formation; - Under the conditions of β, γ-irradiation, resistance to crevice corrosion formation for metal-nonmetal contact and for non-welded/welded samples made of SUS 316L steel at 25 ˚C is preserved only for tests duration that is up to ~ 1100 hours, and during tests that are longer than 2000 hours, foci of crevice corrosion begin to appear (including experiments with [Cl^-] = 100 ppm). - In case of increasing the experiment temperature (to 70 ˚C), crevice corrosion starts appearing (for metal-nonmetal contact) in case of [Cl^-] =100 ppm, starting from short exposition time (~ 1000 hours) and in absence of radiation; - Welded joint (in case of metal-metal contact) has the higher resistance to crevice corrosion. The first signs of crevice corrosion foci appear only at 70 ˚C in water with [Cl^-] = 29000 ppm at both exposures of ~ 1000 and ~2000 hours in conditions of irradiation presence/absence. - The presence of radiation has a high impact on crevice corrosion formation/development

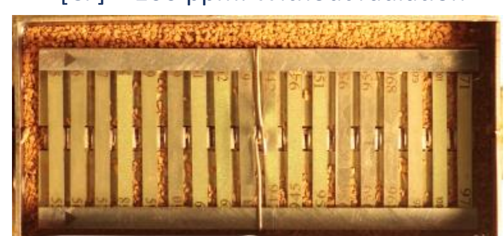
Corrosion Experiments Implementation
INM's Side. Main Findings (2/2)

ROSATOM

Type of Corrosion	Type of Samples	Experimental Conditions	Main Findings of the Experiments
Stress corrosion cracking	Homogeneous metal – Sample type 3-14 Welded Sample – Sample type 3-15 .	Stress corrosion cracking experiments have been implemented under the following conditions: T = 25, 70 ˚C; Loads: $0{,}5\sigma_{0,2}$ ($0{,}5Rp_{0.2}$) – 0.5x300 = 150 MPa; $0{,}75\sigma_{0,2}$ ($0{,}75Rp_{0.2}$) – 0.75x300 = 225 MPa; $1{,}0\sigma_{0,2}$ ($1{,}0Rp_{0.2}$) – 1.0x300 = 300 MPa. Welded/ non-welded samples have been used. Experiments have been implemented with/without radiation	Stress corrosion cracking hasn't been identified



An overall view of the samples. T = 25˚C, t = 3000 h, [Cl⁻] = 100 ppm. Without radiation



An overall view of the samples. T = 25˚C , t = 3000 h, [Cl⁻] = 100 ppm. With radiation

Prediction Model Development

Prerequisites for General/Uniform corrosion assessment

The following dependence of the depth of uniform corrosion on time, concentration of chlorine ions in water and temperature was obtained:

$$h_{gc} = 4.79 \cdot 10^{4} \cdot t^{0.5} \cdot [Cl^{-}]^{0.19} \exp(-3660/T) \qquad (1)$$

Where:
h_{gc} – maximal depth of uniform corrosion, mm;
t – duration of an experiment, h;
$[Cl^{-}]$ – Cl-ions concentration, ppm;
T – temperature, K

Formula (1) is a result of mathematical processing of the following experimental literature data on corrosion of 316L steel in seawater with different chlorine ion content obtained using electrochemical studies:

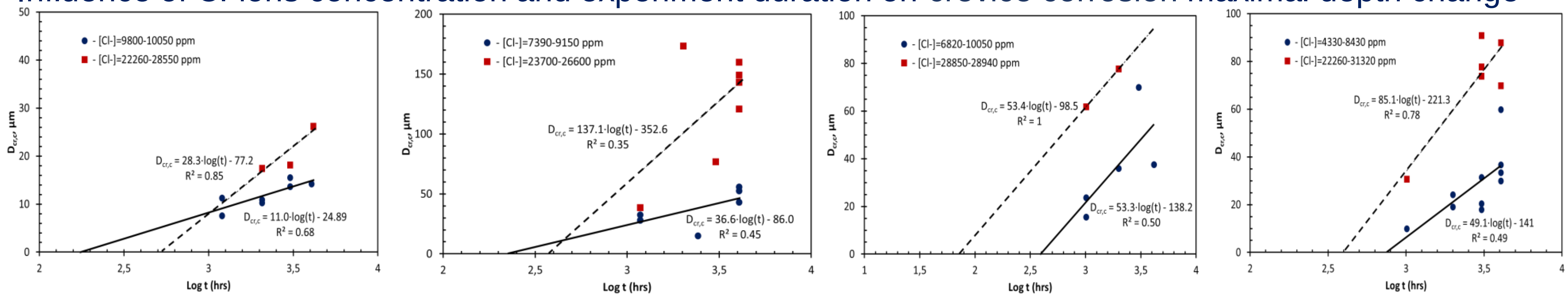
- Malik A.U., Siddiqi N.A., Ahmad S., Andijani I.N. The effect of dominant alloy addition on the corrosion behavior of some conventional and high alloy stainless steels sea water // Corrosion Science. – 1995. – Vol. 37. – No. 10. – pp. 1521–1535;
- Malik A.U., Ahmad S., Andijani I., Al-Fouzan S. Corrosion behavior of steels in Gulf seawater environment / A.U. Malik, S. Ahmad, I. Andijani, S. Al-Fouzan // Desalination, 1999. – Vol. 123. – pp. 205–213.

