Electron Irradiation Test Facilities and methodologies for corrosion assessment and design of reactor structural materials

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Content

- **Introduction**

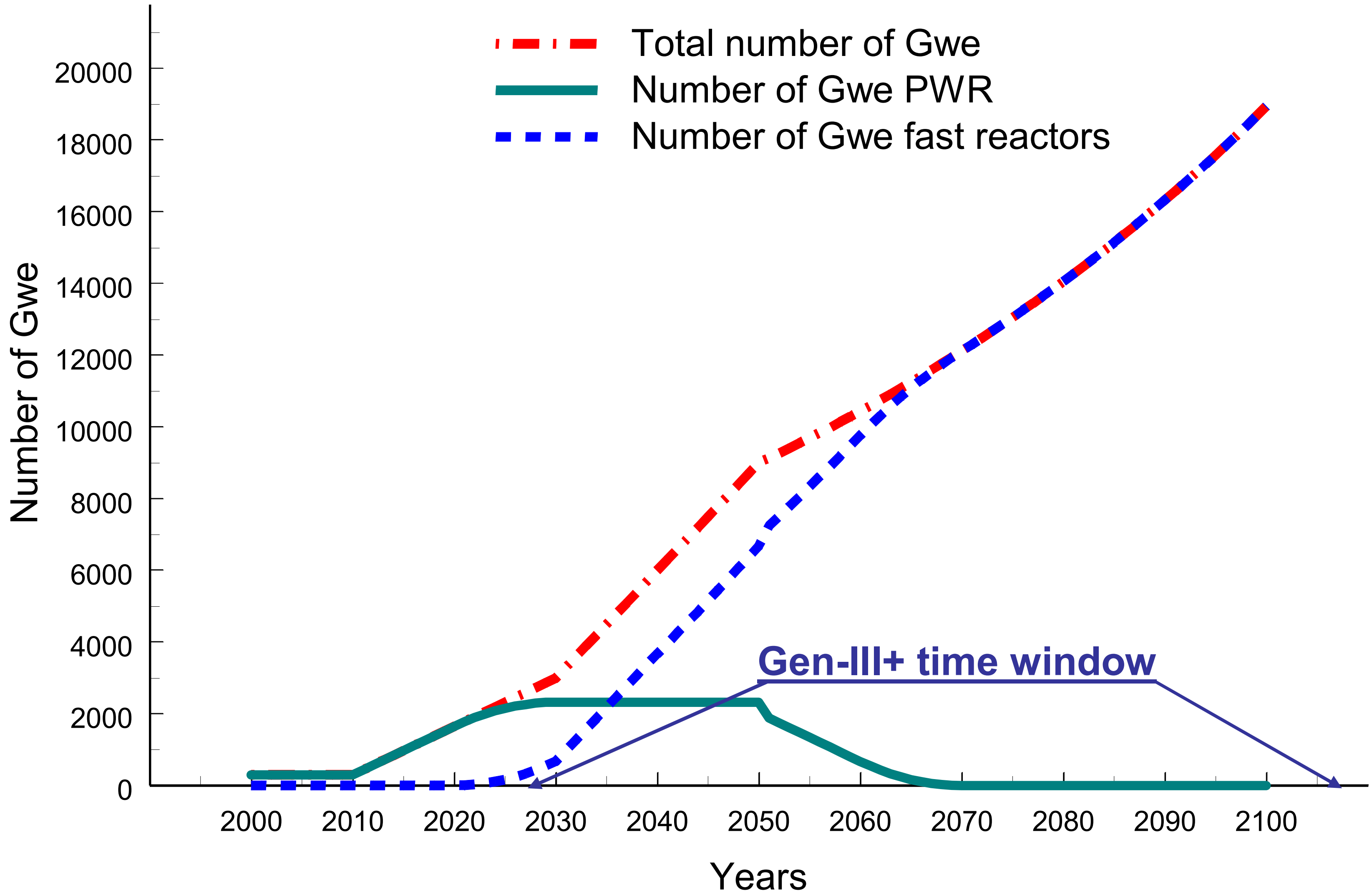
  - Nuclear energy engineering in Ukraine: current state and prospective

  - Design, tests, assessment of the structural materials for reactors of the G-III+ and G-IV generations is a pressing task
- **Electron irradiation test facilities as efficient tools for investigation of the irradiation stimulated**
  - **Corrosion,**
  - **Stress-corrosion cracking**
  - **Corrosion enhanced fatigue**
- **Some instructive results of the irradiation stimulated corrosion of advanced nuclear structural materials in molten salts and supercritical water**
- **Summary**
- **Outlook**

Nuclear Power Engineering in Ukraine

- **15 nuclear units of the G-II of total installed capacity of 13835 MW are now in operation at four NPPs of Ukraine, generating about 50% of electric power**
- **Ukraine possesses reach deposits of U, Zr, Hf, Th, Fe and other components needed for the reactor core. The proved reserves of U-235 will be enough during the next ~100 years (!)**
- **Majority of the currently operating reactors have to be decommissioned before 2030**

Prognostic G-IV Road Map for PWR and FR operation in transition period 2030-2100



Strategic points of the Nuclear Power Engineering development in Ukraine

- **Decommissioned reactors have to be replaced by the G-III+ reactors.**
- **The G-IV nuclear technologies have to be developed and implemented during the transition period 2030-2100**

Accelerated R&D of the reactor structural materials

Accelerated materials evaluation for nuclear applications

M. Griffiths, L. Walters, L.R. Greenwood, F.A. Garner

Journal of Nuclear Materials **488** (2017) 46-62

- We have addressed in this paper the opportunities and complexities of using surrogate reactors at higher neutronflux to study material response to irradiation operating at lower neutronfluxes under different neutronflux spectra. The possibility of successful simulation of the property or process is enhanced if the researcher identifies all operating processes for the property and alloy of interest, then identifies and accounts for the parametric dependencies arising primarily from differences in displacement rate and transmutation-induced changes in composition.