Prediction Model Development

Incubation Periods (PIT/CIT) Assessment (1/5)

ROSATOM

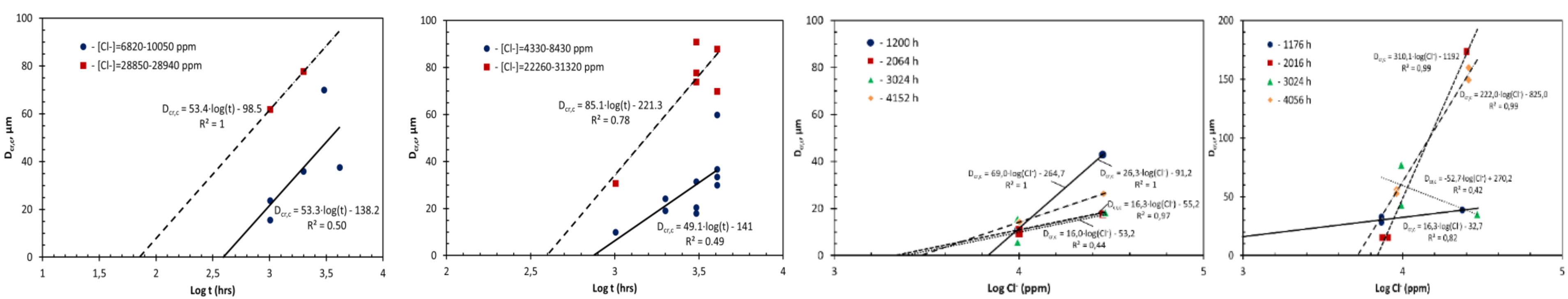
Influence of Cl-ions concentration and experiment duration on crevice corrosion maximal depth change



(a) (b) (c) (d)

a, b – 25 ˚C; c, d – 70 ˚ C; a, c – without irradiation; b, d – with irradiation

Influence of Cl-ions concentration and experiment duration on crevice corrosion maximal depth change



(a) (b) (c) (d)

a, b – 25 ˚ C; c, d – 70 ˚ C; a, c – without irradiation; b, d – with irradiation

Crevice corrosion maximal depth change as a dependence from [Cl^-] in case of fixed values of experimental duration

Prediction Model Development

Incubation Periods (PIT/CIT) Assessment (2/5)

ROSATOM

$[Cl^-]_{crit,\,cr}$ – critical concentration of Cl-ions in water meeting the crevice corrosion formation beginning, without irradiation , ppm;

$[Cl^-]^*_{crit,\,cr}$ – critical concentration of Cl-ions in water meeting the crevice corrosion formation beginning, with irradiation , ppm;

$t_{0,cr}$ - incubation period corresponding the crevice corrosion development beginning for conditions without irradiation, h;

$t^*_{0,cr}$ - incubation period corresponding the crevice corrosion development beginning for conditions with irradiation, h;

Calculated values of $[Cl^-]_{crit,cr}$ (ppm)

T, ºC	Experimental conditions	Duration of experiment, h	$[Cl^-]_{crit,cr}$, ppm
25	Without irradiation	1200	6815
		2064	2415
		3024	2125
		4152	2900
	With irradiation	1008	5215
		1992	2650
		3048	-
		4056	-
70	Without irradiation	1176	325
		2016	6975
		3024	-
		4056	5210
	With irradiation	1008	4515
		1992	-
		3048	1815
		4056	435

For conditions without radiation:

$$[Cl^-]_{crit,cr} = 1,94 \cdot 10^8 \cdot t^{-0.67} \cdot exp(-1745/T),\ R^2=0.73;\ n=6$$

For conditions with radiation:

$$[Cl^-]^*_{crit,cr} = 1,34 \cdot 10^7 \cdot t^{-1.36} \cdot exp(-500/T),\ R^2=0.85;\ n=5$$

For conditions without radiation:

$$t_{0,cr} = exp\{(19.08 - 1745/T - Ln[Cl^-]_{crit,cr})/0.66\}$$

For conditions with radiation:

$$t^*_{0,cr} = exp\{(16.41 + 500/T - Ln[Cl^-]^*_{crit,cr})/1.35\}$$

Where T - temperature

Prediction Model Development

Incubation Periods (PIT/CIT) Assessment (3/5)

ROSATOM

To estimate the incubation period of time required for the formation of pitting and the development of crevice corrosion on austenitic chromium-nickel steel, the following expressions are used:

$$PIT = k \cdot 10^{\frac{PREN(1-\Delta Ec,pit)}{2 \cdot log[Cl-]}}, \quad (2)$$

$$CIT = k \cdot 10^{\frac{PREN(1-\Delta Ec,cr)}{3 \cdot log[Cl-]}}, \quad (3)$$

Where:

PIT – incubation period before pittings formation, h;

CIT – incubation period before launching the crevice corrosion, h;

k – a constant, h;

$[Cl^-]$ - the chloride concentration, ppm;

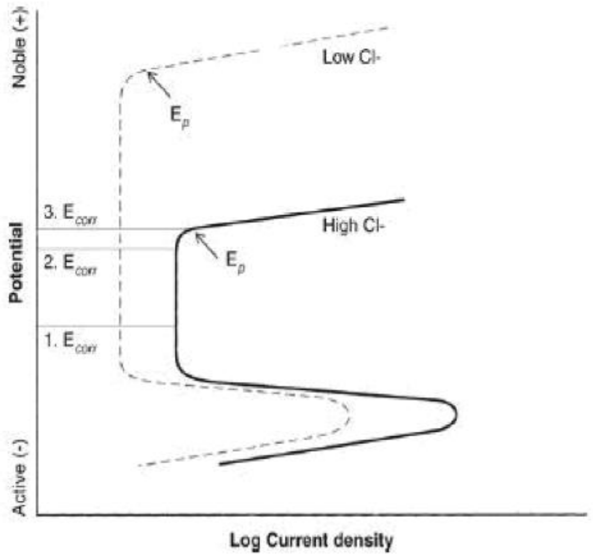
PREN – numerical equivalent of stainless steel resistance to local corrosion, that is calculated as follows:

PREN = %Cr+3.3·%Mo+16·%N (3) (for stainless steels with Mo concentration less then 3% weight);

$$E_c = 925.45 - 3.2 \cdot (T) + 52.6 Log[Cl^-] \quad (4)$$

$$\Delta E_{c,pit} = E_c - E_{pit} \quad (5)$$

$$\Delta E_{c,cr} = E_c - E_{rup} \quad (6)$$



Where:

E_c – potential of corrosion, V (SHE),

E_{pit} – potential of pittiing formation, V (SHE),

E_{rup} – potential of crevice corrosion launching, V (SHE)

Prediction Model Development

Incubation Periods (PIT/CIT) Assessment (4/5)

E_{pit} and E_{rup} have been calculated as follows:

$$E_{pit} \cong \frac{298}{T+273} \cdot \left(\frac{PIN}{25} + log(1+\nu) - 0.25 \cdot log\left[\frac{Cl}{36}+1\right] + \frac{pH-7}{25} \right) \quad (7)$$

$$E_{rup} \cong \frac{298}{T+273} \cdot \left(\frac{PREN}{25} - 0.25 \cdot log\left[\frac{Cl}{36}+1\right] - 0.20 \right) \quad (8),$$

where

E_{pit}, E_{rup}, T, [Cl] – description is shown on the slide № 54,

v – a speed of water moving, m/s;

PIN - Pitting Initiation Number, is a function of stainless steel composition

PIN = PREN - 0.1%Mn - 100%S

Processing of electrochemical measurements of the pitting corrosion of 316L steel gives the following expression for the difference in the pitting resistance bases of base metal samples in water containing chlorine ions:

$$\Delta E_b - \Delta E^*_b = 972.7 - 157.3 Log[Cl^-] - 0.75T; R^2=0.98; n=6 \quad (9)$$

where

ΔE_b - pitting resistance base for conditions without radiation, mV

ΔE^*_b - pitting resistance base for conditions with radiation, mV

$[Cl^-]$ – Cl-ions concentration, ppm

T – temperature, K

(7), (8) - Luciano Lazzari. Engineering Tools for Corrosion. Design and Diagnosis European Federation of Corrosion (EFC). Series 2017. 4 - Pitting and Crevice Corrosion. Pages 61-80. DOI: http://dx.doi.org/10.1016/B978-0-08-102424-9.00004-5.

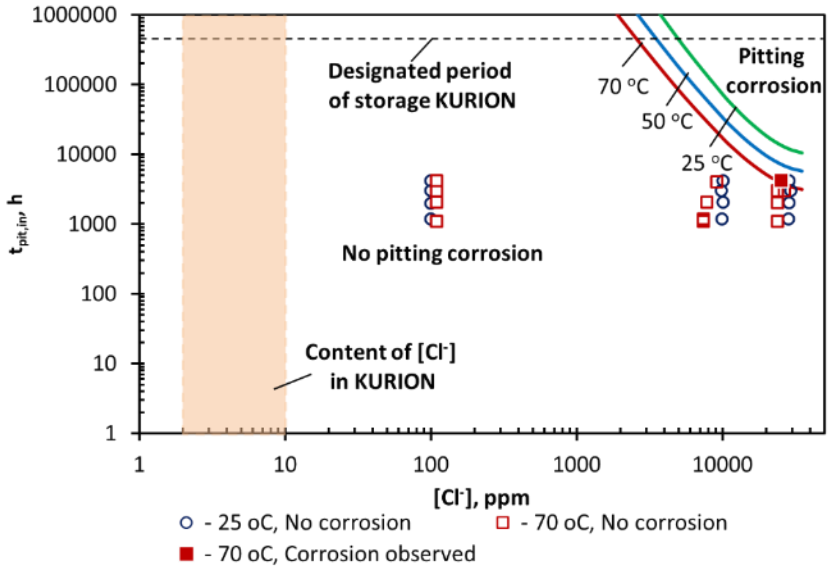
Prediction Model Development

Incubation Periods (PIT/CIT) Assessment (5/5)

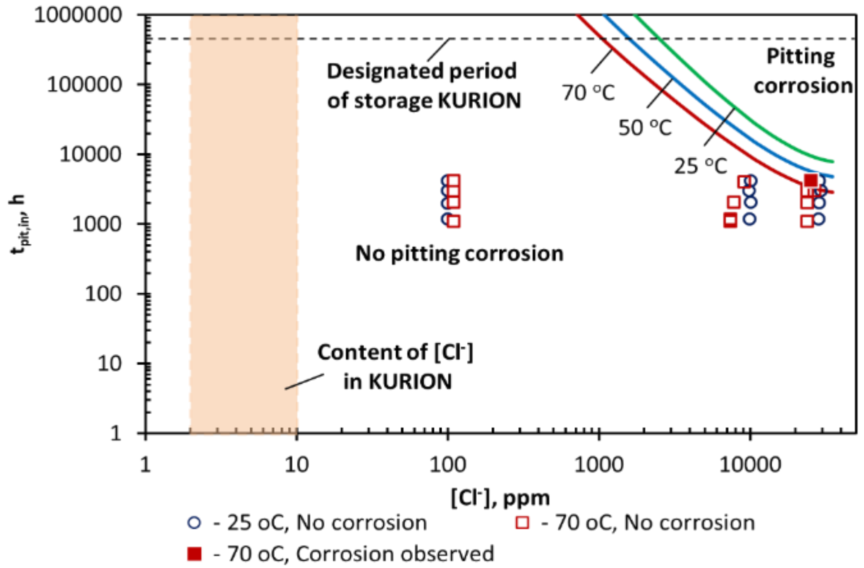
ROSATOM

Results of PIT calculation (in hours, in accordance with expressions (2), (4), (5), (7), (9)

Medium conditions	T, °C	[Cl-], ppm					
		10	100	300	1000	10000	29000
Without radiation	25	3.90E+27	9.07E+12	8.36E+09	4.39E+07	7.96E+04	1.11E+04
	50	3.96E+25	1.04E+12	1.60E+09	1.23E+07	3.52E+04	5.67E+03
	70	1.27E+24	2.05E+11	4.57E+08	4.65E+06	1.88E+04	3.36E+03
With radiation	25	1.08E+20	1.52E+10	1.17E+08	2.90E+06	3.30E+04	8.13E+03
	50	1.89E+18	2.31E+09	2.79E+07	9.73E+05	1.67E+04	4.70E+03
	70	9.42E+16	5.65E+08	9.55E+06	4.28E+05	9.97E+03	3.07E+03



(a)



(b)

a – without radiation; b – with radiation

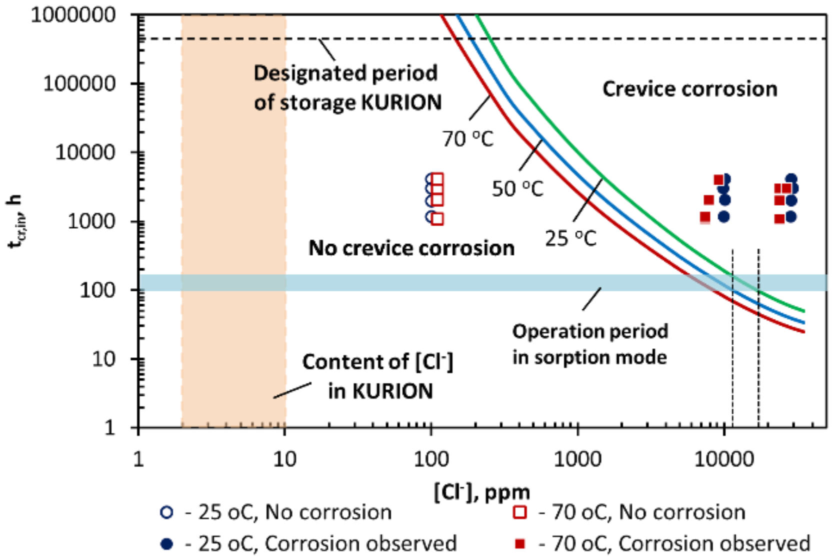
Areas of pitting corrosion resistance as well as tendency to pitting corrosion for steel AISI 316L

In accordance with obtained data, steel AISI316L will be resistant to pitting corrosion.

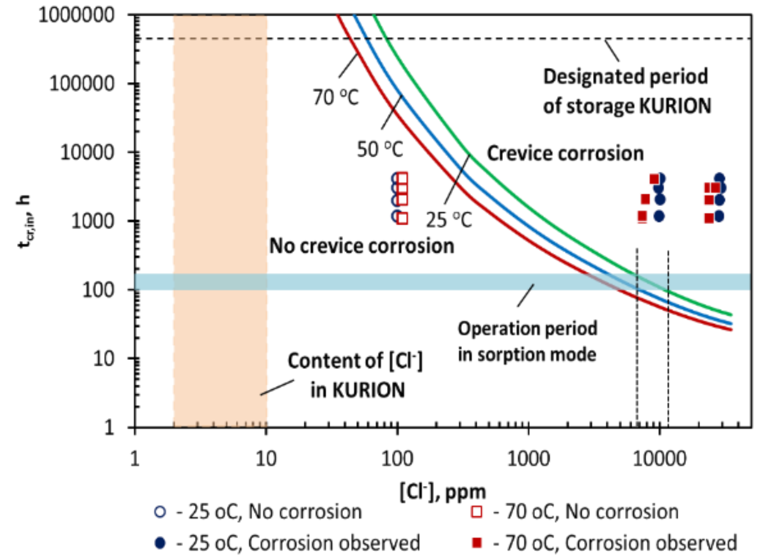
Results of CIT calculation (in hours, in accordance with expressions (3), (4), (6), (8), (9)

Incubation period values (in hours) before crevice corrosion development beginning for steel AISI316L in diluted and saturated (in terms of Cl-ions concentration) artificial seawater

Medium conditions	T, °C	[Cl-], ppm					
		10	100	300	1000	10000	29000
Without radiation	25	1.94E+15	1.85E+07	2.48E+05	9.67E+03	1.94E+02	5.74E+01
	50	1.42E+14	5.06E+06	9.28E+04	4.57E+03	1.22E+02	3.93E+01
	70	1.97E+13	1.89E+06	4.37E+04	2.56E+03	8.44E+01	2.90E+01
With radiation	25	2.94E+10	2.46E+05	1.39E+04	1.54E+03	1.07E+02	4.65E+01
	50	3.06E+09	8.11E+04	6.02E+03	8.24E+02	7.37E+01	3.46E+01
	70	5.62E+08	3.52E+04	3.20E+03	5.11E+02	5.50E+01	2.73E+01



(a)



(b)

a – without radiation; b – with radiation

Areas of crevice corrosion resistance as well as tendency to crevice corrosion for steel AISI316L

Prediction Model Development

Assessment of crevice corrosion depth (2/2)

CIT time dependencies (polynomic dependencies based on the table and graphic data presented on the slide57):