In-pile experiments are in progress in Czech Republic

M. Zychová, A. Vojáček, M. Růžičková, R. Fukač, E. Křečanová.
"New research infrastructure for SCWR in Centrum Výzkumu Řež",
Proc. of the 6th Int. Symposium (ISSCWR), Shenzhen, China, paper #13031, 2013

Developed in the NSC KIPT electron irradiation test methodology is an efficient tool for accelerated investigation of the corrosion effects under irradiation. It provides new possibility of design and assessment of the nuclear structural materials for the G-III+ and G-IV nuclear technologies

Advantages of the electron irradiation at accelerated assessment of materials

- - Electron irradiation is rather efficient tool for essential acceleration of chemical reactions due to ionization and activation of the reacting components
- - (e,n), (e,p) and (e,α) nuclear reactions have energy thresholds near 10 MeV. Therefore electrons of energy less than 10 MeV do not activate materials
- - Investigations of the irradiated materials immediately after irradiation do not need hot cells

Electron Irradiation Test Facility for Designing of MSR Materials 2003-2005

Senior Chief Scientist,
Pacific Northwest National Laboratory, USA
Frank Garner

Head of Theoretical Department
Kharkiv Institute of Physics&Technology, Ukraine
Alexander Balkai

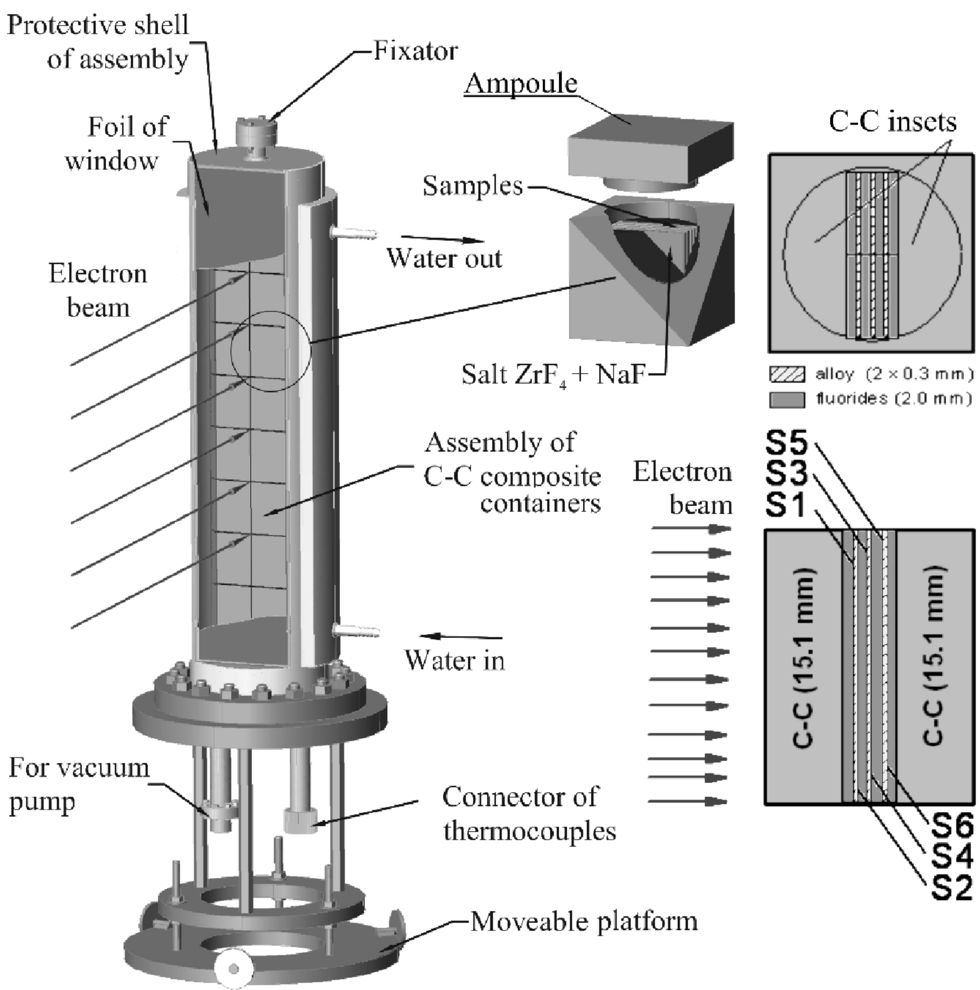
Materials for MSR, Eds. A.S. Bakai and F.A. Garner, Problems of Atomic Science and Technology 4(87) (2005), http://vant.kipt.kharkov.ua.

A.S. Bakai, In: Molten Salt Reactors and Thorium Energy, T. Dolan, Ed., Elsevier (2017) Ch. 26.21