Under the conditions without radiation

$y(25\ ^{\circ}C) = 0.1157x^4 – 1.7001x^3 + 9.6989x^2 – 26.962x + 34.131;$

$y(50\ ^{\circ}C) = 0.1077x^4 – 1.5821x^3 + 9.0214x^2 – 25.063x + 31.665;$

$y(70\ ^{\circ}C) = 0.1016x^4 – 1.4923x^3 + 8.5068x^2 – 23.625x + 29.801;$

Under the conditions with radiation

$y^*(25\ ^{\circ}C) = 0.0618x^4 – 0.9287x^3 + 5.4718x^2 – 15.92x + 21.784;$

$y^*(50\ ^{\circ}C) = 0.0549x^4 – 0.8269x^3 + 4.8864x^2 – 14.272x + 19.644;$

$y^*(70\ ^{\circ}C) = 0.0497x^4 – 0.75x^3 + 4.4457x^2 – 13.036x + 18.041;$

where $y = \log(t_{o,cr});$

$y^* = \log(t^*_{o,cr})$

$x = \log[Cl-]$ ($_{in\ ppm}$).

$D_{cr,max}$ - maximal depth of crevice corrosion

Mathematical processing of the obtained data

$$D_{cr,max} = (1490±5)·(t-t_{cr,in})^{(0.29±0.12)}·[Cl^-]^{(0.63±0.09)}·exp(-(3860±240)/T),\ R^2 = 0.95,\ n = 23.$$

without radiation

$$D^*_{cr,max} = (9.78±2.33)·(t-t_{cr,in})^{(0.44±0.05)}·[Cl^-]^{(0.28±0.05)}·exp(-(1510±160)/T),\ R^2 = 0.92,\ n = 32.$$

with radiation

Prediction Model Development
Assessment of Stress Corrosion Cracking

To determine the operating time for the first failure of samples made of austenitic stainless steels due to transcrystalline corrosion cracking, it is recommended to use the following expression:

$$lnt_{кр} = lnL - 17.79 - 0.5lnC_{O2} - 1.5lnC_{Cl} + ln[exp\{U_o - (\sigma_p/2^{1/2} - \alpha Gb\rho^{1/2})N_A\gamma\}/RT + exp\{U_o - (\sigma_p/2^{1/2} + \alpha GbN\rho^{1/2})N_A\gamma\}/RT]$$

where $t_{кр}$ – time before first failure of a tube , h;

C_{O2} and C_{Cl} – Cl-ions concentration in water, μg/kg;

U_o – energy of activation of a process of dislocated atom self-diffusion, kJ/mol (for Russian steel 08X18H12T U_o = 130,94 kJ/mol);

γ – activation volume, 10^{-28} m^3;

L – thickness of a pipe wall, mm;

b - Burgers vector (for steel 08X18H12T $b = 2{,}53\cdot10^{-10}$ m);

ρ – density of dislocations, m^{-2};

G - shear modulus, N/m^2;

N_A - Avogadro number;

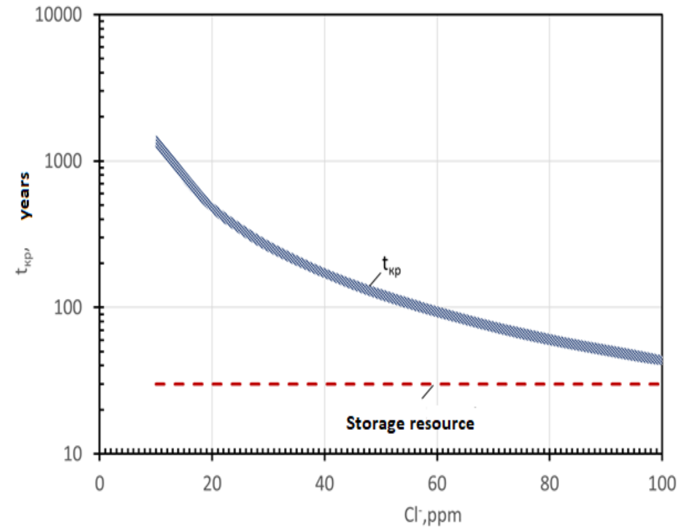
α - coefficient, α = 0,1;

N – number of dislocations in microcluster;

R = 8,317 J/(mol·K) – universal gas constant;

T - temperature, K;

σ_p - total tensile stress in metal, kPa.



Influence of Cl-ions concentration on critical time before appearance of stress corrosion cracking for steel AISI316L

There is no risk related to the Stress Corrosion Cracking during the 50-year storage of the KURION/SARRY adsorption towers

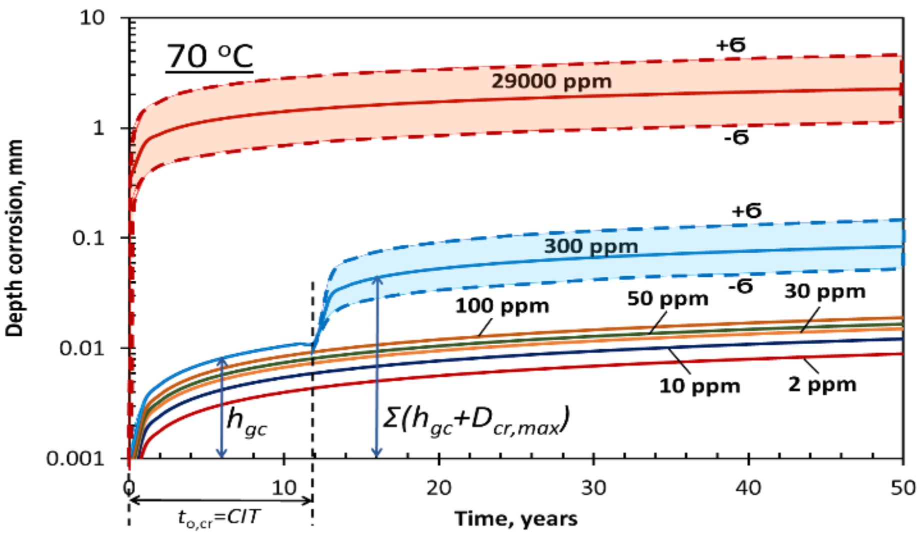
Prediction Model Development

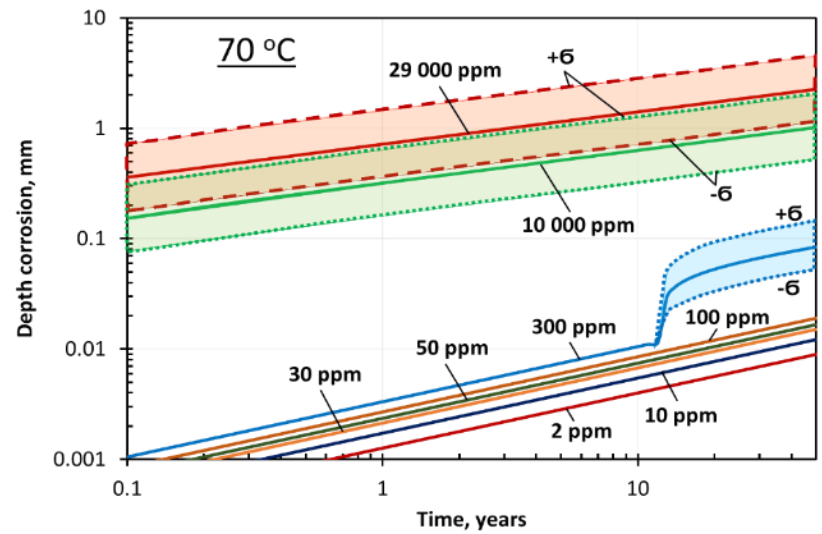
50-year Forecast Development. Without radiation

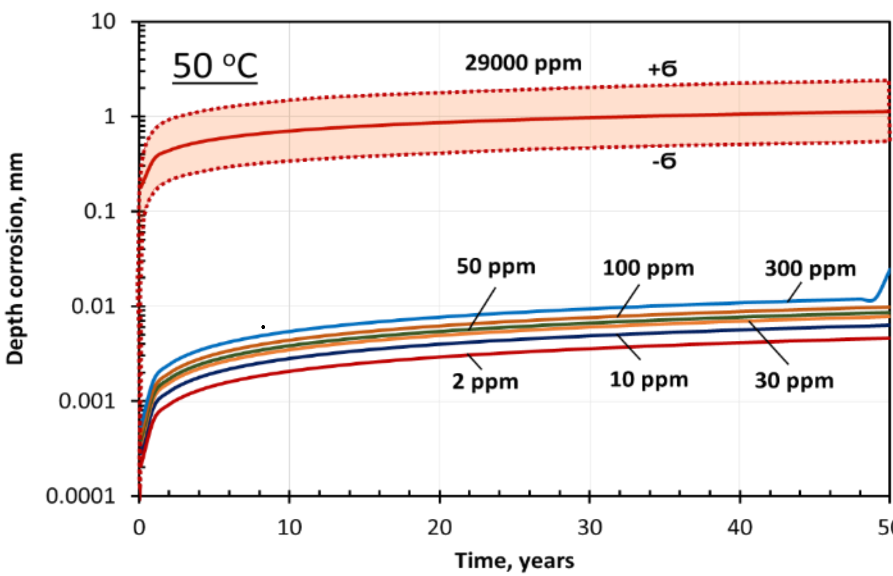
A total corrosion depth (h) has been defined as follows, where:

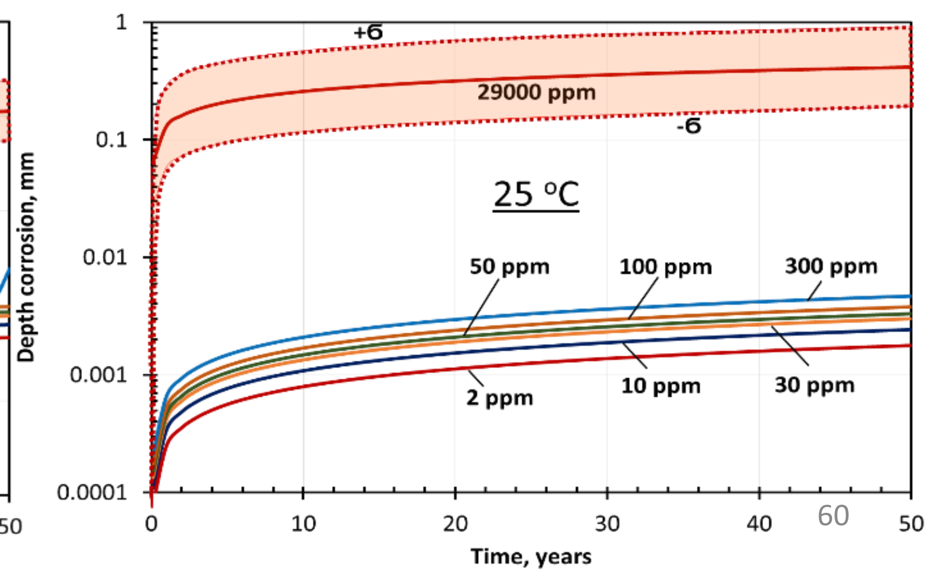
$h = h_{gc}$, if t < CIT; (h_{gc} - general corrosion. See p. 51)