EITF - KIPT

General view of the EITF -KIPT

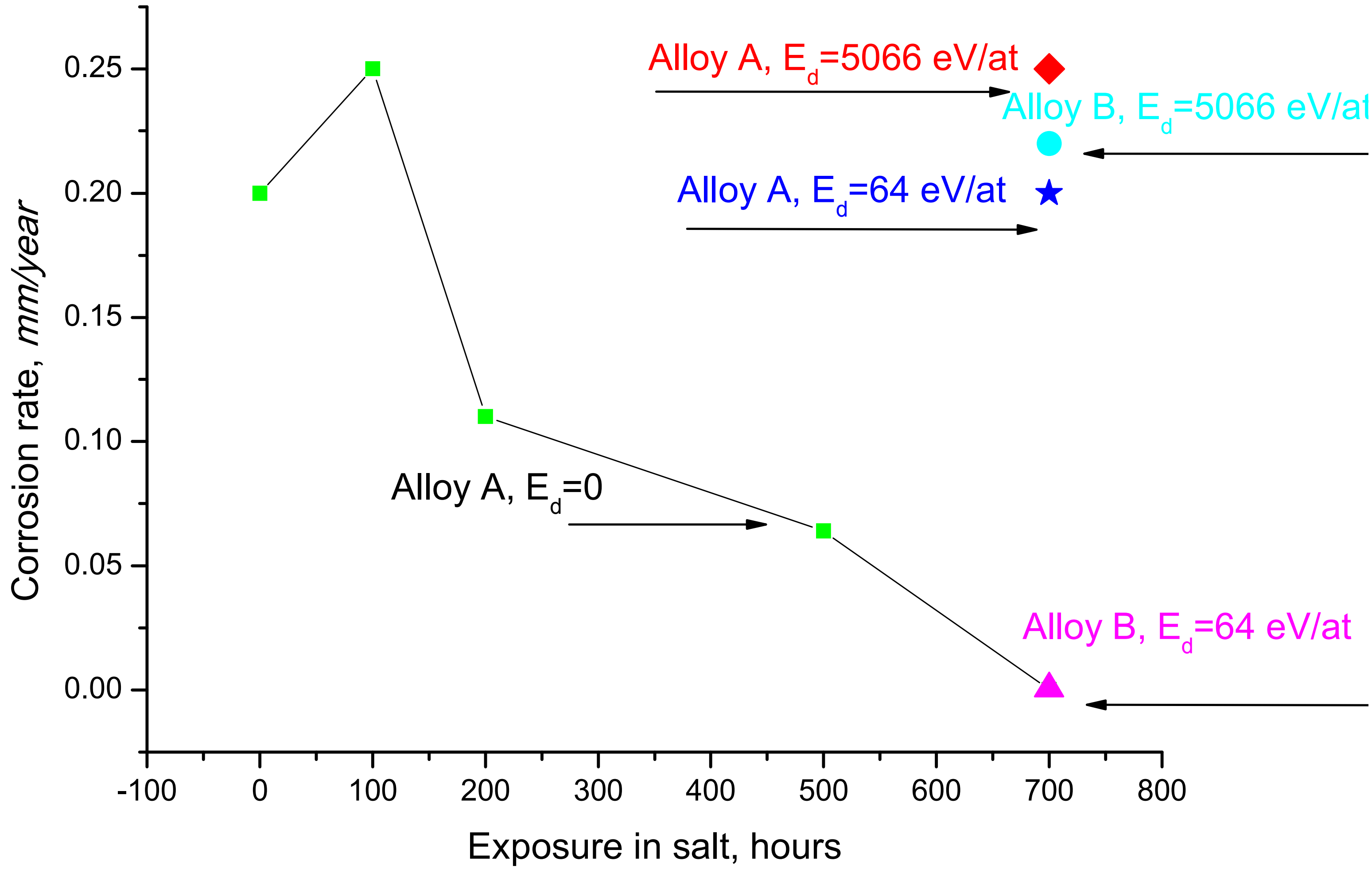
Construction of the irradiation cell



The specimens surfaces are marked by symbols S1- S6.

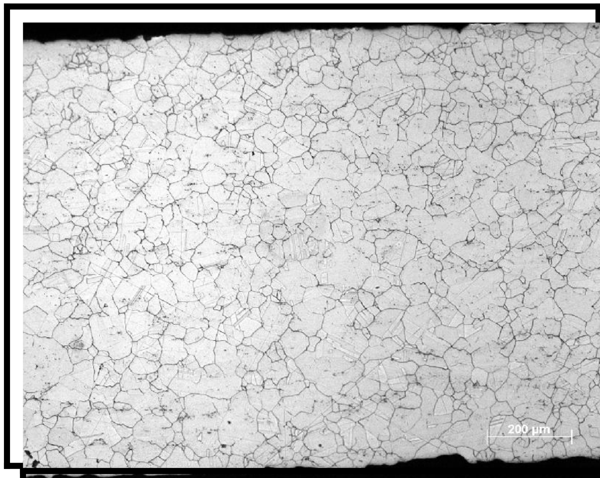
The deposited in S1 energy is 50 times larger than that in the layer S6.

Corrosion Rates of the Designed Hastelloys A and B

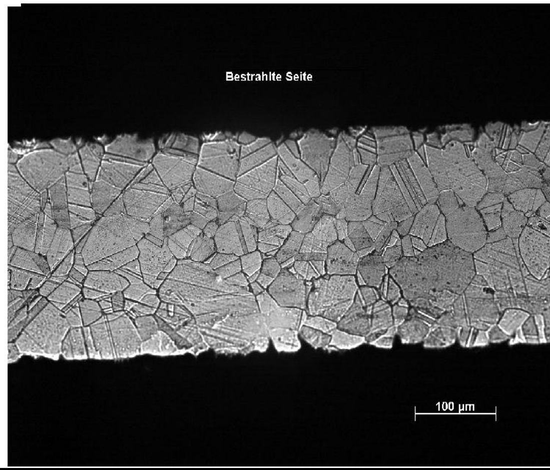


1. Irradiation enhances the corrosion rate by 10^2 -10^3 times
2. Ni-based Alloy B (containing Y additions) has much better corrosion resistance

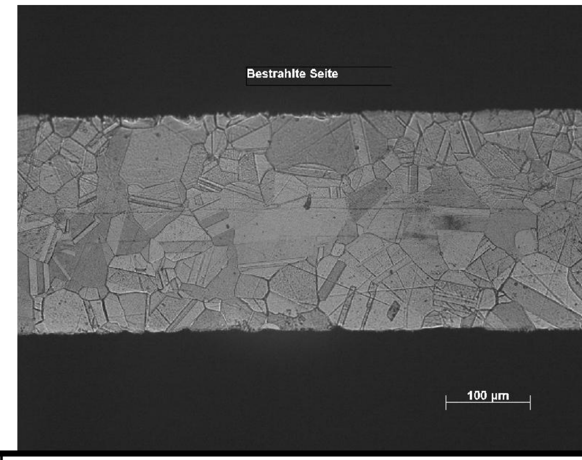
Role of the alloying additions: Nb ~0.5% and Y ~ 0.05% in alloy B



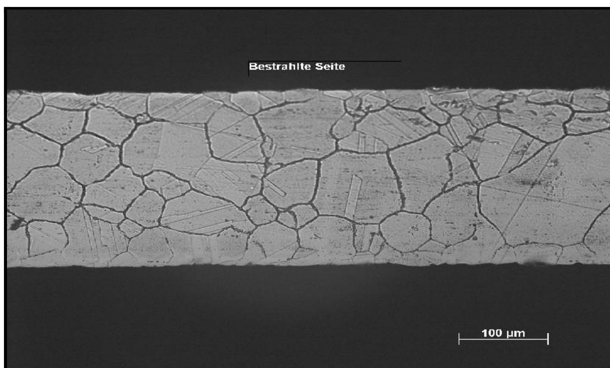
A -0, unirradiated



A-1, irradiated



A-6, irradiated



B-2, irradiated

B-5, irradiated

Role of the alloying additions

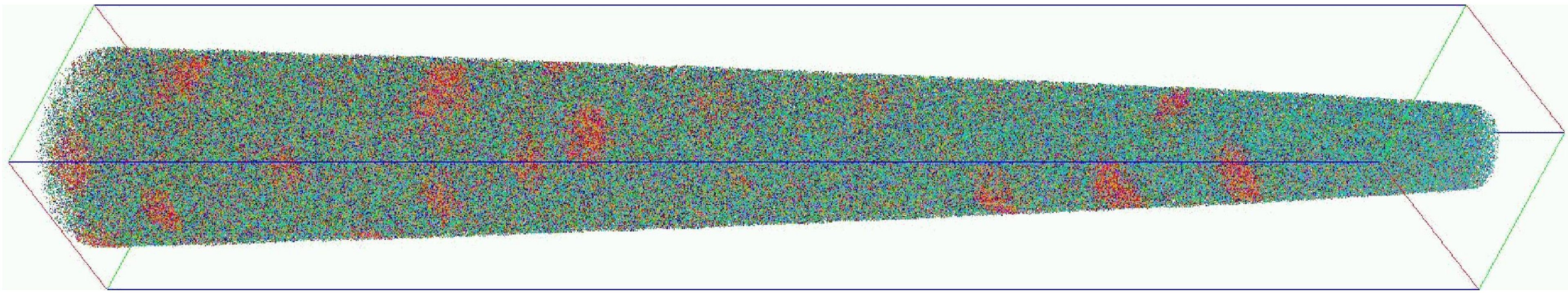
- **The corrosion mode and resistance is rather sensitive to Nb and Y additions and presumably to other dopants. The alloy doped with Nb (0.5%) and Y (0.05%) does not show considerable intercrystalline corrosion, but its corrosion rate is sensitive to the deposited energy dose.**

- **Evidently these dopants will depress the irradiation stimulated stress corrosion cracking and the irradiation enhanced fatigue**

Alloy B, phase nano-structure

3D LEAP Analysis, atomic resolution

**Al atoms are shown in red color, Ni – in blue, etc.
Precipitates of $L1_2$ structure and nanoheterogeneities are seen**



N. Wanderka, D. Isheim, A. Bakai et al. (2007)

Alloy B is Hastelloy with 0.05% Yttrium and 0.5% of Niobium additions. It shows rather good corrosion resistivity

Electron Irradiation Test Facility for Designing and Corrosion Tests of SCWR Materials 2010-2012

Senior Advisor in the Office of the Principal Scientist AECL, Interntional collaboration
Canada
Robert Speranzini

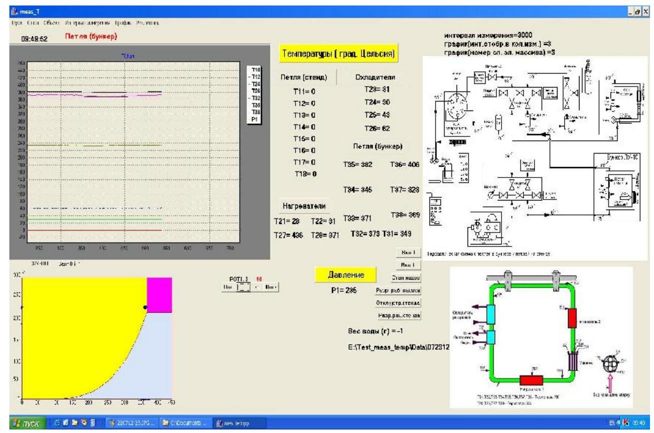
Head of Theoretical Department
Kharkiv Institute of Physics&Technology, Ukraine
Alexander Bakai

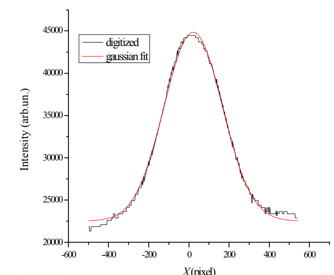
A.S. Bakai, V.N. Boriskin, A.M. Dovbnya, S.V. Dyuldya, D.A. Guzonas, ASME, J. Nucl eng. and Radiation Sci., 2, 021007 (2016)

Loop_1a (free convection)

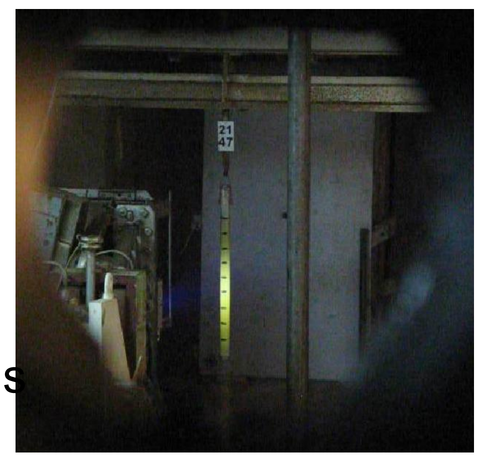
Accelerator, beam, pressure and temperature monitoring and control near critical point

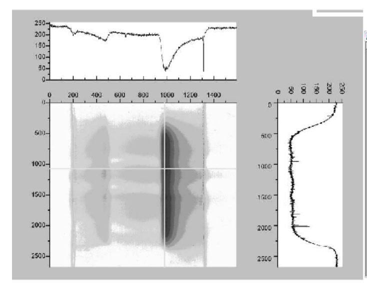
Temperature and pressure monitoring

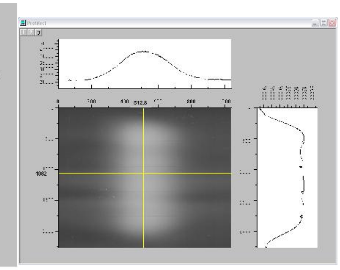




Beam parameters and distribution

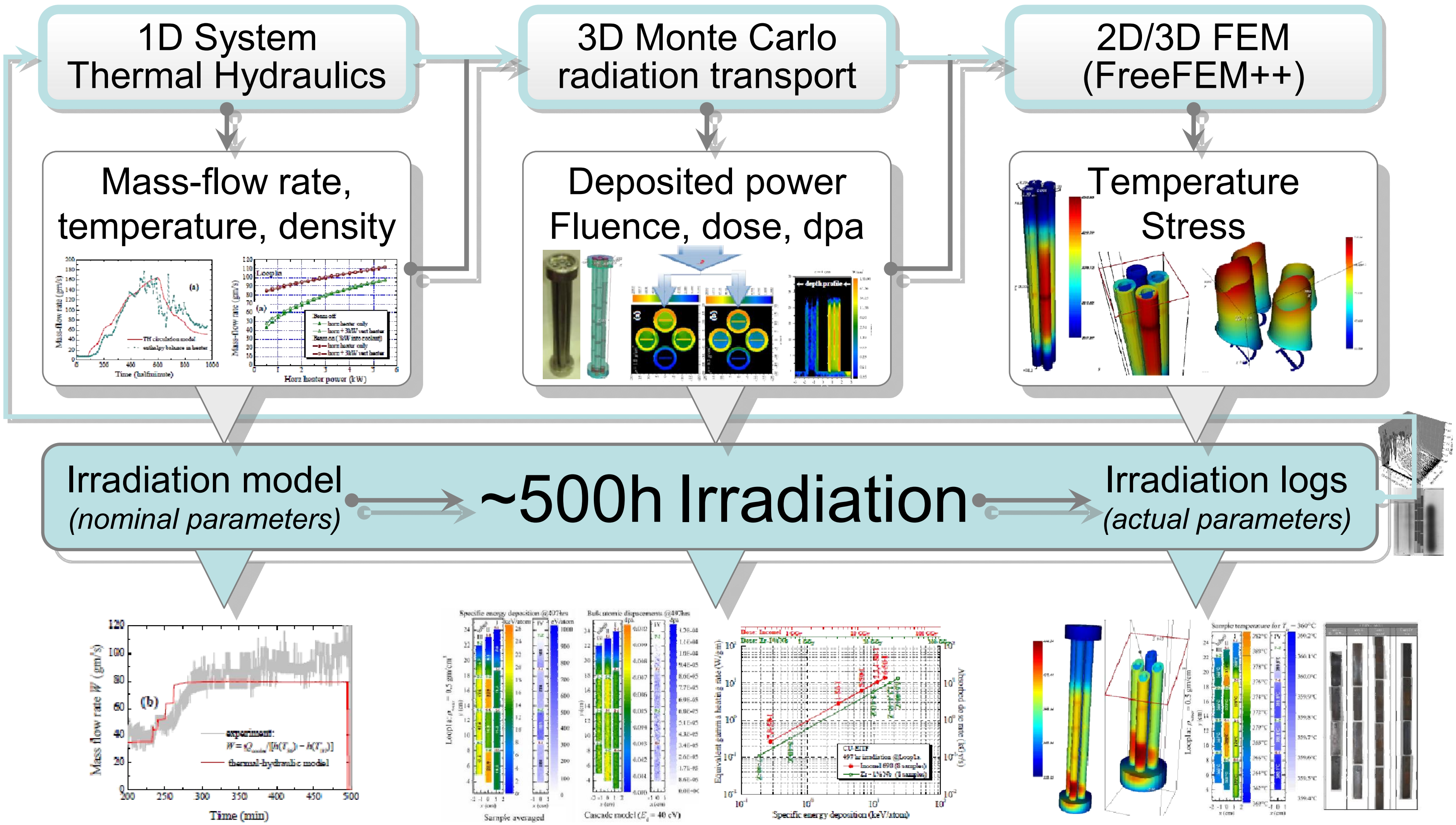






Due to large gradients of the energy deposition rate this parameter was determined with submilimeter spatial resolution by means of computer simulations

Computer Simulation Technique



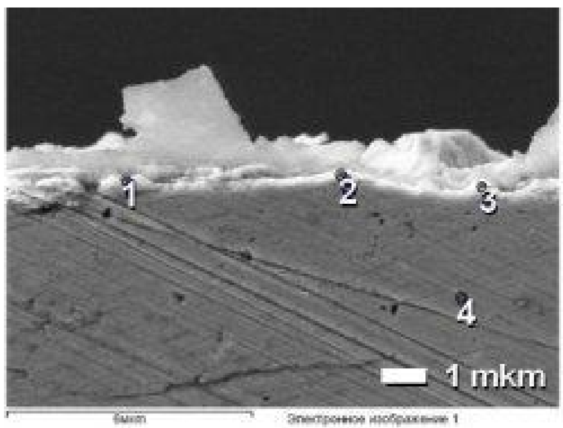
Oxidation rate analysis

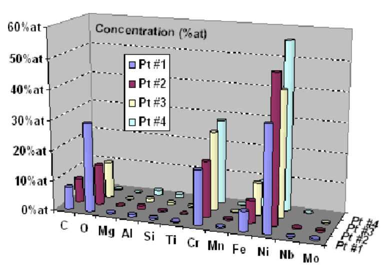
Alloy	Exposure	Pressure (MPa)	Temperature	Irradiation	Weight gain (mg/cm^2)	Oxide film thickness (μm)	Reaction constant ($μm^2/yr$)	Oxidation rate (μm/yr)	Reference
Zr-1Nb	16,000 hrs	16.8	350°C water	N/A	0.8	5.5	**16.6**	**3.0**	I.A. Petelguzov et al. *VANT* 82 (2002) 88
Zr-2.5Nb	16 FPY	9.9	~300°C water coolant	CANDU ~2×10^{22} n/cm^2	3.7	25	**39.1**	**1.6**	D.H. Lister, IAEA-TECDOC-667 (1992), p. 10
	9.7 FPY	9.9	288°C coolant	CANDU ~5.66×10^{21} n/cm^2	0.90	6.1	**3.8**	**0.6**	T. Do, M. Saidy, W.H. Hocking *J. ASTM Int.* **5** (2008) JA101292
	13.3 FPY	9.9	287°C water coolant	CANDU ~1.4×10^{22} n/cm^2	0.95	6.5	**3.2**	**0.5**	
Zr-1Nb	493 hrs	23.5	350°C water coolant	10 MeV *e*-beam	0.27	1.85	**60.8**	**32.9**	This work
Inconel 690	672 hrs	24	500°C SCW	N/A	0.065	0.35	**1.6**	**4.6**	P. Xu, L.Y. Zhao, K. Sridharan, T.R. Allen. JNM 422 (2012) 143-151
	493 hrs	23.5	350°C water	10 MeV *e*-beam	0.58	3.16	**177.6**	**56.2**	This work

Oxides on the surfaces of Inconel 690 and welding joints of Inconel 52MSS

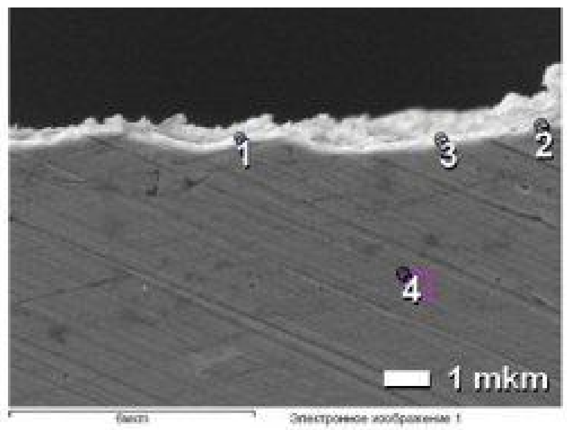
- **Grainy oxides with good adhesion**

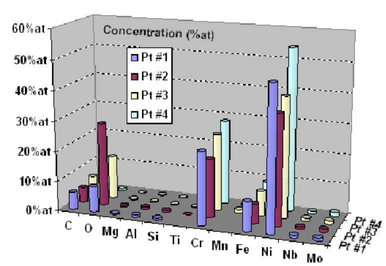
In690



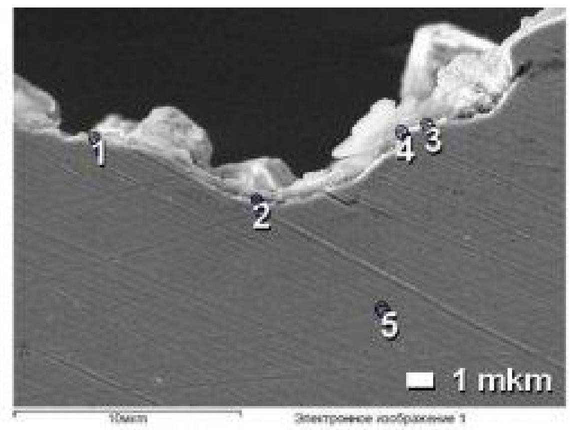


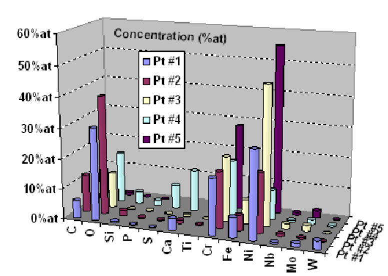
In52MSS





In52MSS

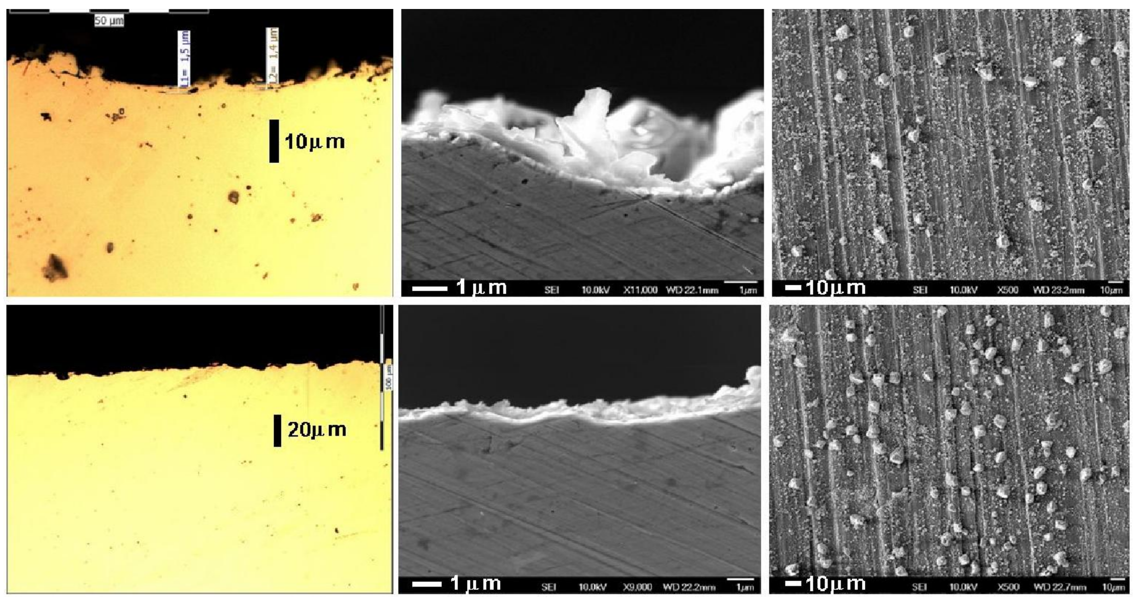




Oxide layers morphology of In690 and those on welding joints In52MSS

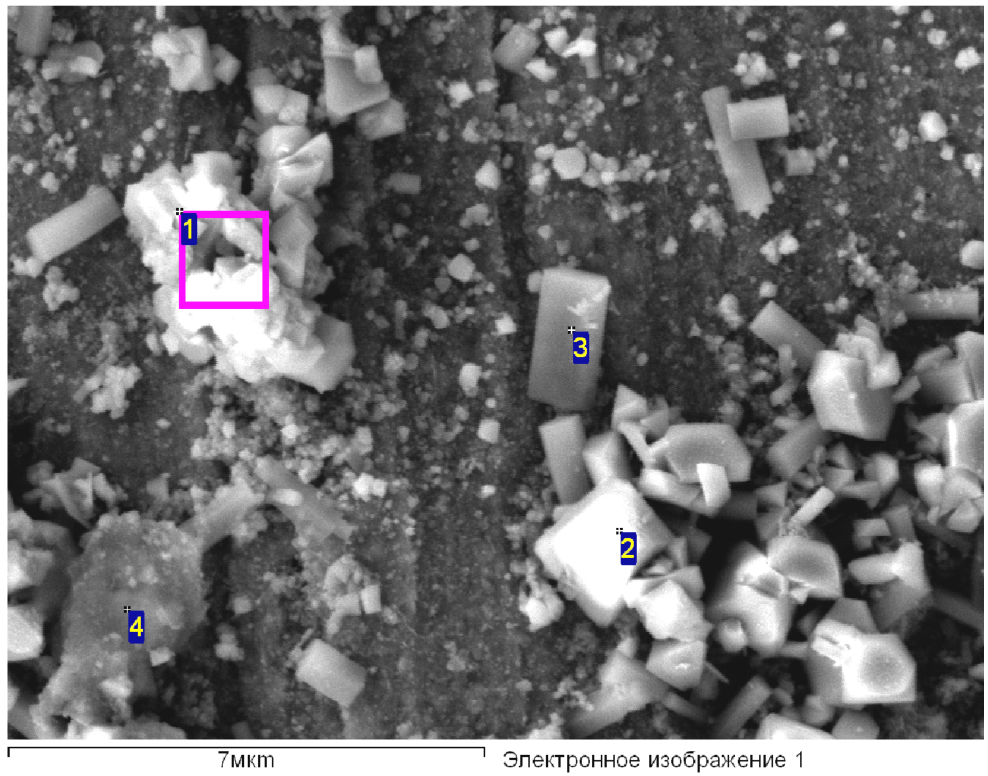
Base In690

Welding joint



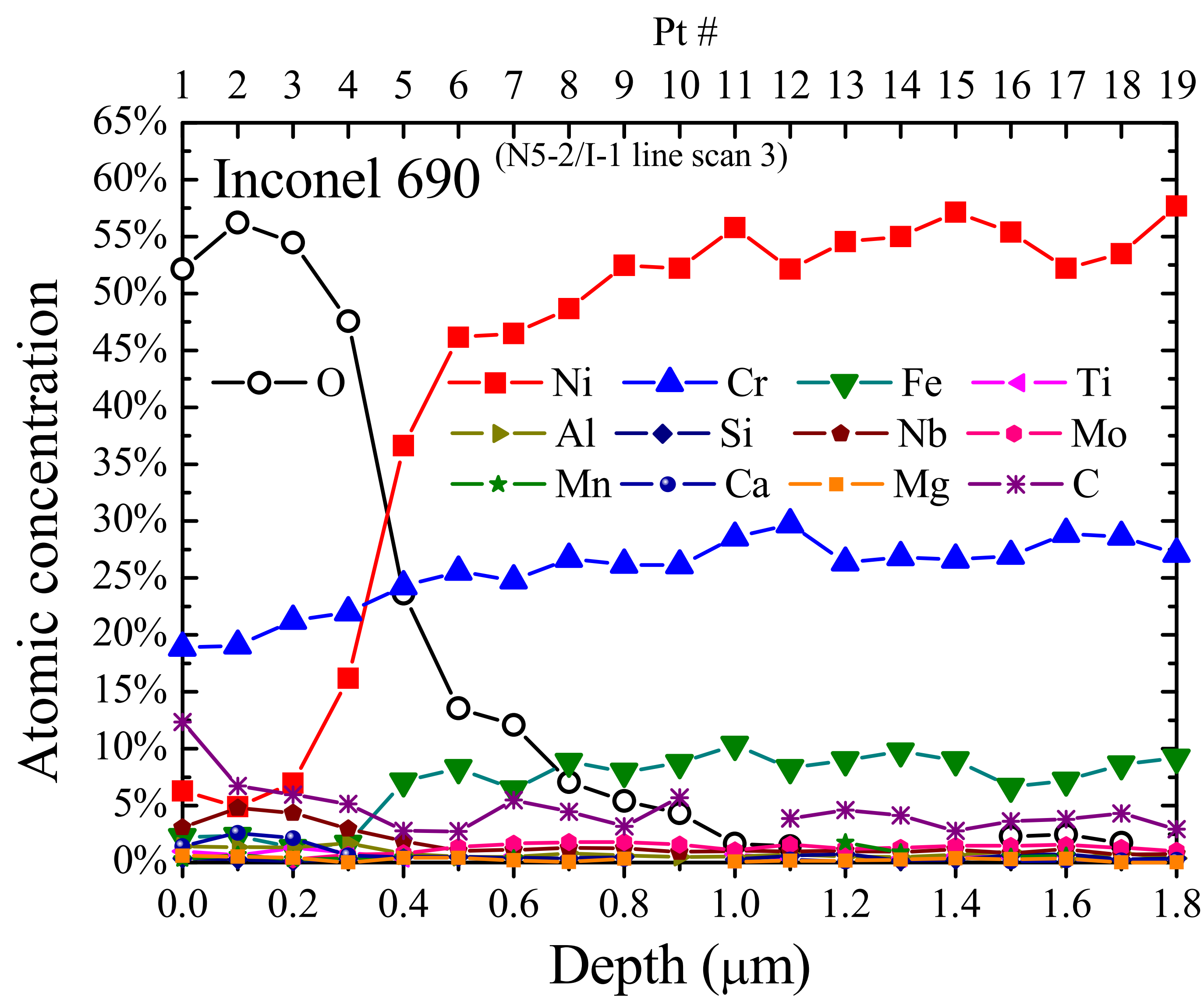
There is larger concentration of the oxides grains on the welding joint but its background oxide layer is thinner

Inconel 690, surface:
Variety of oxides and the electrochemistry effect

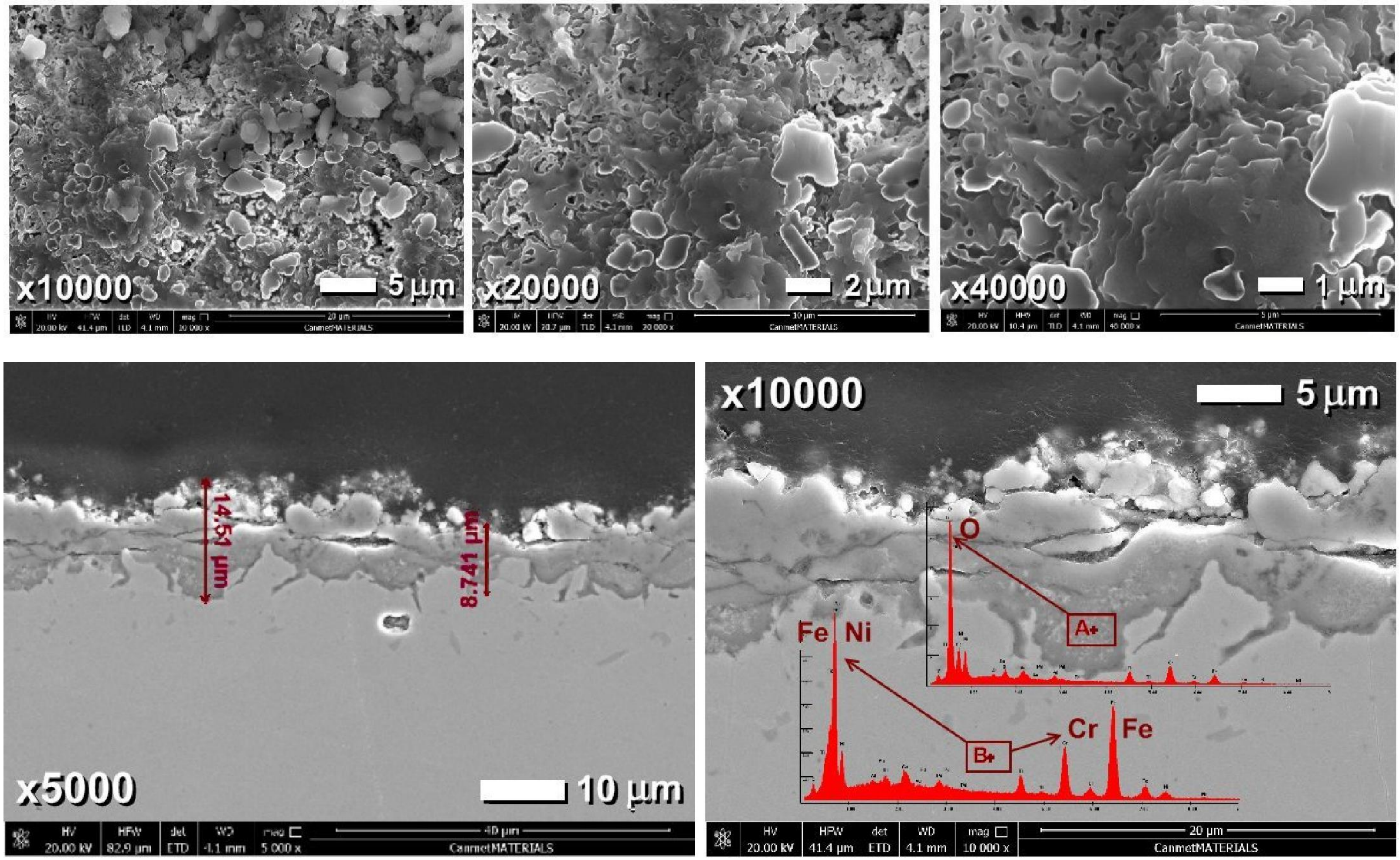


Spectrum, at %	C	O	Na	Mg	Al	Si	P	S	Cl	Ca	Cr	Mn	Fe	Ni	W
1	6.12	56.68	0.55	0.75	2.48	0.40	3.72	0.06	0.18	5.48	4.49	0.07	10.64	8.27	0.12
2	0.90	55.53	0.28	1.11	4.20	0.39	0.24	0.06	0.04	0.51	9.17	1.18	16.65	9.63	0.09
3	3.29	63.54	0.12	0.19	0.51	0.09	10.68	0.48	0.00	17.02	0.60	0.00	0.54	2.81	0.12
4	15.24	50.97	2.93	2.77	2.11	1.44	1.54	0.29	2.39	3.96	0.93	0.24	8.78	4.54	1.88

STEM EDS line scan of the Alloy 690 specimen N5-2/I-1

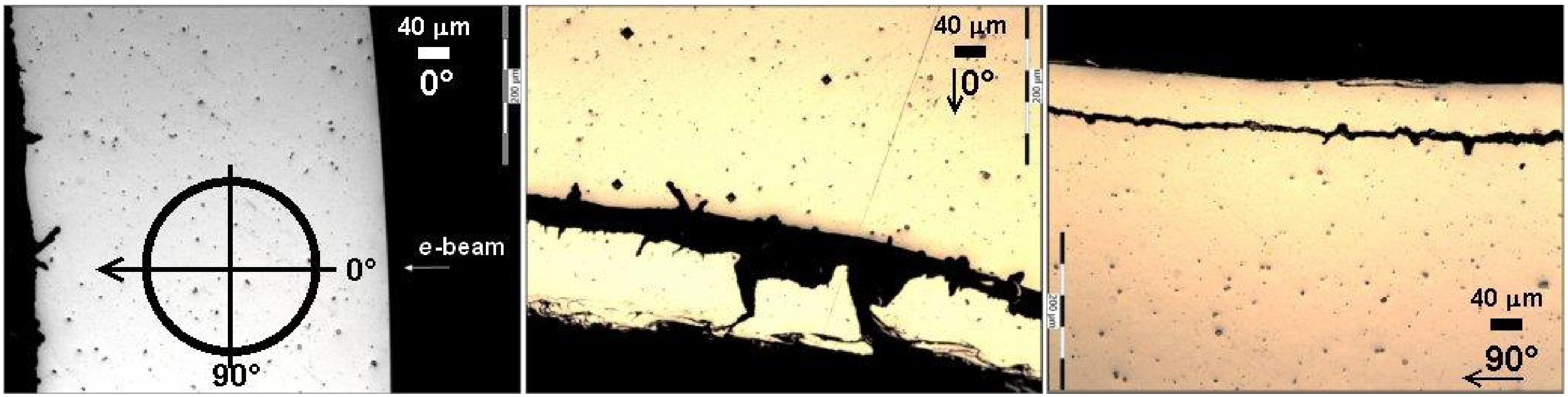


Corrosion of Stainless Steel SS 12X18H10T



Top-view planar (top row) and cross-section (bottom row) SEM images of the SS. Spallation, exfoliation of oxide layers, crevice corrosion and initiation of the severe corrosion cracking is seen

Morphology of the oxide layer on the Stainless Steel at smaller magnification



Irradiation stimulated stress corrosion cracking and the large scale exfoliation of oxide layer

Bob Speranzini in letter to Boris Paton has written…

"...I am pleased to report that excellent progress has been made and Professor Bakai and his colleagues **have built a very unique facility** and have produced **the first results in the world** (as far as I am aware) **of the irradiation impact on corrosion rate under SCWR conditions**. The first observations of the irradiation impact in the corrosion rate were reported in Professor Bakai's seminar at Chalk River Laboratories. **These results would have been very difficult if not impossible to achieve** without Professor Bakai's expert knowledge and expertise, and dedicated and persistent work."

Dr. R.A. Speranzini
Head, National and International Collaboration

Acad. of NAS of Ukraine
Olexandr Bakai

In summary

- **Accelerated materials design and evaluation for the nuclear technologies G-III+ and G-IV is a pressing task**

- **The developed methodology of e-rradiation of materials in circulating sub-crirtical and supercritical water is an efficient tool for solution of fundamental and applied problems of the nuclear materials, especially at investigations of the irradiation stimulated**
  - **Corrosion,**
  - **Stress-corrosion**
  - **Fatigue corrosion effects**
- **Correlation experiments and combined irradiation will enhance the investigations efficiency.**

Outlook

- The developed methodology of the accelerated corrosion tests of reactor structural materials is a powerful tool

- There are different options of its efficient use
- Correlated EITF. in pile, and high neutron flux experiments

- **Fundamentals**. **Experimental** investigations of the corrosion kinetics of "promising" materials in water with specific additions to develop reliable **theoretical** parameterized phenomenological models

- **Practical issues**. **Corrosion, irradiation stimulated stress corrosion cracking, irradiation enhanced fatigue** of specified materials.

For example, comparative tests of the new cladding materials can be performed. Correlation with the in-pile corrosion data (Halden reactor project) would be rather instructive.

The structural materials currently used in the supercritical steam boilers as evident candidate materials for SCWR would be tested.

Many Thanks for Your Attention!