$h = h_{gc} + D_{cr,max}$, if t ≥ CIT ($D_{cr,max}$ see p. 58)



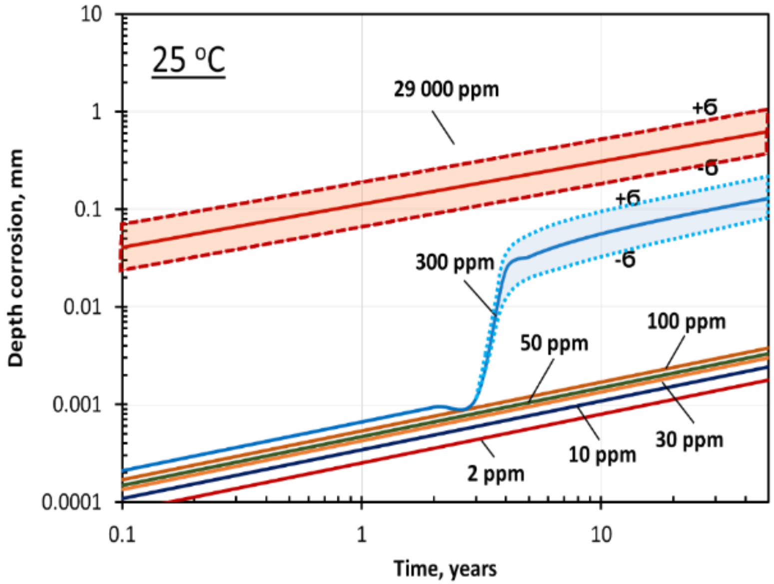


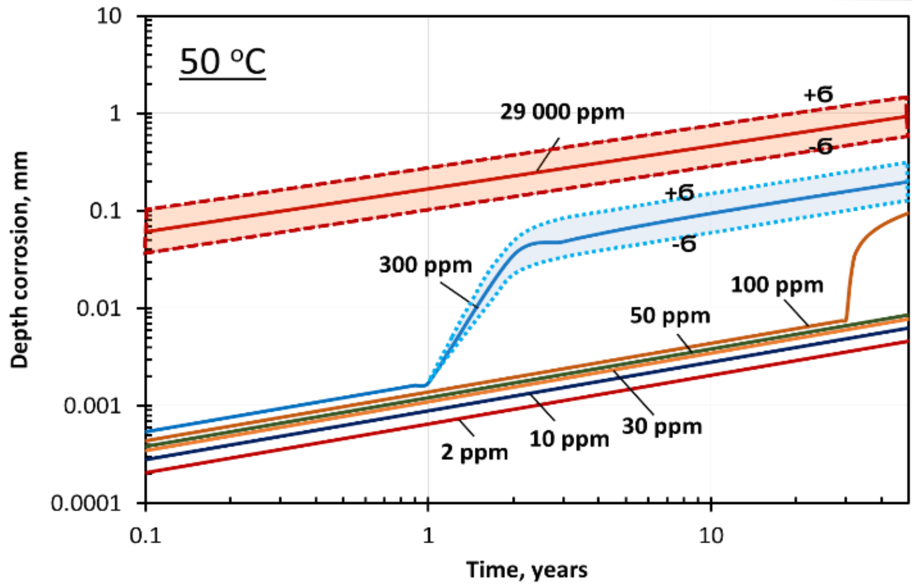


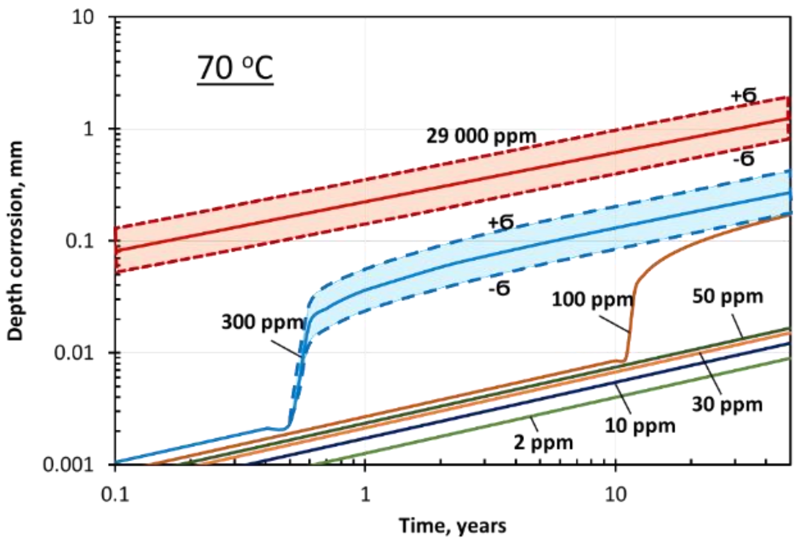


Prediction Model Development

50-year Forecast Development. With Radiation







There is no risk regarding the integrity loss during the KURION/SARRY adsorption towers storage within their 50-year storage under the 1F's storage conditions

Applicability Limits of the Prediction Model

ROSATOM

As for temperature (T):

An Applicable range of T: **10 – 70 ˚C**. There is no possibility to extrapolate temperature higher than 70 ˚C, due to the fact that in case when temperature is higher than 70 ˚C, a mechanism of corrosion occurrence will be different – this is due to oxygen dissolution decreasing in water (when T> 70 ˚C).

As for [Cl-]:

An Applicable range of [Cl^-]: **2 – 29 000 ppm**. IN this range of [Cl^-] there is a single law of corrosion processes occurrence. In case of [Cl^-] value higher than 29 000 ppm (in accordance with existing literature data) there is slowing down corrosion processes – it is due to oxygen dissolution decreasing in water when [Cl^-] > 29 000 ppm.

As for time (t):

An Applicable range of t: up to **160 000 hours** (to provide the parameters deviation equal to deviations obtained when implementing the experiments). In accordance with accepted theory of extrapolation robustness, it is allowed to provide the time extrapolation not higher than 1 -1,5 magnitude order of experiment duration. Thus, for our case t = $5000x10^{1.5}$ = 160 000 hours - in this case, the calculated value deviation will correspond to the deviation obtained in the experiments. When extrapolating beyond this value, the error of the determined value will be higher.

Formulation of a countermeasures set

The following countermeasures have been formulated taking into account the obtained 50-year forecast (for a case when there are no risks related to the integrity loss of the KURION/SARRY adsorption towers during their 50-year storage). Mainly, formulated countermeasures are related to increasing the created 50-year forecast:

- It is proposed to implement the calculation of possible values for crevice corrosion depth (using the expressions obtained during this project) for real operation parameters of the KURION/SARRY adsorption towers;
- Based on the calculated data, it is proposed to develop a risk scale on possibility of integrity loss for the KURION /SARRY adsorption towers;
- It is proposed to implement a KURION /SARRY adsorption towers ranking by degree of risk related to integrity loss;
- It is proposed to develop a list of organizational and technical measures for each class (associated with a certain formulated degree of risk) of the ranked KURION/SARRY adsorption towers.

Achieved Results.
Main Findings/Recommendations

ROSATOM

Achieved Results

(i) A full set of data related to the KURION/SARRY adsorption towers design and storage conditions has been prepared and studied;
(ii) A set of Corrosion Mechanisms that can affect the integrity of the KURION/SARRY adsorption during its 50-year storage has been formulated;
(iii) A research Program describing the methodology of corrosion experiments implementation has been developed (experiments under the conditions close to the real storage conditions) in order to collect the required experimental data for Prediction Model Development;
(iv) Corrosion experiments have been implemented (5000-hour experiments). Experimental data has been processed
(v) Prediction Model has been developed
(vi) 50-year forecast has been developed/Countermeasures Formulated

Main Findings

(i) In accordance with created Prediction Model as well as 50-year forecast (related to the KURION/SARRY storage) there is no expectation regarding the launching and development of Corrosion Processes inside the KURION/SARRY adsorption towers during their 50-year storage (under the accepted storage conditions).
(ii) There is no risk regarding the Crevice/Pitting corrosion launching for the following ranges of storage conditions during the 50-year storage $[Cl^-]$ = 2 -100 ppm, t = up to 70 ˚C
(iii) β/γ activity as well as pH have quite a high influence on Corrosion development

Recommendations

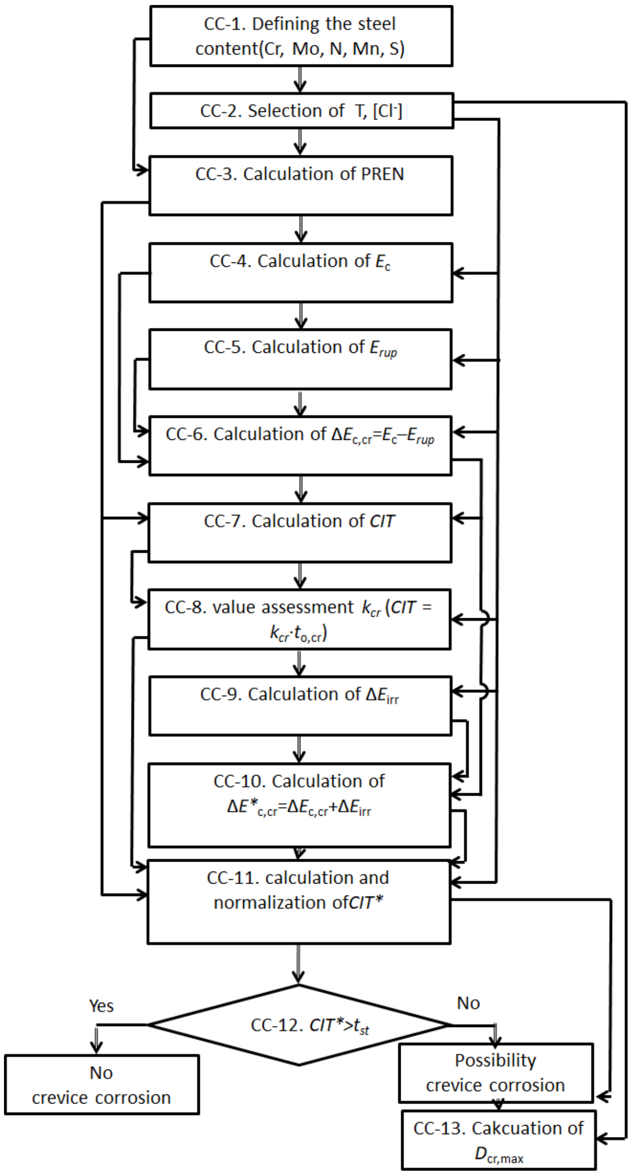
(i) Russian side recommends to take into account the KURION/SARRY operation conditions (operation conditions in the form of the following dependence T = f(t), $[Cl^-]$ = f(t)) in order to improve the Modelling.
(ii) Russian side recommends to take into account the formulated Countermeasures set in order to implement ranking (ranking based on the following parameters- T, $[Cl^-]$) the KURION/SARRY adsorption towers state (from the point of view of potential risk).

Appendix

Logical Schemes of assessment of Pitting/Crevice Corrosion possibility

ROSATOM

Crevice Corrosion:



Pitting Corrosion: