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Abstract

This European Commission funded International Workshop "Materials resistant to extreme conditions for future energy systems" was organized 12-14 June 2017, Kyiv – Ukraine. The three main objective of the Workshop are:

- To review the state-of-the-art knowledge and on-going research and to identify the re-search needs concerning structural materials for future energy systems that are exposed to extreme operational conditions. Special emphasis will be on how to use R&D for engineering applications.
- To explore future collaboration opportunities between EU member states and target countries* both in terms of specific R&D projects, as well as in terms of collaboration mechanisms.
- To bring together scientists, engineers and managers from academia and industry representing different energy technologies to promote such integration as well as representatives from the European Commission and national government organizations.

The Workshop is organized as technical sessions with invited keynote presentations and oral presentations by the participants and Poster session as well as a final networking sessions. This Book-of-Abstracts includes all Abstracts for keynote presentations, oral presentations and Posters.

1 Introduction

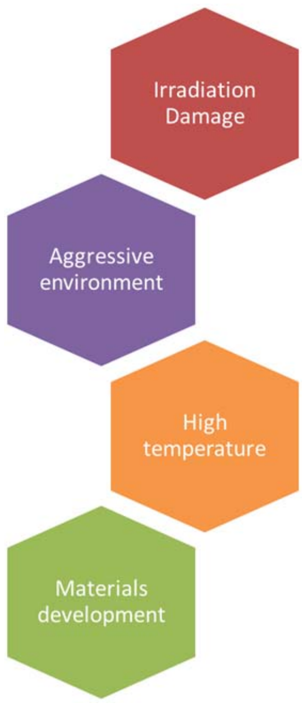
The development of future low-carbon energy systems that provide sustainable and secure supply of energy at competitive costs is a tremendous challenge that requires both basic research and implementation at engineering level. Materials is the key to almost all future energy systems based on renewable energy sources, sustainable nuclear energy systems as well optimal use of some fossil energy. The materials and components in future energy systems are exposed to very harsh conditions in terms of for instance high temperature, corrosive environments systems and irradiation. The topic of this Workshop is therefore: "*Materials resistant to extreme conditions for future energy systems*". This includes both the assessment of the functioning and structural integrity and degradation mechanism of candidate materials as well as the development of new materials with superior properties and/or materials and components that can be produced at lower cost.

The Workshop is funded by the EU Enlargement & Integration Action (E&IAT) and co-organized by the Joint Research Centre of the European Commission, the National Academy of Sciences of Ukraine (NASU), and the Joint Programme on Nuclear Materials (JPNM) of the European Energy Research Alliance (EERA).

The first objective of the Workshop is to discuss the state-of-the-art knowledge and on-going research and to identify the research needs concerning structural materials for future energy systems that are exposed to extreme operational conditions. Special emphasis was given how to use R&D for engineering applications.

The second objective is to explore future collaboration opportunities between EU member states and target countries* both in terms of specific R&D projects, as well as in terms of collaboration mechanisms.

This Workshop brings together scientists, engineers and managers from academia and industry representing different energy technologies to promote such integration as well as representatives from the European Commission and national government organizations.



The workshop is based on the oral presentations from the invited international lecturers, as well as by presentations by participants and a poster session. The Workshop will have the following sessions:

Session 1: Overview of National and international Research programmes/projects

Session 2: High temperature assessment of components and materials

Session 3: Structural Materials Development for energy applications

Session 4: Irradiation damage

Session 5 Long-term Plant Operation

Session 6 Assessment of environmental impact

Session 7 Networking for collaboration between target countries and EU Member States

The first session gives an overview of national and international research projects and programmes including EU networks and national initiatives in the target countries covering different future energy system where components and materials are exposed to harsh conditions.

Each of the topical technical sessions (2- 5) consists of keynote lectures by invited experts and oral presentations by the participants. The Poster Session covers all topics.

The number of oral presentations is rather limited and orals are expected to provide an overview of topics related to the different sessions whereas the Poster Session is meant for more detailed and specific research results. Basic research, as well as engineering applications, covering both experimental work and modelling, are within the scope of the Workshop.

The main objective of the networking Session, which concludes the Workshop, is to identify topics and mechanisms for collaboration between target country organizations and EU Member State.

The Workshop will be hosted by National Academy of Sciences of Ukraine and take place in the Great Conference Hall of NASU in Ukraine’s capital Kiev, Volodymyrska Street 54.

*Target countries are:

EU candidate and potential candidate countries (Albania, Tur-key, Serbia, The former Yugoslav Republic of Macedonia, Montenegro, Kosovo, Bosnia-Herzegovina),

H2020 Associate countries (Switzerland, Israel, Norway, Liechtenstein, Faroe Islands, Ukraine, Iceland, Moldova, Georgia, Armenia, Tunisia)

2 Technical Programme

Monday, June 12

08:45-09:00	**Registration**
09:00	**Opening** • Maksym Strikha, Deputy Minister of Education and Science • Academician Anatoliy Zagorodniy, Vice-President of NASU • Karl-Fredrik Nilsson, JRC and Workshop Chairman
09:20 – 10:10	**Session 1a Overview of National and international Research programmes/projects** • EU nuclear activities o The joint programme on nuclear materials of the European Energy Research Alliance (L. Malerba, Belgium) o Overview of ATF research and ongoing experiments at the Halden reactor project (R. Van Nieuwenhove, Norway)
10:10-10:30	**Coffee break**
10:30-11:30	**Session 1b Overview of National and international Research programmes/projects** • PPP Initiative “Resource materials”, the EU-UA high-tech cooperation (A. V. Ragulya, Ukraine) • Non-nuclear European projects (R&D and engineering) o Concentrating Solar Thermal Systems: high radiant flux and temperature requirements. (E. Zarza, CIEMAT, Spain) o Innovative high temperature material concepts drive clean energy technologies forward (P. Pohjanne, VTT, Finland)
11:30 – 12:00	**Session 2 High temperature degradation** • Keynote Experimental Testing and Failure Analysis for High Temperature Plant Environments (C. Mair, Imperial College, UK)
12:00 – 13:10	**Lunch**
13:10 – 14:50	**Session 2 High temperature degradation** • Keynote Physically-based modelling of high temperature low cycle fatigue and thermo-mechanical fatigue for 9CR ferritic-martensitic steels (S. Leen, NUI Galway, Ireland) o Research and development of coatings for Zirconium fuel claddings (A. Kuprin, Ukraine)
14:50 – 15:20	Coffee Break
15:20 – 17:10	**Session 3a Structural Materials Development for energy applications** • Keynote Design of healable steels for energy applications (C. Cem Tasan, MIT USA) • Oral presentations o Materials resistant to extreme temperature and pressure for future hydrogen and steam turbines, modern 2- and 4-pole NPP turbogenerators (A. Balitskii, Ukraine) o Materials under extreme energy and particle loads: from surface damage to surface modification (V. Makhlay, Ukraine) o Multicomponent (high entropy) alloys as a basis for new generation of high-temperature materials (S.A. Firtsov, Ukraine) o Fractal nature of nano-micro structure and energy (V. Mitic, Serbia)
19:30 - 21:30	**Workshop Dinner** (paid by the organisers)

Tuesday, June 13

09:00 -09:50	**Session 3b Structural Materials Development for energy applications (continuation)** • Keynote Effect of ausforming temperature on the microstructure of grade G91 steel (C. Capdevila, CENIM, Spain) o Micromechanical characterization of SiC-SiC fiber composite for accident tolerant fuel applications (Y. Zayachuk, University of Oxford, UK)
09:50 – 10:30	**Coffee Break & Poster 1 session**

10:30 – 12:30	**Session 4 Irradiation damage**
	• Keynote Statistical physics for the modeling of non-equilibrium metallic alloys driven by irradiation (M. Nastar, CEA, France)
	• Keynote Irradiation embrittlement and RPV metal service life: state-of-the-art and challenges (S. Kotrechko, IMP, Ukraine)
	• Oral
	  o F/M steels - prospective materials for GEN IV reactors. Structural stability and swelling resistance during irradiation to high damage doses (V. Voyevodin, Ukraine)
	  o Radiation-induced softening vs. hardening effects in metals and alloys during simultaneous action of irradiation and mechanical strain (V.I. Dubinko, Ukraine)
	  o Radiation-induced formation of hardening solute clusters in ferritic/martensitic alloys: an object kinetic Monte Carlo model (L. Malerba, Belgium)

12:30 – 13:45	**Lunch**

13:45 – 15:45	**Session 5 Long-term Operation and Degradation Mechanisms**
	• Keynote Irradiation embrittlement of austenitic stainless steels in PWR vessel's internals – experiments and modelling from micro to mesoscale (B. Tanguy, CEA, France)
	• Oral presentations
	  o Progress in unified fatigue laws (M. Ciavarella, Italy)
	  o Mechanics of surface damage: A new look at the old problem of wear (R. Aghababaei, Switzerland)
	  o Nanofluids for emergency cooling of overheated surfaces of power equipment (B. Bondarenko, Ukraine)

15:45 – 17:45	**Poster session 2 with refreshments**
Evening 17:45 – 19:15 19:00 – 21:00	**Social Event** (on participant's choice and expense) Walk in historical centre of Kyiv National Opera and Ballet Theatre of Ukraine. Ballets: G. Bizet – R. Shcedrin, Carmen-suite & N. Rimsky-Korsakov, Sheherazade

Wednesday, June 14

09:00 – 11:00	**Session 6 Environmental and Corrosion Effects** • Keynote Challenges of materials qualification for nuclear systems with heavy liquid metal coolant: Effect of LBE on materials property (S. Gavrilov, SCK•CEN, Belgium) • Keynote Electron Irradiation Test Facilities and methodologies for corrosion assessment and design of reactor structural materials (O. Bakai, KIPT, Ukraine) • Oral presentations o Corrosion issues in steels contacting Pb-Bi eutectic at high temperatures – overview of KIT activity (V. Tsisar, Germany) o Modern destructive and non-destructive methods for evaluation of in-service degradation of structural steels operated in aggressive environments (O. Zvirko, Ukraine) o Basalt-boron fiber as reinforcement of composites for nuclear energy applications (V. Gulik, Ukraine)
11:00-11:30	**Spare time Summary & Conclusions. Coffee break**
11:30 – 13:30	**Networking Session** Short Presentations • JRC activities - possible field of cooperation with Ukraine (V. Esteban Gran, EC-JRC) • RTD activities, EURATOM Work Plan and Action B5 on Ukraine (M. Serrano, CIEMAT, Spain) • EURATOM Program Committee and Technology Platforms (G. Wrochna, NCBJ-Poland) • The status and activities of EURATOM NCP-Ukraine (O. Volobuyev, KIPT, Ukraine) Topics discussion - Possible projects in the area of Cybersecurity of critical infrastructures (S. Serwiak, NCP, Poland)
13:30	**End of Workshop**
13:30 – 14:30	**Lunch**
14:30 – 17:30	**EURATOM/H2020 Training** - Hints and Tips on H2020 Project Preparation - Merle Lust (2h 15’) (coffee break) - Discussion how to boost Ukrainian participation in EURATOM

Poster Session 1, June 12

Group 1. Steels and Alloys for Energy conversion

1. A METHODOLOGICAL APPROACH FOR SELECTING STEAM TURBINE BLADE MATERIALS, Sh. Caslli Tafaj*, E. Lamani, F. Bidaj, D. Elezi

2. FATIGUE BEHAVIOR OF 316L AUSTENITIC STEEL IN AIR AND LWR ENVIRONMENT WITH AND WITHOUT MEAN STRESS, Wen Chen*, Ph. Spätig, H.-P. Seifert

3. EFFECT OF ANNEALING ON THE MICROSTRUCTURE AND HARDNESS OF IRRADIATED TUNGSTEN, B. Horvath*, Y. Dai, Y. Lee

4. DISPERSION REINFORCED ALLOYS FOR OPERATION UNDER EXTREME CONDITIONS OF HIGH TEMPERATURE PLASMA, I. Husarova, V. Solnchev, A. Potapov, T. Solncheva, K. Petrash, G. Frolov

5. RECENT RESEARCH AND DEVELOPMENT OF ODS STEELS AS MATERIAL FOR EXTREME CONDITIONS, M. Ivanchenko*, J. Lagerbom, P. Moilanen, J. Rantala, S. Penttilä, U. Ehrnstén

6. NANO INDENTATION CHARACTERIZATION OF T91 AND EUROFER STEELS FOR NUCLEAR APPLICATIONS, H. Namburi*, O. Libera, A. Ruiz-Moreno, L. Kurpaska

7. NEUTRON DIFFRACTION STUDY OF IN-SITU STRAINED MARTENSITIC/FERRITIC OXIDE DISPERSION STRENGTHENED STEELS, M.A. Pouchon*, S. Van Petegem, A. Froideval, J. Chen

8. MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AUSTENITIC ODS STEEL AND ODS HIGH ENTROPY ALLOY, M.A. Tikhonovsky*, V.N. Voyevodin, A.N. Velikodny, A.S. Kalchenko, I.V. Kolodiy, S.V. Starostenko, V.S. Okovit

9. IMPROVING OF PHYSICO-MECHANICAL AND TRIBOLOGICAL PROPERTIES OF THE Nb-Ti ALLOY BY THERMODIFFUSION OXIDATION, Ratska N.B., Vasyliv Ch.B.*

10. SOFTENING EFFECT AND FEATURES OF AN ELECTRONIC SPECTRUM OF HIGH-TEMPERATURE Mo-Re, Mo-Re-Nb ALLOYS, O. Velikodnyi

Group 2. High temperature ceramic materials

1. HIGH TEMPERATURE MATERIALS FOR MOST EFFECTIVE THERMIONIC CONVERTERS OF HEAT ENERGY INTO ELECTRICAL ONE, O. Dekhtyar

2. THE INFLUENCE OF IN SITU REACTIONS ON STRUCTURE AND MECHANICAL PROPERTIES OF ULTRA-HIGH-TEMPERATURE ZRB_2-SIC AND ZRB_2-SIC-C CERAMICS, S. Chornobuk, V. Vishnyakov, O. Popov, A. Goncharenko*

3. MODIFICATION OF ZIRCONIA CERAMICS FOR OPERATION IN EXTREME CONDITIONS, Danilenko, T. Konstantinov*, I. Brukhanova, G. Volkova, V. Glazunova, V. Burkhovetskii

4. LOW THEMPERATURE HEAT CAPACITY OF $Gd_2Hf_2O_7$ AS A PROMISING MATERIAL FOR IMMOBILIZATION OF NUCLEAR WASTE, A. Kopan, M. Gorbachuk, S. Lakiza, Ya. Tischenko, D. Korablov*

5. RADIATION RESISTANCE OF $MgAl_2O_4$- SPINELS: EFFECT OF 3d IONS ON DAMAGE RESPONSE, N. Mironova-Ulmane

6. ZrB_2 – BASED CERAMICS AND THERMAL SPRAYED COATINGS ON CARBON COMPOSITES, M. Parco, I. Fagoaga, L. Silvestroni, O. Grigoriev, , I. Podcherniaeva, I. Neshpor

7. OVERVIEW OF THEORETICAL AND EXPERIMENTAL STUDYING OF CRYSTALLINE CERAMICS IN SI IEG NASU, B. Shabalin*, B. Zlobenko, S. Bugera

8. REINFORCING BASALT FIBER IN THE MANUFACTURE OF WIND TURBINES, M. Shvangiradze

9. A LOW-TEMPERATURE FUEL CELL OPERATING ON HYDROGEN SULFIDE (H_2S), T. Marsagishvili, E. Tskhakaia, G. Tatishvili*, N. Ananiashvili, J. Metreveli, M. Kikabidze-Gachechiladze, M. Machavariani

10. MATERIALS AND PANELS FOR INTEGRATED THERMAL PROTECTION SYSTEMS, O. Udovyk

Group 3. Modelling

1. NUMERICAL INVESTIGATION THE EFFECTS OF GEOMETRICAL PARAMETERS ON FRACTURE CHARACTERISTICS OF NOTCHED SMALL PUNCH TESTING SPECIMENS, B. Deliktas*, IC Türtük, and M. Sakacı

2. SIZE EFFET AND INTER-GRANULAR LOCALIZATION IN POLYCRYSTALLINE MATERIALS, Tuncay Yalçınkaya*, Aytekin Demirci

3. FRACTURE ANALYSIS FOR LIFE TIME EXTENSION OF REACTOR PRESSURE VESSEL, I. Orynyak, Y. Dubyk*, A. Orynyak*

4. MODELING AND DIAGNOSTICS OF THE BEHAVIOR OF NUCLEAR MATERIALS UNDER NORMAL OPERATING CONDITIONS AND THE ACTION OF EXTREME FACTORS, A.V. Babich, M.I. Bazaleev, V.V. Brukhovetskiy, S.Ye. Donets, V.F. Klepikov, V.V. Lytvynenko*, Yu. F. Lonin, Ye.M. Prokhorenko, A,G. Ponomarev, V.T. Uvarov

5. NUMERICAL PREDICTION OF RESIDUAL STRESSES IN THE PRESSURE VESSEL SHELL OF REACTOR WWER-1000, O. Makhnenko*, E. Velikoivanenko, G. Rozynka, N. Pivtorak, E. Kostenevich

6. MODELING OF CONSTRAINED IRRADIATION-INDUCED SWELLING OF UC PELLETS IN FUEL RODS, A.L. Maximenko*, E.A. Olevsky, O. Izhvanov

7. MULTILEVEL MODELING DEFECT STRUCTURE FORMATION IN PURE ZIRCONIUM UNDER PARTICLE IRRADIATION, D.O. Kharchenko, V.O. Kharchenko, Yu.M. Ovcharenko

8. AN XFEM BASED ALGORITHM FOR FATIGUE CRACK GROWTH PATH AND LIFE EVALUATION UNDER VARIABLE AMPLITUDE LOADING, H. Dirik, T. Yalçinkaya

9. CHARACTERIZATION OF HOLD TIME INFLUENCES ON CYCLIC SOFTENING OF FERRITIC-MARTENSITIC STEELS, U. Führer*, J. Aktaa

Poster Session 2, June 13

Group 4. Composite & Polymer-based materials

1. PERSPECTIVE DIRECTION FOR DEVELOPING NEW ELASTOMERIC MATERIALS USING NANOTECHNOLOGY, M. Elkady,* M. Khorolskyi, A. Sanin

2. HIGH TEMPERATURE RESISTANT POLYMER NANO- AND SUBNANOCOMPOSITES, A. Fainleib*, V. Bershtein, O. Grigoryeva, K. Gusakova, D. Kirilenko, O. Starostenko, P. Yakushev

3. MULTI-SCALE MODELLING OF CARBON NANOTUBE REINFORCED POLYMER COMPOSITES, Gözdenur Toraman*, Mine Konuk, Hasan Gülaşık, Elif Sert, Hande Üstünel, Ercan Gürses

4. HIGH TEMPERATURE RESISTANT POLYMER NANOPOROUS FILMS, O. Grigoryeva*, A. Fainleib, O. Starostenko, K. Gusakova, E. Espuche, D. Grande

5. HIGH TEMPERATURE RESISTANT BINDER FOR CARBON PLASTICS BASED ON POLYFUNCTIONAL EPOXIES AND NITRILES, Fainleib, K. Gusakova, O. Melnychuk, V. Petropolskiy, O. Andrieiev, M. Kazakevich

6. DEVELOPMENT OF DIMENSIONALLY STABLE STRUCTURE OF DRAWTUBE OF OPTICAL DEVICE MADE OF COMPOSITE MATERIAL, V. Maslyey, A. Kulyk*, A. Sanin, S. Moskal'ov, V. Kavun, A. Schudro

7. WIND ENERGY: MATERIALS DEVELOPMENT AND REQUIREMENTS, Leon Mishnaevsky Jr.*

8. FRACTAL NATURE OF WIND ENERGY, V.V. Mitic*, Lj. Kocic, D. Petković, V. Paunovic

9. NOVEL THERMOSTABLE NANOPOROUS POLYMER FILMS OF CYANATE ESTER RESINS DESIGNED BY USING IONIC LIQUIDS AS POROGENS, Vashchuk A., Fainleib A., Starostenko O.*, Grigoryeva O., Rogalsky S., Grande D.

10. GRAPHENE: METHODS OF OBTAINING, O. Usatova*, V. Kirichenko

11. SINTERING KINETICS OF TETRAGONAL ZIRCONIA NANOPOWDERS. THE SILICA ADDITIVE IMPACT, M. V. Lakusta, I.A. Danilenko, T. E. Konstantinova

Group 5. Reactor materials

1. STRUCTURAL MATERIALS CROSS-CUTTING ISSUES BETWEEN GENIV AND GENII/III FISSION REACTORS AND FUSION ENERGY SYSTEMS, J. Kalivodová, K-F. Nilsson, M. Serrano, M. Angiolini, C. Pareige, and L. Malerba
2. MATHEMATICAL MODELLING OF IRRADIATION SWELLING OF THE REACTOR WWER-1000 CORE BAFFEL, S. Kandala, O. Makhnenko*

3. GRAPHENE SEALS FOR NUCLEAR POWER PLANTS, B. Bondarenko*, A. Kozhan, V. Dmitriev, E. Strativnov, A. Khovavko, V. Ryabchuk
4. The Effect of Neutron Irradiation Hardening on the Results of Fast Fracture Evaluation, O. Kharytonov, Igor Kadenko, Olexiy Kutsenko, Nadiia Sakhno

5. OBTAINING OF NANOSTRUCTURED ZIRCONIUM AND ZR-1%NB ALLOY AND ITS PROPERTIES, I.V. Kolodiy*, A.N. Velikodnyi, V.N. Voyevodin, M.A. Tikhonovsky, N.F. Andrievskaya, G.Ye. Storozhilov

6. MINIMIZING THE RADIOACTIVE LEAKAGE INTO THE REACTOR CIRCUIT UNDER EXTREME CONDITIONS OF NORMAL OPERATION, S. Pelykh*, H. Zhou, M. Maksymov

7. THE SELF-POWERED NEUTRON DETECTOR WITH THE EMITTER OF HAFNIUM FOR DETECTING THERMAL AND RESONANCE NEUTRONS IN THE NUCLEAR REACTORS OF THE 2-3 GENERATIONS, A.V. Rybka, V.E. Kutny, B.A. Shilyaev, A.L. Ulybkin, K.V. Kovtun, A.O. Pudov*

8. AN ESTIMATION OF RADIATION EMBRITTLEMENT FOR WWER-1000 RPV WELD METAL USING THE CHARPY IMPACT AND FRACTURE TOUGHNESS TEST DATA, V. Revka*, L. Chyrko, Yu. Chaikovsky, O. Trygubenko, O. Shkapyak

9. THE INFLUENCE OF HE ATOMS ON THE FORMATION OF SMALL VACANCY COMPLEXES IN HCP-BERYLLIUM, A. Timoshevskii*, B. Yanchitsky, A. Bakai

10. A NEW METHOD FOR THE PREDICTION OF WWER RPV METAL CRITICAL TEMPERATURE OF BRITTLENESS, M. Zarazovskii*, I. Oryniak

11. SPENT NUCLEAR FUEL AND RADIOACTIVE WASTE MAGNETO-PLASMA REPROCESSING, V.B. Yuferov, V.O. Ilichova, S.V. Shariy, V.V. Katrechko, A.S. Svichkar, M.O. Shvets, E.V. Mufel, T.I. Tkachova

12. RESEARCH OF GRAPHITE ^{14}C WASTE FROM RBMK-TYPE REACTORS, B. Zlobenko*, G. Lysichenko, V. Skripkin, Yu. Fedorenko, S. Bugera

Group 6. Others Posters

1. OPTICAL PROPERTIES OF CARBAZOLE BASED FERROMAGNETIC NANOCOMPOSITE MODIFIED BY UV IRRADIATION, E. Harea*

2. NANOINDENTATION STUDY AND PHOTO-INDUCED EFFECTS IN AMORPHOUS $(As_2Se_3)_{1-x}$: Sn_x and $(As_4S_3Se_3)_{1-x}$: Sn_x CHALCOGENIDES, D. Harea, E. Harea, O. Iaseniuc, M. Iovu

3. APPLICATION OF FRICTION TECHNIQUES TO MANUFACTURING OF ADVANCES STRUCTURAL MATERIALS, D. Kocanda

4. DETERMINATION OF HYDROGEN IN ZIRCONIUM ALLOYS BY VACUUM HOT EXTRACTION USING GAS CHROMATOGRAPHY, S. Danilchenko, V. Kuznetsov*, V. Chivanov, X. Wu, L. Wu, W. Zhang

5. THE PROSPECTS OF CREATING NUCLEAR ENGINEERING BASED ON HELIUM-3, O. Prontsevych, I. Husarova

6. NANOSIZED ZIRCONIA AS A MEDIUM FOR CREATION OF HIGH-CAPACITY ENERGY STORAGE SYSTEMS, A.V. Shylo, A.S. Doroshkevich, A.I. Lyubchyk, T.E. Konstantinova

7. “GREEN” CORROSION INHIBITORS BASED ON BIOGENIC SURFACTANTS, V.I. Pokhmurskii, I.M. Zin*, S.A. Korniy, O.V. Karpenko

3 Oral presentations

3. 1 Session 1: Overview of National and International Research programmes/projects

THE JOINT PROGRAMME ON NUCLEAR MATERIALS OF THE EUROPEAN ENERGY RESEARCH ALLIANCE

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[9]Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Departamento de Tecnología, División de Materiales de Interés Energético, Avda. Complutense 22, 28040 Madrid, Spain

The goal of sustainability is common to all low-carbon energy sources. Generation IV reactors, along with the necessary fuel cycle facilities, are the nuclear energy way to sustainability. However, the operating conditions envisaged for these systems are demanding and will impact on the performance of structural and fuel materials. Materials capable of withstanding extreme conditions like high temperature, prolonged irradiation, and chemically aggressive environments, must be selected or developed, properly qualified, and their behaviour in operation fully understood. The safety and the feasibility of GenIV nuclear concepts and their optimization will depend crucially on the capability of the chosen materials to withstand the expected extreme operating conditions. Consistently, materials for extreme operating conditions are the topic of the present workshop.

The Joint Programme on Nuclear Materials (JPNM, www.eera-jpnm.eu) was created in 2010 as part of the European Energy Research Alliance (EERA, www.eera-set.eu) to coordinate European research on GenIV reactor materials. The reason for the focus on GenIV materials is the pivotal importance of materials in view of safety and sustainability of nuclear energy, as well as innovation in the energy field in general. As a matter of fact, some of the conditions expected in GenIV reactors are common to both current nuclear systems and fusion, as well as non-nuclear high energy efficiency systems. The large overlap between the topics addressed in this workshop and those in the focus of the EERA JPNM is the reason of the involvement of this platform in the organization of the workshop.

In this paper the goals, grand challenges, structure, roadmap, projects and strategy of the EERA JPNM will be briefly presented, with a view to promoting international cooperation on GenIV reactor materials, specifically having Ukraine as target country.

**Presenting Author*

OVERVIEW OF ATF RESEARCH AND ONGOING EXPERIMENTS AT THE HALDEN REACTOR PROJECT

R. Van Nieuwenhove

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The accident at the Fukushima nuclear plants in 2011 made it very clear that the choice of zircaloy as fuel cladding material leads to dramatic consequences under accident conditions, when the cladding temperature reaches 1000 °C. At these high temperatures, the strength of the material is reduced significantly and severe corrosion leads to additional heat generation and hydrogen release.

Since the Fukushima accident, a lot of research has been initiated all over the world to identify materials which can sustain much higher temperatures and which do not suffer from exothermic corrosion reactions liberating significant amounts of hydrogen. An overview will be given on the various routes which are pursued worldwide to develop new cladding materials. Besides the strength and corrosion resistance, the importance of hydrogen and tritium permeation through the cladding will be discussed as well.

At the Halden Reactor Project, a significant amount of research has been performed on investigating the effect of commercially available coatings on the reduction of corrosion. It was found that CrN coatings provide corrosion protection under BWR, PWR, CANDU and supercritical water reactor conditions. Furthermore, it was also demonstrated that an AlCrN coating provides perfect corrosion protection in liquid lead. Additional benefits from coatings, such as increased fretting resistance and reduction of hydrogen or tritium diffusion will be discussed as well.

Besides the cladding, new types of accident tolerant fuel types are being explored. These accident tolerant or improved fuel types have the characteristic that they have much higher thermal conductivity such that the amount of stored heat is considerably reduced. An overview of some of these fuel types will be given, highlighting their main advantages and limitations. Research has also been initiated at Halden to develop UO_2 fuel in which a small percentage of graphene is added for increased thermal conductivity. Pellets have been successfully produced for the first time in which such nanomaterial was included.

An overview of ongoing and planned experiments at the Halden reactor on ATF claddings and ATF fuels will be provided. It will be shown how the most important fuel and cladding properties can be monitored online by in-pile measurements.

CONCENTRATING SOLAR THERMAL SYSTEMS: HIGH RADIANT FLUX AND TEMPERATURE REQUIREMENTS

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Concentrating Solar Thermal (CST) systems are considered a promising option to achieve a more sustainable energy market. However, these technologies are at an early stage of development and a great R+D effort is still needed, with special emphasis on materials. These systems concentrate and transform the direct solar radiation into thermal energy that can be then used not only for electricity production, but also to feed endothermic industrial processes. Although current commercial applications of CST systems are within the temperature range of 125ºC-600ºC, temperatures above 1000ºC could be achieved if materials suitable for high solar radiant fluxes (>2 MW/m2) and high temperatures (>1000ºC) are available.

The temperature step from current 600ºC to more than 1000ºC is a very interesting goal because a significant efficiency increase would be thus achieved (for thermodynamic reasons, the higher the temperature the higher the efficiency of the CST systems). However, commercial materials currently available are not suitable for the required working conditions and further R+D is therefore needed.

Peculiarities of CST systems and the technical requirements to be fulfilled by innovative materials suitable to achieve higher temperatures will be explained in this presentation. Research infrastructures currently available at the Plataforma Solar de Almería (PSA) for this R+D effort will be presented also. PSA is the largest public R+D Centre in the World devoted to CST technologies (www.psa.es).

PPP INITIATIVE "RESOURCE MATERIALS" THE EU-UA HIGH-TECH COOPERATION

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National academy of sciences of Ukraine comes with a proposal to major scientific and technological initiatives "Advanced Long-lasting resource materials for Transport, Energy, medicine and environmental protection - "RESOURCE MATERIALS." It is considered in Cross-Cutting format.

The Objectives of PPP Cross-Cutting initiative "Resource Materials" are at creating the segment of new materials, critical products and components of products based on them, that have increased life service in infrastructure of energy, transportation, medicine and environmental protection by the implementation of the results of systematic researches and pilot-scale production technologies developed as well as subsequent commercialization through the Public-Private Partnership mechanisms.

The anticipated results of the PPP Cross-Cutting Program Initiative "Resource Materials" concern:

- The materials solutions for expensive infrastructures to replace the obsolete ones in EU countries and Ukraine;
- The collection of resource materials technologies covering the needs of the next step - the construction of new infrastructure;
- Rapidly developing Society, High-tech jobs in all EU countries and Ukraine;
- Reducing the migration tension due to the equalization of living standards;
- Reducing technological risks in the developing countries of the EU and at the EU borders;
- Industry Modernization;
- Development of transport systems: vehicles and equipment (ships, aircraft, electric vehicles, high-speed trains, highways, etc.) competitive for megaprojects like "New Silk Road" and the Trans-European Transport Network.
- A new generation of Power supply systems: hybrid storage, electric transportation and energy conversion;
- The new system of environmental protection and waste management;

Grounding on the expected results of the Program Initiative "Resource Materials", the EU and Ukraine will be able to develop series of projects for new infrastructures for transit corridors, transport, energy and environment protection facilities making future development sustainable.

INNOVATIVE HIGH TEMPERATURE MATERIAL CONCEPTS DRIVE CLEAN ENERGY TECHNOLOGIES FORWARD

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The transition to a low carbon future is a big challenge, which requires innovative technologies, materials and systems. The aim of the EERA-JP AMPEA "Advanced Materials and Processes for Energy Applications" is to foster a multi-disciplinary approach to develop enabling tools and new concepts for future emerging energy technologies. The main objective is to harness and integrate materials science and process innovation for high performance sustainable energy technologies, in order to enhance the long-term competitiveness of European Industry. One challenge is related to high operating temperatures which are required for many low carbon energy technologies e.g., concentrated solar power, geothermal, bioenergy and fuel cells as well as for highly efficient conventional energy conversion processes (e.g. gas turbines). In future process temperatures are expected to increase further for significant increase of Carnot-based efficiency. This trend requires new material concepts combining properties such as high thermal stability, corrosion resistance, sufficient strength and creep resistance at extreme temperatures, thermomechanical stability, specific thermal conductivity. In order to rapidly meet the new demands for materials, a number of aspects needs to be improved. It is mandatory to understand how alloy composition, microstructure, nanostructure and processing interact and affect performance and degradation of materials in operating conditions. In this context, multiscale material modelling needs to be developed to predict and control processes to give the desired properties and to predict lifetime.

PPO/2017-05-11

3.2 Session 2: High temperature degradation

EXPERIMENTAL TESTING AND FAILURE ANALYSIS FOR HIGH TEMPERATURE PLANT ENVIRONMENTS

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The safety and reliability of power generating facilities is strongly dependent on the integrity of their high temperature components. Maximising operating temperatures is the key to exploit energy efficiency, however the deformation and failure behavior under high temperature conditions must be understood and reliably predicted. Due to the nature of the energy market, fluctuations in demand and the availability of renewable energy, there is a great need for current and future energy generation facilities to be 'load-following' which can lead to interactive creep-fatigue failure mechanisms taking place. Weldments are often primary sources of failures due to their complex microstructures with a gradient in material properties in addition to the role of weld induced residual stresses. Most experimental tests, which underpin damage and defect assessments, have been performed in air, however it is important to understand the role of operating environment and aging effects on materials' long term behavior.

In recent years a number of developments have been made in high temperature creep strain and crack growth measurement and monitoring techniques. The digital image correlation technique has been used to characterise the creep strain behavior of the various regions of weldments in uniaxial samples and the creep strain development and crack growth in notched samples. In addition a novel low-frequency ACPD technique has been developed to monitor creep strains in test samples and components. Examples of these techniques will be presented and where appropriate, they will be compared to each other. Furthermore the low frequency ACPD technique has also been developed to provide measurements of creep crack initiation and growth. It benefits from low noise compared to the DCPD technique and thus provides more accurate measurements. The technique has been applied to a number of test samples and it's accuracy in measuring creep crack initiation has been evaluated and will be presented.

Novel tests samples have been developed to examine the influence of residual stress on creep crack growth (CCG), where the residual stress is either simulated in the sample as a fixed displacement or introduced using an electron beam (EB) weld. In the UK advanced gas cooled reactors (AGRs) the CO_2 coolant has been found to carburize the surface of some boiler components. The influence of carburization on creep and fatigue life of 316H stainless steel has therefore been examined. An overview of these recent experimental studies will be presented in addition to finite element model predictions.

PHYSICALLY-BASED MODELLING OF HIGH TEMPERATURE LOW CYCLE FATIGUE AND THERMO-MECHANICAL FATIGUE FOR 9CR FERRITIC-MARTENSITIC STEELS

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The drive towards increased use of renewable energy requires significantly more flexible operation of fossil fuel power plant such as combined cycle gas turbines (CCGT). The need for fuel and energy efficiency requires higher operating temperatures and pressures for such plant. Heat recovery steam generators (HRSGs), which fulfil a critical function in CCGT plant, are typically manufactured using martensitic-ferritic 9Cr steels, such as P91 and P92. HRSGs are a common location for premature cracking and represent a key design concern for next generation, high flexibility, high efficiency CCGT. Of particular concern is the potential for increased incidences of thermal fatigue, creep-fatigue, high temperature low cycle fatigue (HTLCF) and thermo-mechanical fatigue (TMF). Weldments are specifically susceptible to premature cracking, due to the inherent weakness associated with welding-induced microstructural heterogeneities, e.g. Type IV cracking in the inter-critical heat affected zone (ICHAZ).

Progress towards a physically-based modelling framework for design of next generation welded connections for high flexibility, high efficiency HRSG is described. 9Cr martensitic-ferritic steels are microstructurally-designed for high temperature creep performance under HRSG operating conditions, with a view to ultra-supercritical operating conditions for future plant. This includes a hierarchical microstructure consisting of blocks, packets and laths, along with precipitate, solute and grain boundary strengthening. A key challenge for predicting high temperature cyclic performance of such alloys, e.g. quantitative prediction of fatigue crack initiation, is simulation of the key physical micro-mechanisms of strengthening and softening. Hence, cyclic viscoplasticity modelling of 9Cr steels is presented for high temperature monotonic and cyclic loading of parent and welded materials and connections, including comparison with experimental test data and plant failure data. HTLCF and TMF experimental testing is employed for characterisation, as well as for calibration and validation of the modelling methods presented. The focus is on quantitative prediction of fatigue crack initiation and lifing models for elucidation of the effects of thermal history (temperature, in-phase and out-of-phase TMF), as well as the effects of welding-induced microstructure heterogeneity.

TOWARDS A PHYSICALLY-BASED MODELLING METHODOLOGY FOR 9CR STEELS UNDER HIGH TEMPERATURE FLEXIBLE OPERATION

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9Cr steels are a key candidate material for next generation power plant components operating at higher temperatures and increased flexibility due to their (i) high creep strength, (ii) high corrosion and oxidation resistance, (iii) favourable fatigue performance and (iv) relative expense compared to austenitic stainless steels and Ni-based superalloys. The high strength and high temperature performance of 9Cr steels is attributed to the complex precipitate and solid solution strengthened hierarchical microstructure, with the inclusion of 9 wt.% Cr and small amounts of Si providing the primary resistance to oxidation and corrosion. The key benefit of 9Cr steels for highly flexible operation is their low coefficient of thermal expansion and hence, reduced fatigue degradation induced on components compared to other candidate materials due to thermal transients. However, 9Cr alloys are susceptible to complex microstructural degradation including loss of the martensitic lath microstructure due to low-angle boundary dislocation annihilation leading to cyclic softening, strain- and thermal-driven particle coarsening, loss of solid solution strengthening due to Laves phase formation and $M_{23}C_6$ carbide depletion due to leeching of Cr and W to an oxide layer. Coupled with the high probability for failures of weldments due to the heterogeneous nature of the microstructure at such discontinuities, there exists an urgent requirement to develop a microstructure-sensitive modelling capability which can be implemented efficiently and effectively at the component level.

This paper presents a new physically-based model for 9Cr steels. Chemical composition and heat treatment represent key parameters for the performance of a 9Cr alloy, and hence, the proposed modelling framework is developed based on the material microstructure. A mechanistic and temperature-independent hyperbolic sine flow rule, derived from Gibbs free energy, is implemented to predict the strain-rate effect in 9Cr steels. The model incorporates a kinematic back-stress to account for the key strengthening mechanisms due to (i) MX and $M_{23}C_6$ precipitate strengthening, (ii) dislocation pile-up formation at high-angle grain boundaries and (iii) the dislocation substructure, as well as a dislocation-mechanics yield stress term driven by the evolution of the microstructure. The model, which relies on thermodynamic simulations and microstructural measurements to determine the initial phase, solute composition and precipitate microstructure of the material based on a thermal history, is implemented in a UMAT user material subroutine for use with the commercial finite element software, Abaqus. The model has been successfully applied to 9Cr steels across a range of strain-rates, temperatures and strain-ranges and demonstrates excellent agreement with experimental data, both at the macro-scale and via comparison with microstructure evolution measurements. Through the use of a physically-based yield stress term, the model illustrates excellent agreement with experimental data for a range of martensitic alloys, validating the microstructure-driven approach, with the addition of up to 3 wt.% tungsten predicted to significantly increase the strength of 9Cr steels. However, the loss of the hierarchical precipitate and solute strengthened microstructure is shown to significantly affect the high temperature performance of 9Cr steels. Hence, maintenance of this hierarchical microstructure and thermal stability of the precipitate and solute microstructure remains a critical goal for future 9Cr steel material developments.

RESEARCH AND DEVELOPMENT OF COATINGS FOR ZIRCONIUM FUEL CLADDINGS

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Zirconium alloys are used as a base material of fuel claddings in the WWER-type thermal neutron reactors. The Zr-based alloys, possessing a high chemical stability provided by the zirconium oxide film, are widely applied due to their low thermal-neutron capture cross-section, good mechanical properties and high waterside corrosion resistance at normal operating temperature up to 350 °C. However, in the case of accidents with increasing temperature, the zirconium cladding can no longer operate as a reliable barrier preventing fuel release into the coolant and the environment. The use of zirconium alloys in the GenIV reactors is also limited due to their low corrosion resistance in supercritical water. To prevent fuel cladding damage, it is necessary to protect the zirconium alloy from the high-temperature corrosion in steam as well in air. For protection of the zirconium cladding in case of an accident scenario like loss of coolant accident (LOCA) it is proposed to utilize corrosion resistant coatings.

The report presents the results on the development of coatings for the protection of zirconium claddings of the fuel rods in the case of LOCA, and under normal operating conditions. Results of own research into the effect of ion-plasma treatment on mechanical properties, corrosion resistance of zirconium alloy tubes, saturation of the hydrogen from gas phase, as well as resistance to high temperature oxidation in air and steam flow of the layouts of gas-filled fuel rods are presented. Information review on the international experience of development of such coatings is also given.

3.3 Session 3: Structural Materials Development for Energy Applications

DESIGN OF HEALABLE STEELS FOR ENERGY APPLICATIONS

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Metals are poor at self-repair due to the ambient temperature sluggishness of transformations compared to, for example, polymers. On the other hand, they respond well to external repair treatments aimed at macroscopic discontinuities (see, for example, repair of bridge steel cracks, worn turbine blades, forging of casting defects, etc.). This forgiving nature of metals, however, has not been utilized to focus on early stages of microscopic damage nucleation, where preventive healing becomes a more feasible option. The challenge thereof arises due to the complexity of plasticity & damage micro-mechanics, and phase transformation kinetics in multi-phase microstructures. For the case of power-plant steels, for example, the embrittlement is linked to spinodal decomposition, or the G-phase formation. In the Tasan Group, by developing ***multi-field mapping*** tools and methods, we improve our understanding of these microstructural processes, and by utilizing this understanding, we design ***resettable-alloys*****:** alloys where each microstructural constituent has the capability to revert back to its exact pre-deformation state, with feasible rejuvenation treatments. This ***design-for-reuse*** approach thus sets the foundations for the introduction of metals that can be used continuously. In this talk our investigations towards a resettable power plant steel will be presented.

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EFFECT OF AUSFORMING TEMPERATURE ON THE MICROSTRUCTURE OF GRADE G91 STEEL

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The development of novel thermomechanical treatments (TMT) has a high potential for improving creep-strength in 9Cr-1Mo ferritic/martensitic steel (grade 91) to operate at temperatures beyond 600ºC. In order to maximize the number of nanoscale MX precipitates, it was used an ausforming procedure at temperatures selected from the precipitation reactions, as supported by thermodynamic calculations from Thermo-Calc, to increase the number of nucleation sites for precipitation inside the martensite lath. Relative to standard heat treatments (consisting of austenization at about 1100ºC followed by tempering at about 750ºC), this new processing concept allowed to achieve in a steel grade 91 a microstructure containing approximately two orders of magnitude higher number density of MX precipitates having a size about four time smaller. On the other hand, this TMT has little effect on size and number density of M23C6 particles, since these carbides mostly precipitates along the lath boundaries and along the prior-austenite grain boundaries. The increase in the number of nanometre-size MX precipitates, which are very stable during long-term aging and very effective to pin dislocations, will cause a significant improvement on the creep strength, and could rise the temperature application up to 650ºC.

MATERIALS RESISTANT TO EXTREME TEMPERATURE AND PRESSURE FOR FUTURE HYDROGEN AND STEAM TURBINES, MODERN 2- AND 4-POLE NPP TURBOGENERATORS

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Power equipment on NPP and advanced FPP requires their modernization due to increasing of working parameters up to the super high, extreme level. Companies, which produce advanced energy equipment (for example - Turboatom (Kharkiv, Ukraine), Zorya-Mashproekt (Mykolaiv, Ukraine)) can produce energy units satisfy the requirements for the energy safety and efficiency. The production of future turbine equipment requires a wide usage of dispersive hardened heat-resistant Fe-Ni and Ni-Co alloys. Heat-resistant steels and alloys are exploited at high temperatures steam (up to 700 °C), hydrogen containing gas mixtures (up to 800…900 °C). Therefore one of the most important requirements for such steels and alloys is their resistance to high temperature, high pressure gaseous environments. In other words their ability to keep high level of mechanical properties under the action of hydrogen in wide range of exploitation parameters.

During long term service in hydrogen or hydrogen containing gas structural material has been alloyed by hydrogen. For example stable high nitrogen steels P-900 (for retaining rings of NPP turbogenerarors): 7…20 ppm; dispersive hardened steels (23Ni;1,5Mo;3Ti), (27Ni;1,5Mo;2W): 8…25 ppm; Ni-Cr-Fe alloys (Ni55Cr19Fe12Mo9Nb2) (for distributive face of combustion chamber of gas turbine), (63Ni;6Mo;3Ti), (Ni56Mo6Nb4), (Ni42Fe36Cr14Nb3Mo2) (for inlet gas turbine nozzle), Ni-Co alloys (Ni56Co15Cr9W6Al5Mo4, Ni64Cr14Co10Mo5Al3Ti3) (for gas turbine rotor disks and blades), which strengthenid by γ′ $(Ni)_3(Al,Ti)$ (stable up to 1100 ºC), γ″$(Ni)_3(Nb)$ (stable up to 1300 ºC) phases: 8…30 ppm. In most cases, the influence of steam, gaseous hydrogen on mechanical properties, plasticity, crack resistance weakens as pressure, temperature increases and the upper temperature of embrittlement under the analyzed conditions is equal 300 °C. At the same time, we reveal a significant decrease in the plasticity of heat-resistant nickel alloys in hydrogen under a pressure of 35 MPa at 800 °C. Maximum hydrogen effect on properties of Cr15Ni27Ti3W2BMo austenitic dispersion-hardened steel and Cr19Ni55Nb2Mo9Al alloy achieved on hydrogenated specimens at hydrogen pressure above 10 MPa. The comparison of the K_{th} threshold values of and the cyclic fracture toughness K_{fc} of 15Cr12Ni2MoNMoWNb and 10Cr15Ni27Ti3W2BMo steels has shown, that on the temperature dependence of K_{fc} and K_{th} of 15Cr12Ni2MoNMoWNb steel are absent the hydrogen embrittlement extremums. Hydrogen negative influence of the fatigue crack growth resistance characteristics of this steel, as a rule, essential and monotonic decrease with temperature increasing.

**Presenting Author*

MATERIALS UNDER EXTREME ENERGY AND PARTICLE LOADS: FROM SURFACE DAMAGE TO SURFACE MODIFICATION

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Simultaneous impacts of high energy and particle loads to the material surface are typical for material performance in various extreme conditions: space apparatus in upper atmosphere, operation of turbines, nuclear engineering, fusion etc. The paper discusses main features of material response to the repetitive powerful plasma impacts caused either the damage mechanisms and erosion behaviour or modification of surface layer and alloying with plasma species, aimed at improvement of material performance.

Influence of powerful plasma impacts on number of the energy system materials has been discussed: different tungsten grades, carbon fibre composites (CFCs), RAFM steels, hafnium, zirconium based alloys and Hastelloy N, EP-823 etc. Also modification of plasma sprayed coatings of Co-32Ni-21Cr-8Al-0.5Y and Ti64, various PVD coatings were studied. Material exposures with hydrogen, helium and nitrogen plasma streams was performed in high current pulsed and quasistationary plasma accelerators providing variation of power load to the surface and particle flux in vide range: energy density 1-25 MJ/m^2, particle flux up to 10^{28}-10^{29} ion/m^2s, plasma stream velocity ~500 km/s, pulse duration 1-250 μs. Highest energy loads were applied for material characterization in extreme conditions while moderate short pulsed loads were used for surface modification issues [1,2].

It is demonstrated that broad combination of mechanisms of powerful plasma influence on material properties includes not only the surface damage due to the different erosion mechanisms but also significant improvement material properties in surface layer of 20-100 μm, its structure and substructure due to high-speed quenching, shock wave formation, material alloying with plasma impurities. Fast heating and melting of the treated surface, giving rise to considerable temperature gradients (~10^6 K/cm) in the surface layer of material under the pulsed plasma impact. This contributes to high speed diffusion of plasma stream ions into the depth of the modified layer, resulting in phase changes in the surface layer and the formation in the course of subsequent fast resolidification the fine-grained or quasi-amorphous structures, which possesses the unique properties and advanced performance characteristics during subsequent tribology tests.

Creation of unique surface structures (including ordered nanostrucrures) and considerable improvement of physical and mechanical properties of different materials can be achieved also by pulsed plasma alloying i.e. pre-deposited coating modification and mixing by impacting plasma streams.

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**Presenting Author*

MULTICOMPONENT (HIGH ENTROPY) ALLOYS AS A BASIS FOR NEW GENERATION OF HIGH-TEMPERATURE MATERIALS

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In recent years, starting from the pioneering works of J. W. Yeh, S. Ranganathan, B. Cantor, D. Miracle, O. Senkov (2003-2007), etc. there have been extensively studied a variety of features in structure and mechanical behavior of a new class materials – high-entropy alloys. Most interesting consequence of the high entropy of the atomic mixtures is thermal stability of such alloys (both solid solutions and intermetallic phases).

Since 2008, such researches have been carried out in IPMS NASU. The basic laws have been established to understand formation and stability of solid solutions with BCC, FCC and HCP lattices, various intermetallic phases and amorphous state. The peculiarities of crystalline structure of such alloys exist due to significant lattice distortions and the formation of specific nanocluster structure, which has been observed under HRTEM (high resolution transmission electron microscopy).

The temperature dependences of the yield strength of solid solutions with BCC and FCC lattices and two-phase alloys will be widely discussed. The controlled distortions of the crystalline lattice inherent in such solid solutions were established to significantly affect the temperature-dependent and athermal components of the yield stress. The presence of a fairly wide plateau on this dependence σ(T) was revealed, which extends unchanged to temperatures of 1000 ^{o}C and even higher.

Due to this reason, and taking into account the "sluggish" diffusion, we can expect the creation of alloys highly competitive against with well-known alloys of Inconel and Haynes 230 types.

Such alloys can be considered matrix for some composite materials. The specific interest concerns their possible applications as nuclear energy materials, especially for the creation of such alloys using low activated elements.

It was also established that the high-entropy carbides and nitrides can be obtained in bulks and coatings with significantly increased wear resistance and hardness.

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FRACTAL NATURE OF NANO-MICRO STRUCTURE AND ENERGY

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Fractal microelectronics is a new developing topic that uses fractal nature to improve understanding, analyzing and modeling processes and developing advantageous methods for energy producing, harvesting and storage. In this sense the new experimental-theoretical approach frame methodology is developed by the authors. It includes theoretical models of fractal dimension extraction, building computer models that simulate an energetic source phenomena being studied (energetic cells, solar collectors, wind turbines etc.). The most experiments were done on ceramics capacitors by direct measuring of impedance for given fractal characteristics. The concept design main goal is to predict performances of final products, and their optimization. Through this method and results, we are opening the Fractal microelectronic new frontiers and technological processes, especially specific intergranular relations within grains surfaces coatings and thin film's fractal nature microelectronics. Since the fractal approach offers a coherence on the wide continuous metric scale from macro to micro world, even to nanoscale, it opens the new "window" for further development in achieving universality of relationship between forms and energy in the broad sense as well as miniaturization improvement.

**Presenting Author*

MICROMECHANICAL CHARACTERIZATION OF SIC-SIC FIBER COMPOSITE FOR ACCIDENT TOLERANT FUEL APPLICATIONS

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Silicon carbide is a candidate material for the use in novel accident tolerant fuel cladding due to its favorable properties, in particular reduced (compared to Zircaloy) oxidation under accident conditions, as well as good neutronic performance, high temperature strength and stability under irradiation. It is suggested to be used in the form of SiC-fiber reinforced SiC-matrix (SiC-SiC) composite.

Highly non-uniform and anisotropic nature of the composite materials means that in order to reliably model their behavior the knowledge of the individual properties of fiber and matrix, and, crucially, the fiber-matrix interfaces, is required. Micromechanical testing techniques, such as microcantilevers beam fracture, allow determination of such localized properties. This contribution reports the results of micromechanical measurements, coupled with microstructural characterization, on SiC-SiC composite material.

Material used in this study was provided by General Atomics. It consists of the commercially available Tyranno SiC fiber weaved reinforcement structure and matrix grown in-situ using the chemical vapour infiltration (CVI) technique. General structure of the composite, including fiber arrangement and porosity, was assessed using scanning electron microscopy (SEM) and X-ray tomography. Microstructure of fibers and matrix was characterized with electron backscatter diffraction (EBSD), transmission electron microscopy (TEM) and transmission Kikuchi diffraction (TKD) techniques. Micromechanical studies included hardness measurements on fibers and matrix performed with nanoindentation, and interfacial fracture tests using focused ion beam (FIB) manufactured microcantilevers, both at room and elevated temperatures.

Observed localized mechanical properties of fibers and matrix materials, and of fiber-matrix interfaces are presented, their correlations with local microstructure are discussed.

**Presenting Author*

3.4 Session: Irradiation damage

STATISTICAL PHYSICS FOR THE MODELING OF NON-EQUILIBRIUM METALLIC ALLOYS DRIVEN BY IRRADIATION

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In materials exposed to irradiation, the dissolution and precipitation of new chemical phases are currently observed. Two famous examples are the formation of late blooming phases in Reactor Pressure Vessel (RPV) steels and the dissolution of oxide nanoparticles in Oxide Dispersion-Strengthened (ODS) steels. Such phase transformations affect the mechanical properties, and more generally the stability of materials exposed to irradiation. These non-equilibrium phenomena are essentially controlled by the thermodynamic and kinetic interactions between the atoms of the materials and the point defects created by irradiation. Close to a point defect, the energy of an atom and its interaction with the neighboring atoms are modified. Moreover, the exchange between a point defect and a neighboring atom is the main mechanism responsible for the transport of atoms, the spatial redistribution of solute atoms and the formation of new phases. It will be shown by means of atomic scale simulations and statistical physics developments, how the formation/dissolution of phases and the resulting microstructure are related to the production and migration of point defects induced by irradiation. First example will be the study of stability of oxide nanoparticles in a model alloy Fe (X=C, N, O) of ODS steels. Second example will be devoted to the study of phase formation and solute segregation at grain-boundaries in Fe-based model alloys of RPV steels.

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*Presenting Author

IRRADIATION EMBRITTLEMENT AND RPV METAL SERVICE LIFE: STATE-OF-THE-ART AND CHALLENGES

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Lifetime extension of nuclear power plants (NPP) is the challenge for nuclear industry. In most cases, radiation embrittlement of RPV metal is the main factor limiting the service life of nuclear reactors. Prediction of both the degree of such embrittlement and its influence on integrity of the power unit are a challenging interdisciplinary problem. It requires both to develop physics-based models of radiation embrittlement of metals and to transform them into engineering approaches to prediction of RPV integrity under a long-term operation.

In addition to the considerable economic benefit, NPP lifetime extension will enable to get the invaluable information about micro-mechanisms of metal degradation in the conditions of long-term operation; the latter may be used to design new radiation-resistant materials.

In line with this, the report reviews the two main components of this problem, namely:

1. Micro-mechanisms of radiation embrittlement of RPV metal, and, in particular, "the late blooming effect".

2. Development of physics-based engineering methods for prediction of RPV integrity during their long-term operation.

In addition to the conventional analysis of micro-mechanisms of radiation-induced hardening, the report discusses the physical nature of decrease in the critical stress of fracture initiation (brittle strength) of irradiated metal.

Regularities of change in mechanical properties of metals not only *after* irradiation but also *under* irradiation are addressed in present report. It is shown that the mechanical properties during irradiation may differ from those after irradiation. This can influence the predicted value of NPP lifetime.

The report summarizes the existing engineering approaches to prediction of RPV integrity under *thermal-shock load*. In general, they don't enable to use directly advances of physics of fracture of the irradiated material. A large "gap" exists today between the physics-based models of degradation mechanisms and engineering models for assessment of NPP lifetime. It is shown that engineering version of the Local Approach to fracture, proposed by the author, can be one of the ways to solve this problem. It enables to account for physical features of resistance to fracture of irradiated metal in terms of fracture mechanics. The results of employment of this approach to predict life-time of RPVs of Ukrainian NPPs are presented.

F/M STEELS -PROSPECTIVE MATERIALS FOR GEN IV REACTORS. STRUCTURAL STABILITY AND SWELLING RESISTANCE DURING IRRADIATION TO HIGH DAMAGE DOSES

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Various nuclear concepts require high radiation stability of structural materials at very high exposures (>200 dpa), high temperatures (700^{0}C) and in any cases at super high levels of helium and hydrogen (few thousand of appm). Void swelling is a phenomenon with important consequences on dimensional and mechanical stability. Due to high swelling of austenitic steels (life-limited by swelling to <150 dpa with concurrent limitation on fuel burn-up to 10-12%) the nuclear materials community has moved toward ferritic and ferritic–martensitic alloys.

This presentation describes results of swelling investigations for wide spectrum of F/M model and commercial steels.

It is shown than all investigated alloys have a much better resistance to swelling than austenitic based materials.

Features of chemical composition and crystal structure are shown to result in characteristics of dislocations evolution, segregation processes and precipitates behavior.

In temperature irradiation range 430-550^{o}C parameters of voidage, duration of incubation period, range of doses where transition to steady stage occurs, swelling rate are determined. It is shown that value of swelling of ferritic steel may exceed 20%. FM steels can swell strongly even in the absence of He & H Obtained results show that radiation swelling of ferritic-martensitic steels is the critical parameter which may considerably limit the commercial use of reactors of 3-4 generation.

It is shown that the void swelling of oxide-dispersion-hardened alloys under irradiation is very sensitive to the details of oxide dispersion and can changes drastically from grain to grain. Based on our observations, the swelling resistance appears to be associated with a high and stable density of oxide particles and high grain boundary areal density with denuded zones. Obtained results show that low level of swelling can be attained not only by the increase of incubation period but also by decrease of stationary rate of swelling. Performed investigation had showed the high swelling resistance of steel in all studied range of doses and temperatures.

**Victor Voyevodin*

RADIATION-INDUCED SOFTENING VS. HARDENING EFFECTS IN METALS AND ALLOYS DURING SIMULTANEOUS ACTION OF IRRADIATION AND MECHANICAL STRAIN

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Defects formed under irradiation in the bulk act as additional pinning centers for dislocations resulting in the well-known effect of *radiation-induced hardening* (RIH*)*. On the other hand, there is a poorly understood but well-established effect of instant and reversible softening of metals subjected to various types of irradiation [1]. This *radiation-induced softening* (RIS) effect should be taken into account both in the theory of radiation effects and in the engineering approach for technological applications. In the present paper, the RIS vs. RIH effects are investigated in fcc Al, Al-3Mg, Cu, bcc Fe and Fe-based alloys. The effect of the *in situ* electron irradiation (E = 0.5÷0.8 MeV) on the flow stress of metals is compared with the effect of *in situ* neutron irradiation (E>0.1 MeV) on the internal friction of Fe-based alloys. Reversible decrease of the flow stress is detected in the former case, which has the same physical nature as the reversible increase of the internal friction in the latter case related to radiation-induced unpinning of dislocation from the obstacles. Rate theory of RIS is proposed, which takes into account the radiation-induced excitation of *moving discrete breathers* (DBs), i.e. large amplitude non-linear atomic oscillations, recently proven to exist in metals [2], and their interaction with dislocations, which facilitates their unpinning from structural defects [3]. We propose that a considerable amount of DBs with energies of the order of eV exist before decaying in the material under operational conditions as in a reactor, affecting substantially its properties and producing RIS. This phenomenon is overlooked if tests of material properties are performed after irradiation or "post-mortem" when the DB population has become negligible. It is of obvious importance for the nuclear materials industry since accurate prediction of the materials lifetime is essential and hard to make due to the difficulty and high cost of testing properties inside the reactor. The present results show that the actual reactor lifetime may be longer than presently believed.

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**Presenting Author*

RADIATION-INDUCED FORMATION OF HARDENING SOLUTE CLUSTERS IN FERRITIC/MARTENSITIC ALLOYS: AN OBJECT KINETIC MONTE CARLO MODEL

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High-chromium ferritic/martensitic steels are candidate materials in commercial GenIV reactors, as well as for the breeding blanket of the fusion DEMO. Despite an optimal resistance to swelling, however, these steels are penalized by low-temperature (<350°C) hardening and embrittlement. Recent investigations with atom-probe tomography (APT) have revealed that 3-4 nm diameter diffuse CrSiPNi solute clusters, invisible in transmission electron microscopy (TEM), are formed at ~290°C in high density (~10^{23} m^{-3}), at all Cr contents, both under neutron and ion irradiation. These TEM-irresolvable clusters are currently suspected to be important contributors to radiation hardening. Since no experimental technique is truly able to tell anything fully conclusive about the possible association of these solute clusters with radiation-defects and therefore their hardening properties, atomic-scale and microstructure evolution models are essential to cast light on their nature and formation process.

In this work, we present an object kinetic Monte Carlo (OKMC) model for microstructure evolution under irradiation that describes the formation of these clusters and is validated against available experimental data. The transport of these solutes is described in terms of dragging by single point defects, as derived from accurate parameters evaluated with DFT calculations. Our results show satisfactory agreement with APT in terms of density and size of solute clusters.

**Presenting Author*

IRRADIATION EMBRITTLEMENT OF AUSTENITIC STAINLESS STEELS IN PWR VESSEL'S INTERNALS – EXPERIMENTS AND MODELLING FROM MICRO TO MESOSCALE

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In PWR's, internals made of austenitic stainless steels (Cold Worked (CW) 316 austenitic steels for bolts, 308 for welds and Solution Annealed (SA) 304 for baffle plates, former and core barrel) are subjected to irradiation embrittlement with doses that will reach up to 80 dpa locally after 40 years of operation at temperatures between 280°C and 380°C. The irradiation exposure alters the nanostructure and so consequently do the mechanical properties of stainless steels: it increases the yield strength, decreases ductility and promotes plastic instabilities. Moreover, neutron irradiation at low temperature generally causes a reduction in fracture toughness of stainless steels. In addition, these changes seem to be the basis of an increased sensitivity to stress corrosion cracking said to be assisted by irradiation (IASCC). The tensile properties evolutions are commonly ascribed to the formation of a high density of nano-sized irradiation defects clusters mainly fine dislocation loops in stainless steels. Others defects (e.g. precipitates, bubbles and voids) may develop at higher doses. Homogeneous deformation that is observed for virgin material or at low doses is shifted to heterogeneous deformation at higher doses. Ductility loss is mainly ascribed to increased plastic strain localization. So far, much effort has been made to identify radiation effects on material microstructure and to determine experimentally the evolution of mechanical properties. Security and reliability of nuclear power plants have become a main issue and a better understanding of the physical mechanisms leading to the change in mechanical properties is now required. In addition it is also necessary to develop micromechanical constitutive equations to be able to carry out numerical simulations of core internals structures to improve safety and better study the possibility of extending the lifetime of nuclear power reactors.

This talk will present some recent works developed to assess the irradiation embrittlement of austenitic stainless steels in PWR's environment.

In the first part of the paper, recently proposed crystal plasticity physically-based constitutive equations for neutron-irradiated austenitic stainless steel that have been used in this study are described. The proposed model, based on the dispersed barrier hardening model, aims to capture the irradiation-induced hardening followed by softening due to the formation of defect-free channels on each slip plan during plastic deformation. Based on a dislocation dynamics inferred mechanism, hardening and subsequent strain localization due to dislocation motion impedment is also taking account. The proposed model is applied on single and polycrystals simulations of virgin and irradiated AISI 304 steels. Tensile curve predictions are presented and compare to experimental data.

Irradiation leads to voids formation in grains of austenitic stainless steel. When these austenitic stainless steels are subjected to loadings, ductile fracture happens as the results of void growth and coalescence. At initial stage of fracture, voids are much smaller than the grain size so that one can consider the voids as embedded in an infinitely large single crystal under homogeneous loadings. Thereby, it is necessaire to model behaviours of irradiated austenitic steels at the grain scale, i.e. single crystal. The second part of this talk will be devoted to the description of a multiscale modelling of growth and coalescence of pre-existing voids leading to transgranular ductile fracture of irradiated austenitic stainless steels. Based on continuum crystal plasticity theory, FE simulations are performed on unit cells for studying effects of lattice orientation and stress triaxiality on void growth and coalescence. The influence of post-irradiation hardening/softening on void growth and coalescence is evaluated with the physically based crystal plasticity model presented in the first part. Besides, an elastoviscoplastic model at finite strains is proposed to describe void growth up to coalescence in single crystals, and is assessed based unit cell simulations.

Last part of the paper will be devoted to IASCC. Firstly experimental investigations of the mechanisms of IASCC and the contribution of localized deformation in intergranular cracking of austenitic stainless steels in PWR environment using ions irradiation will be presented. Considering the intergranular nature of the cracking observed, determination of the mechanical fields at the grain scale was then assessed. A first approach investigates the stress distribution in polycrystalline aggregates based in crystal plasticity framework. Finally, it is discussed how these stress evaluations can be combined with a grain boundary failure criteria in order to predict cracking at the grain scale.

PROGRESS IN UNIFIED FATIGUE LAWS

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Fatigue design has seen significant progress in the last 150 years, but still many components structures, including critical energy systems exposed to severe conditions, fail by fatigue. Many design rules have been proposed, and in general following two separate approaches: the one originating from the classical Wohler curve approach, modified by a number of factors to consider surface finish, notch gradients and many other effects, and the one starting from Paris law, for fatigue crack propagation. The two schools also involve completely separate material constants. In the last 15 years, the first author and his collaborators have tried to unify several aspects of these, hoping to make the "best of two worlds" (see reference list). In present time, we are trying to extend this treatment to the very important case of variable amplitude loading. The presentation will elucidate this progress.

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**Presenting Author*

MECHANICS OF SURFACE DAMAGE: A NEW LOOK AT THE OLD PROBLEM OF WEAR

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Wear, the process of severe surface damage and eventual material detachment, causes a huge amount of material and energy losses annually, with serious environmental, economic and industrial consequences[1]. Resultant detached particles dreadfully contribute to the traffic-related particulate air pollution and critically impacts the performance of all mechanical systems ranging from automotive and aerospace sectors to biomedical devices and nano/micro electromechanical systems. Therefore, it is of critical importance to diminish wear by developing wear-resistant materials and coatings. To further this goal, a fundamental understanding of the microscopic origins of the wear process and particle formation event is crucial.

Despite the three-centuries-long history of inquiry into the subject[2-4], wear remains one of the least understood areas of mechanics and our understanding remains fully empirical. One reason for that is that the mechanics of wear emerges from a rich variety of mechanisms (e.g. friction, severe plastic deformation, fracture, and fatigue) at disparate time and length scales under extreme conditions (e.g. high temperature, oxidation, radiation, large electrochemical forces and thermo-mechanical stresses). This complexity has restricted wear prediction to fully empirical models with limited transferability.

In this talk, we present a new look toward the understanding of wear mechanisms and the physical origins of material detachment process. Using a novel numerical technique, we show that there exists a critical length scale, above which surface asperities lead to "fracture" and thus produce wear debris particles while the smaller ones merely exhibit "plasticity"[5]. Inspired by this new finding, we also statistically examine the origins of the wear coefficient, viewed as the probability of debris formation at the contact and the influencing parameters[6]. In addition, we provide an exact prediction of detached volume at the most fundamental level, i.e. wear debris particles, which opens the possibility of developing new physics-based wear models with increased predictive ability[7].

Overall, these new understanding shines new light on longstanding challenges in wear by localizing the problem from the level of purely empirical fitting to the level of physics and mechanics of surfaces. Microscopic and macroscopic wear observations and models are then discussed, and a roadmap for future studies is presented.

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NANOFLUIDS FOR EMERGENCY COOLING OF OVERHEATED SURFACES OF POWER EQUIPMENT

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To prevent accidental overheating in metallurgy, electrical engineering, power engineering, etc. we have developed nanofluids (NFs) stable under high-temperature boiling and radiation. The principled possibility of NFs use for emergency cooling of a superheated heat exchange surfaces was studied. For this it was created the automatic unit for simultaneous recording of NFs boiling curves and the changes of the main parameters of heat transfer (heat flux, heat transfer coefficient and temperature of the heating surface) in a real time at conditions of a constant rise of a velocity of specific heat load.

There were investigated NFs on the basis of metals oxides, aluminosilicates and carbon nanomaterials (CNM). Nanodiamonds, multi-walled carbon nanotubes (MWCNTs) and graphene FLG (Few Layers of Graphene) obtained from thermally expanded graphite (TEG) have been used as CNM. MWCNTs and TEG produced on the pilot plants of Gas Institute of NAS of Ukraine.

Studies have shown the possibility of increasing the critical heat flux (CHF) into 2-3.5 times, compared to distilled water. The effectiveness of emergency cooling of a superheated heat transfer surface by NFs addition into a boiling water in the case of boiling crisis was explored.

It was found that the introduction of small portions of NFs into a boiling coolant (distilled water) in a state of film boiling ($t_{heater} > 500^oC$) can dramatically reduce the temperature of a heat transfer surface to the level of 130-150^{o}C, which corresponds to the transition to a safe bubble boiling regime with no reduction in a heat flux. Thus it's very important that this mode continues long enough at a specific heat load exceeding the critical heat flux for water and at the t_{heater} = 125-130^{o}C. This makes it possible to prevent a potential accident (e.g., like LOCA – loss of coolant accident) resulting in a damage to the nuclear reactor vessel) and to ensure the uninterrupted operation of the equipment or perform the accident-free stoppage.

We have obtained the convincing evidence that increased heat transfer and cooling capability of NFs at their boiling in comparison with water is associated with the changing of a nature and microrelief of a heating surface due to the deposition of a structured layer of nanoparticles, providing the stable bubble boiling regime.

On the other hand it is known that many nuclear power plants with water cooling have limited power reserve till arising of a critical flux and heat transfer crisis during boiling. Our research has shown that the use of NFs as a cooling agent not only allows to increase CHF on 100-200%, but also to avoid a sudden boiling crisis, in contrast to a single-phase coolant (water). It promises not only for direct economic benefits, but also to increase the level of NPP safety in general.

Gas Institute will continue researches devoted to nanofluids applying together with NNEGC "Energoatom".

3.6 Session 6: Environmental and Corrosion Effects

CHALLENGES OF MATERIALS QUALIFICATION FOR NUCLEAR SYSTEMS WITH HEAVY LIQUID METAL COOLANT: EFFECT OF LBE ON MATERIALS PROPERTIES

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Innovative nuclear reactor systems with heavy liquid metal coolants provide new opportunities and number of advantages for safety and performance compared to existing systems. Nevertheless application of a new coolant creates new challenges. One of these challenges is selection of structural and functional candidate materials able to withstand high temperature heavy liquid metal environment in combination with fast neutron irradiation. Another important issue is incorporation of environmental degradation effects of structural and functional materials into the design of nuclear installation. Two of these effects Liquid Metal Embrittlement (LME) and Liquid Metal Corrosion (LMC) are of greatest importance for lead based coolants.

LME cause deterioration of various mechanical properties of originally ductile metal in contact with specific liquid metals. In the last decade large numbers of tests have been performed to investigate the compatibility of steels with liquid lead-bismuth eutectic (LBE). It was found that one of the promising candidate materials ferritic-martensitic steel T91 indeed demonstrates susceptibility to LME (Figure 1). Moreover the materials properties used in the reactor design as for instance fracture toughness are significantly affected by LBE and it has different parametric dependence in comparison with the fracture toughness measured in an inert atmosphere. If LME effect can be incorporated in the design of nuclear installation is still under discussion. However, for the nuclear system under development the decision was made not to use T91 steel as the candidate material for structural components due to its susceptibility to LME. This decision had consequences for the design as for instance reduction of temperature limits and therefore lowers performance of nuclear installations.

LMC is complex physicochemical phenomena, which might result in significant losses of material if appropriate corrosion mitigation measures are not applied. The three major modes of corrosion are of particular importance for steels exposed to lead based alloys are oxidation, dissolution and erosion corrosion. For the austenitic stainless steels considered currently as the principal candidate materials for nuclear systems with lead based coolant the dissolution mode of corrosion is the most important components lifetime limiting phenomena. The mechanism of this phenomena is not completely understood despite of many investigations performed. It was found that microstructure of the material as well as deformation might have effect on the development of the corrosion damages. Various corrosion mitigation approaches are under development now and the most promising path is surface modification of steels to create corrosion resistant layer. Development of these technologies and qualification for application in components of nuclear systems are the subjects for combined efforts in framework of European projects.

Synergetic phenomena are the most challenging subjects for investigation due to limited knowledge and limited availability of irradiation facilities. Few irradiation experiments performed so far revealed enhance of LME effect in irradiated T91 steel and contradictory evidences on the effect of irradiation on LMC. Further programs are required in order to investigate effect of irradiation on surface modification technologies for corrosion mitigation.

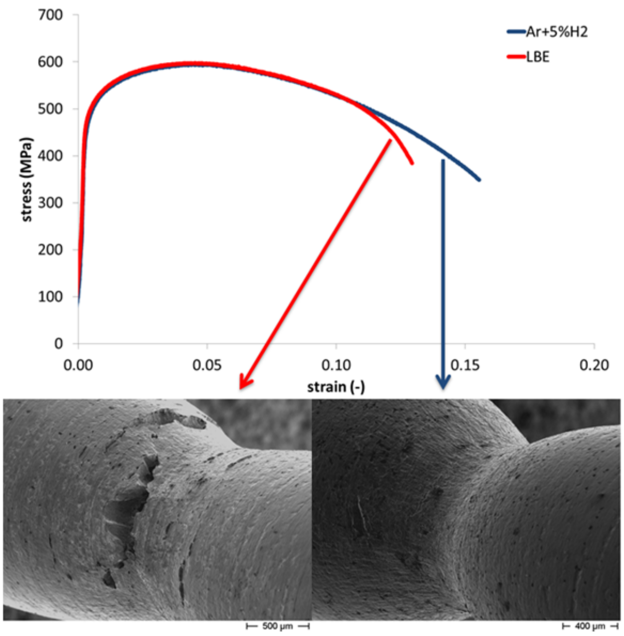

Figure 1. Liquid Metal Embrittlement of T91 steel in liquid lead-bismuth. (a) Stress-strain curves of T91 obtained at 350 °C in argon-hydrogen mixture and in LBE; (b) necking region of the specimen tested in lead-bismuth; (c) necking region of specimen tested in argon-hydrogen mixture.

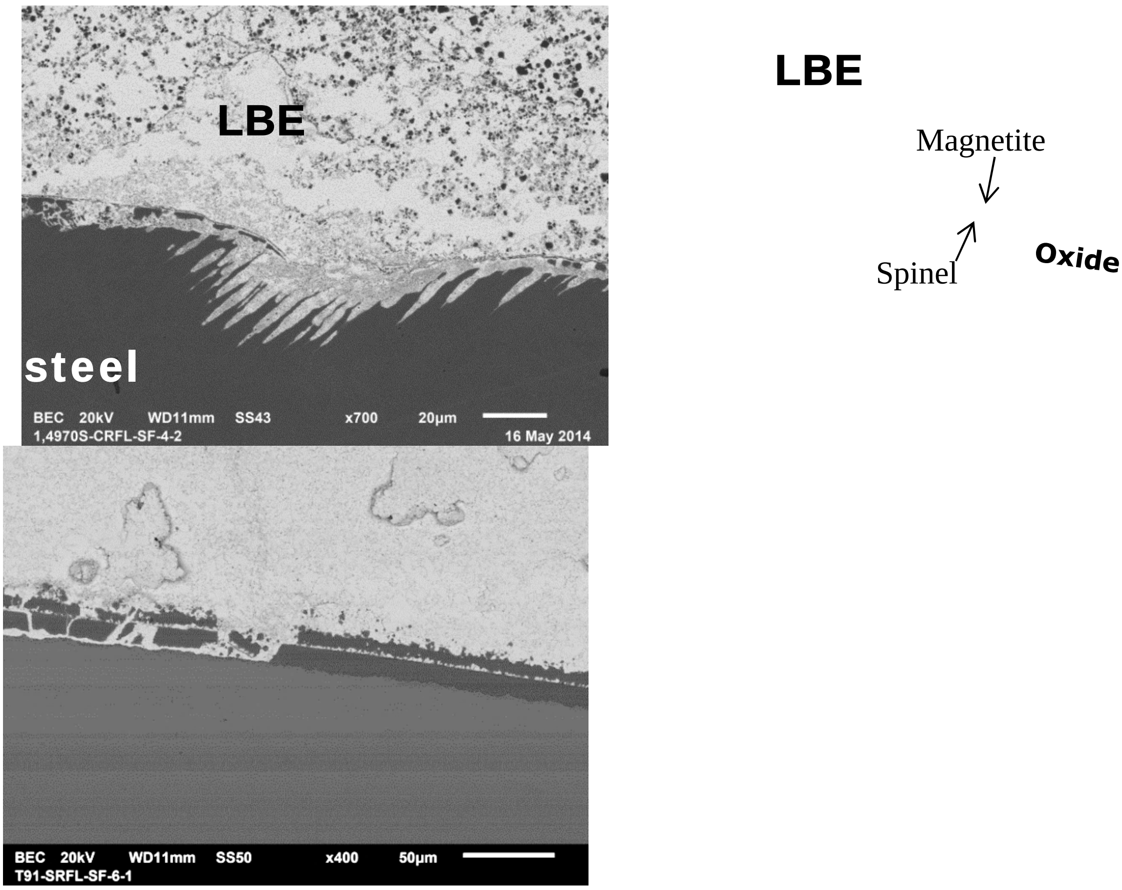

Figure 2. Liquid Metal Corrosion effect (a) dissolution zone in 1.4970 steel; (b) oxidation of T91 steel. Exposure in CRAFT loop in LBE flow of 2.2 m/s at 500 °C and oxygen concentration $7{\cdot}10^{-7}$ wt%.

ELECTRON IRRADIATION TEST FACILITIES AND METHODOLOGIES FOR CORROSION ASSESSMENT AND DESIGN OF REACTOR STRUCTURAL MATERIALS

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Design, tests and commissioning of the structural materials for nuclear reactors takes a long time due to hard specific requirements. Creation and improvement of materials for operating reactors (majority of them belongs to Generation II and III, i.e. G-II and G-III) is continuing for many decades. According to the Road Map of G-IV nuclear technologies the next generation reactors, with new operation conditions, have to be designed and put into operation in 2030 or later. Despite the experience gained in the design and use of structural materials for reactors of previous generations, we still face a tremendous challenge of creating advanced materials of the next generation. Therefore, to meet the tight schedule the efficient technologies for design and tests of advanced structural materials for G-III+ and G-IV reactors have to be developed.

In this communication, the Electron Irradiation Test Facilities (EITFs) built in the National Science Center Kharkiv Institute of Physics & Technology (NSC KIPT) and methodologies developed for corrosion tests of advanced structural materials for Molten Salt Reactors (MSR) and for Water Cooling Reactors (WCR) are described. In these facilities the 10 MeV electron irradiation is used to activate the corrosion kinetics within the loop with circulating subcritical and supercritical water.

Results of tests of two Hastelloy-type alloys and carbon composites in EITF (as structural materials for MSR) are reported. Samples of ferritic-martensitic steel, nickel-based alloys with welding joints and Zr-Nb alloy were prepared and tested using the EITF within the water circulation loop. Microscopy and microstructural analysis were the most useful instruments for studying pre- and post-irradiated samples. First results obtained during investigation of mentioned materials demonstrated the efficiency of the developed methodology, which allows one to estimate impact of the irradiation and temperature on the corrosion rates of tested materials. Comparison of the irradiation effect on corrosion of Zr-Nb alloy in pile and in the EITF was performed. We found that one-month corrosion test within the EITF loop is comparable with 10 years corrosion within the CANDU reactor.

In this communication I would like also to highlight the significant contribution of the theoretical group that designed the EITF, simulated the irradiation kinetics and participated in the analysis of the test results.

We are planning to use these facilities for investigations of the stress-corrosion cracking and fatigue-corrosion of advanced WCR structural materials as well as structural materials for G-III+ water-cooled reactors. To this end, the EITF has to be properly modified.

Our experience shows that synergism of active international cooperation is needed to get required results in a reasonable time period using our facilities and methodology to assess advanced structural materials for water-cooled G-III+ and G-IV reactors.

CORROSION ISSUES IN STEELS CONTACTING Pb-Bi EUTECTIC AT HIGH TEMPERATURES – OVERVIEW OF KIT ACTIVITY

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Development of novel reactors foreseeing using of Pb or Pb-Bi eutectic as a coolant and/or spallation target in contact with steels requires considering compatibility issues caused by aggressive corrosion nature of lead melts at high temperatures which results in leaching of main steel constituents (Ni, Cr, Fe etc.) and marked material loss. Corrosion resistance of steels, however, could be improved by means of controlled in-situ oxygen addition into the liquid metal via gas or solid phases, promoting oxidation of the steel constituents and mitigating, in that way, more severe leaching attack. In this presentation, an activity of Karlsruhe Institute of Technology (KIT) regarding actual state-of-the-art of corrosion issues is overviewed based on the results obtained during last five years of experimental activity using a forced-convection loop "CORRIDA" (CORRosion In Dynamic lead Alloys) and Oxygen Control System (OCS) constructed and operated in KIT.

Long-term corrosion behaviour of candidate austenitic (1.4970, 316L) and ferritic/martensitic (T91) steels is discussed with respect to the phenomena and kinetics of corrosion processes depending on temperature (400-550 °C) and oxygen concentration in liquid metal (10^{-6} – 10^{-7} mass %O). Peculiarities of oxidation and solution-based leaching are revealed. It is specified that a local solution-based attack, started as a results of degradation of oxide layer initially formed on steel surface, is a critical factor affecting corrosion resistance of steels in oxygen-controlled Pb-Bi eutectic.

The obtained results testify about substantial influence of structural state of steels on their corrosion response to the Pb–Bi melt. It plays an important role in the origination and growth of oxide layers and subsequent development of local corrosion attack. Therefore, the specific attention is paid to the effect of the structural state of the steels, like a grain boundary type distribution in material and state of boundaries with respect to the accumulated stresses, on their corrosion response to the liquid metal. Information on grain-boundary character distribution is analyzed quantitatively by applying Scanning Electron Microscopy based Electron Back Scatter Diffraction (SEM-EBSD) / Orientation-Imaging Microscopy (OIM). Effect of structural state of steels on oxidation and solution corrosion modes is discussed.

The prospective of Alumina-Forming Austenitic (AFA) stainless steels with improved creep resistance and oxidation resistance in gas media at high temperatures is discussed with respect to the applicability in Pb or Pb-Bi eutectic based on the initial experimental results.

**Presenting Author*

MODERN DESTRUCTIVE AND NON-DESTRUCTIVE METHODS FOR EVALUATION OF IN-SERVICE DEGRADATION OF STRUCTURAL STEELS OPERATED IN AGGRESSIVE ENVIRONMENTS

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During long-term service structural steels, especially in extreme conditions, can degrade. Embrittlement, deterioration of mechanical and corrosion properties is often the results of in-service degradation. A significant decrease of mechanical properties of operated steels, mostly brittle fracture resistance, in comparison with them in as-received state can finally cause structure failure. Because corrosive hydrogenating environments are typical for energy infrastructure and belong to extreme conditions, corrosion is a key issue in safe operation: it accelerates in-bulk material degradation due to a destructive role of hydrogen absorbed by metal during corrosion. Therefore, working environments should be considered as aggressive not only from the point of corrosion damaging of metal, but also as a source of hydrogen, which together with working stresses facilitates a development of in-bulk damages on nano- and microscales. It is often the main reason of decrease of energy infrastructure materials characteristics of brittle fracture resistance under long-time operation.

Deterioration of responsible steel structures under operation calls for effective methods for condition evaluation. Destructive and non-destructive methods for an evaluation of in-service degradation of structural steels are considered in the paper. The structural elements of oil and gas transit pipelines, oil storage tanks and other structures operated during 30–100 years were studied. All these objects were undergone hydrogen accelerated in-bulk material degradation during long-term service, so these studies are jointed by the same scientific methodology.

It was shown that the most sensitive characteristics for an evaluation of in-service degradation by destructive methods are impact strength, fracture toughness (*J*-integral), resistance to stress corrosion cracking and fatigue strength. Sensitivity of these parameters to in-service degradation assessment can be increased by preliminary hydrogen charging of tested specimens. Some peculiarities, which do not allow defining correctly a level of materials degradation, are considered. For example, elongation cannot serve as characteristic of materials plasticity, if it detects an opening of in-bulk multiple microcracks: in such case elongation is increasing, however brittle fracture resistance is decreasing. Another important feature is essential influence of cutting direction on results at testing specimens from steels manufactured by rolling. Thus, hydrogen absorbed by metal facilitates delamination between fibers of microstructure and this negatively influences on integrity of structural elements. Nevertheless, if the main crack at mechanical testing cross such delamination damage, resistance to fracture, for example, impact strength, are increased.

From non-destructive testing methods, which do not in any way breach the integrity of the tested structure, the special attention is paid to the electrochemical one. It is based on a good correlation found between relative changes in electrochemical and mechanical characteristics of structural steels caused by their operational degradation and it enables non-destructive in-service assessing of the level of materials degradation.

Presenting Author

BASALT-BORON FIBER AS REINFORCEMENT OF COMPOSITES FOR NUCLEAR ENERGY APPLICATIONS

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The sustainable development of nuclear energy is bound to be improbable without implementation of new structural materials that will have the desired strength, durability, radiation shielding properties, as well as cost-efficiency. The accident at the Fukushima Nuclear Power Plant (NPP) has acutely displayed the problem of the development of new structural materials that can permit the stable operation of NPP for a long period of time. There is also the necessity of using new construction materials with similar properties for intermediate storage of high-level waste (HLW) and spent nuclear fuel (SNF) for countries with "deferred disposal" strategy.

One of the frequent and recurring problems of concrete used in industrial applications is cracking. Cracking leads to the penetration of moisture into concrete which leads to gradual degradation eventually destroying reinforcing elements. For this reason, cracking can be considered as the main reason of degradation in construction and building materials. This problem becomes even more important in case long construction and maintenance periods. For example, NPP, HLW and SNF storages, and other repositories should in theory operate tens or even hundreds of years. And concrete structures designed for such purpose should ensure not getting radioactive wastes into the environment for such a long operating life. As noted from previous literature, cracking can be considered as the main reason of degradation in NPP. It is noted that the simplest and most practical solution is the use of fiber reinforcements in concrete which has been observed to decrease the probability and ratio of crack formations. Fiber reinforced concrete has the following advantages: modification of cracking mechanism in post-elastic phase, so that fiber can bridge cracks. Basalt fiber (BF) is a relatively new product that has been the focus of several investigations in recent years. BF can be considered as environmentally safe and a non-toxic product. The reinforced concrete with BF will have following advantages: (1) high chemical and corrosion resistance, (2) longevity, (3) high abrasion and shock resistance, (4) high frost resistance. Application of BF reinforcement could significantly reduce the cost of the concrete without sacrificing mechanical properties.

The analysis and consideration of the radiation shielding properties of concrete are essential for NPP applications where the obvious risk of radiation exposure exists. In this study, we would like to draw attention to the investigation of gamma-ray and neutron radiation shielding of concrete with basalt-boron fiber.

**Presenting Author*

4 Posters

A METHODOLOGICAL APPROACH FOR SELECTING STEAM TURBINE BLADE MATERIALS

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Albania has no turbine manufacturing industry and research activity in this field is modest, but the current education of future engineers at the Polytechnic University of Tirana aims to help bridge this gap. We seek to prepare them to become promoters of the energy sector modernization, able to communicate and establish effective cooperation with their counterparts in developed countries. To illustrate this idea, we present a case study that we develop with our students of the master level, using the Ashby's methodology and the CES software. The case concerns the selection of materials for stationary steam turbines; we take a SST-6000 type turbine as a basic reference and search for the ways of the performance improvement – mainly related to the materials quality of their blades.

Based on the turbine operating principle, we derive the materials selection procedure into two subprojects, having differing inputs:

- First stage blades must be able to work at the highest values of pressure and temperature (up to 300 bar; 720ºC); so, the appropriate resistance to the bending loads in creep and fatigue conditions is the most challenging requirement.
- Last stage blades, being larger and working at higher speeds, must withstand the great traction loads resulting from the centrifugal forces, in addition to unstable vibrations, which cause high alternating stresses. The severe centrifugal load stresses that when combined with the alternating stresses are responsible for fatigue failures. Consequently, the high specific strength and the resistance to the crack propagation are the most important requirements that the material must meet. Other requirements are the resistance to the steam oxidation and to the cavitation-corrosion.

Using the CES software, we perform the screening of all the materials stocked in the database and we rank them according to their performance indexes. Such indexes, for the first stage blades include mainly the maximum service temperature, the fatigue strength and the resistance to steam oxidation. For the last stage blades, the main indexes are the specific strength and the fracture toughness. Among the "winners" for both types of blades appear the austenitic, ferritic and martensitic stainless steels, while the best materials for the first stage of the USC turbines are Ni-base super alloys. (e.g., some Inconel and Haynes® alloys).

The case study is finalized by acquiring additional information for the "winners", related to technological aspects of their manufacturing processes. The opportunity of the application of different barrier coatings is discussed too.

**Presenting Author*

FATIGUE BEHAVIOR OF 316L AUSTENITIC STEEL IN AIR AND LWR ENVIRONMENT WITH AND WITHOUT MEAN STRESS

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The influence of mean stress on fatigue life of 316L austenitic steel in air and light water environment at 288 °C was determined using load-controlled experiment. It was observed that the mean stress has essentially a beneficial effect on fatigue life due to the extra cyclic hardening it induces. The stress-fatigue life curve (S-N curve) without mean stress in LWR environment was shifted towards smaller N values comparatively to the S-N curve in air, re-flecting the detrimental environment influence. The shift was found in good agreement with shifts previously observed of the strain-fatigue life curve (ε-N curve) for similar environ-mental conditions. Fatigue data obtained from load-controlled experiments with and without mean stress were found to be consistent with strain-controlled experiments when correlated with one another using a slightly modified Smith-Watson-Topper parameter.

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*Presenting Author

HIGH TEMPERATURE MATERIALS FOR MOST EFFECTIVE THERMIONIC CONVERTERS OF HEAT ENERGY INTO ELECTRICAL ONE

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Technological approaches to use the unused high temperature (about 2000K) heat energy of thermal power stations to convert it directly into additional electrical one have been elaborated. We suggest to convert the lose heat in burners of combustion chambers into electrical energy with the help of thermionic converters. The last have been the devices, in which two electrodes are corresponded the coaxial cylinders made from Mo or W single crystals by about 1 mm thickness with 0.2-0.3 mm gap between them. One of electrodes is the emitter and the other is the collector of electrons. Emitter is heated by burner, collector is cooled by water and, therefore, temperature difference between them can achieve 800-1000K. In interelectrode space cesium is placed to decrease the electron work function of emitter as much as possible when cesium atoms will absorbed onto emitter surface. As sequence the potential difference and electric current has appeared between electrodes.

The cylinder electrodes made from single crystalline strips by spiral twisting around shaft at elevated temperatures. After twisting the spiral joints welded by electron beam. Such technology has provided the achievement of two most important features of electrodes. The first, crystallographic orientation with the most absorption energy of cesium atoms at any point of the cylinder surface is the same. The second, the dislocation substructure strengthened the electrodes has been formed at twisting deformation. Such structure composed of the excess dislocations of one sign is provided the maximal creep resistance of electrodes at 2100-2200K and tangential stress 10 MPa. By this creep mechanism during one test is changed from dislocation into diffusion one. Creep rate was not exceeding 10^{-12} s^{-1}. It was directly shown by the life test of rings cut from the cylinders.

The materials for surface protection, electric insulation, and vacuum seal of thermionic converters and the methods of their manufacturing have been also elaborated and proven. It was shown that electrical power, which one can get in converters, may achieve 20 W/sm^2. It was estimated that at mass production of thermionic converters and their use in thermal power stations (to insert thermionic converters sequentially with water-steam devices of power stations) the coal saving will achieve 20% and water saving will achieve 28%.

NUMERICAL INVESTIGATION THE EFFECTS OF GEOMETRICAL PARAMETERS ON FRACTURE CHARACTERISTICS OF NOTCHED SMALL PUNCH TESTING SPECIMENS

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The non-destructive techniques have the great advantage to evaluate the material properties in-situ, in particular the small punch test shows to be very attractive and promising as it relies on a small, but representative material volume of the component in-service and it has been successfully applied in other research fields. Widely used specimens of small punch testing in literature, are round and flat specimens. However, the existence of micro-cracks and microstructural irregularities enforces the usage of specimens with a pre-defined notch, in an attempt to model such irregularities. As it is a newly emerging testing technique, there is currently very limited research on the effects of a predefined notch on fracture characteristics of specimens.

Therefore, the aim of this study is a numerical investigation of the effects of geometrical parameters of a predefined notch on fracture characteristics of small punch testing specimens. Taking the experimental research of notched specimens published by Turba et.al, finite element based study of small punch fracture specimens made of P91 steel, have been modeled in ABAQUS. Calibration of the finite element model is performed by modeling the benchmark experiment. Then, using this model as a departure point, geometrical parameters of the predefined notch (such as notch radius, placement, depth) have been varied and the effects of such geometrical changes on fracture response of the specimen is investigated numerically.

**Presenting Author*

SIZE EFFET AND INTER-GRANULAR LOCALIZATION IN POLYCRYSTALLINE MATERIALS

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Structural materials in the reactor pressure vessels are exposed to a harsh environment, resulting in a number of material degradation processes. Irradiation generates a number of point defects in the atomic structure of a material. In addition, plastic slip localization occurs on the grain level size where highly deformed narrow bands free from irradiation (e.g. clear bands) appear already at the moderate strain levels. Moreover, inter-granular stress localization is observed due to the grain boundaries and the interaction between the slip bands. The grain boundaries results in grain boundary damage increasing the possibility of inter-granular cracking. The size of the grains and the orientation distribution are other crucial micromechanical features affecting the constitutive and degradation behaviour. The classical phenomenological constitutive models are not capable of modelling the intra-granular, inter-granular plastic localization and the size effect phenomenon due to the plasticity at the grain boundaries. For this reason, micromechanically motivated constitutive models have been developed taking into account the effect of microstructural features on the plasticity and damage behaviour of the material. In this context, strain gradient crystal plasticity approach is one of the microstructural models which links dislocation slip activity occurring at micron scale to the macroscopic engineering problems. In this work, the behaviour of polycrystalline materials is studied through a strain gradient crystal plasticity framework which considers the displacement and plastic slip as global solution variables and takes into account the effect of plastic slip gradients on the hardening behaviour. The model is able to capture the localization due to orientation mismatch at the grain boundaries and it is possible to describe the boundary conditions for plastic deformation at the grain boundaries. The single crystal behaviour is extended to aggregates containing up to hundreds of grains through Voronoi tessellation to model the inter-granular stress localization in the context of finite element method. Macroscopic stress-strain responses and microscopic stress and strain distributions are presented for various boundary value problems for different loading rates, grain boundary conditions for microstructures having different number of grains and grain size. The plasticity behaviour at the grain boundaries is obtained at different loading and boundary conditions which allows us the incorporation of crack opening and propagation models in the future for the simulation of inter-granular fracture phenomena. The simulation of polycrystalline materials with strain gradient crystal plasticity framework is quite limited in the literature where only small number of grains and simple shapes have been considered. Therefore, the current study enables us to get more realistic conclusions considering large number of grains and more complicated grain structures.

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**Presenting Author*

AN XFEM BASED ALGORITHM FOR FATIGUE CRACK GROWTH PATH AND LIFE EVALUATION UNDER VARIABLE AMPLITUDE LOADING

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Fatigue crack growth (FCG) path and life estimation of structural components exposed to fatigue loading is a crucial issue in various industrial areas. A number of commercial tools have been developed up to now, to solve the FCG problem of a predefined planar crack under either constant or variable amplitude uniaxial loading. But, most of the industrial components, especially in aircrafts and energy systems, are usually under the action of mixed mode loading. Hence, the propagating crack paths are mostly curvlinear, contrary to assumption of damage tolerance approaches. Experimental studies are inevitable in this area, however they are quite lengthy, therefore cost effective, practical and reliable computational models for fatigue crack growth (FCG) path and life evaluation under practical service loading conditions are required in the industry. In view of this deficiency, main objective of the undertaken work is to propose a general reliable and practical computational methodology for FCG analysis of curvilinear cracks exposed to variable amplitude loading.

In this context, a mesh independent automatized computational algorithm for crack growth analysis under mixed mode loading has been developed. The betting algorithm calculates the stress intensity factor (SIF) at predetermined small crack growth increments in a commercial finite element software by Extended Finite Element Method (XFEM) and uses the appropriate crack growth direction criteria and the crack growth rate equation based on the equivalent SIF range. The aforementioned algorithm computes the FCG life by means of cycle-by-cycle integration method by accounting the loading history which has substantial effects on crack growth life. The algorithm takes advantage of XFEM where there is no need re-mesh during crack propagation. For verification purpose, the results are compared with the experimental crack path trajectories and FCG life data from the literature and good agreements are obtained. The obtained accuracy of XFEM based algorithm in predicting FCG under variable amplitude loading gives the users the confidence to apply the methodology to industrial components under practical service loadings.

**Presenting Author*

FRACTURE ANALYSIS FOR LIFE TIME EXTENSION OF REACTOR PRESSURE VESSEL

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This article represents calculation experience for lifetime extension of reactor pressure vessel of Zaporizhzhya Nuclear Power Plant. Modern methodology of fracture analysis is analysed. Different aspects of fracture analysis are disscussed: crack type (surface and sub-cladded), submodel dimensions, mesh around the crack tip, residual stresses, fracture toughness of cladding. Some comparison between elastic and elastic-plastic fracture mechanics SIF calculations is given for possible crack shapes.

**Presenting Author*

PERSPECTIVE DIRECTION FOR DEVELOPING NEW ELASTOMERIC MATERIALS USING NANOTECHNOLOGY

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Elastomeric materials and their products are widely handling in almost types of equipment either ground-based or airborne. Anyway, there is no general material could be utilized to produce items for all working conditions. In this way, researches are consistently applied to upgrade technical properties. It is not an exception that products of elastomeric materials, which ensure the capacity of many notes and aggregate of rocket and space equipment that can be operated in extreme conditions.

Specifically it involves heat-shielding materials for solid propellant rocket motors that must withstand high temperatures.

Nowadays, a special rubber produced by various rubber fillers which have different activities is using as internal thermal insulation material. At the same time, their heat-shielding properties need to be improved.

One of attitudes for improving protective properties of rubber composite materials is using carbon nanotubes as filler (long cylindrical structure with a diameter from one to several nanometers and a length of several hundred nanometers). This filler structure makes ability for developing more effective rubber composite heat-shielding coating. Vulcanizates with carbon nanotubes as an active filler will enhance heat-shielding properties such as elastomer and strength properties, tear and abrasion resistance.

In addition, it should be taken into account that the volume of the thermal insulation coating in solid rocket is substantial and density of carbon nanotubes does not exceed 1400 kg/m^3 makes them auspicious not only for using as an active filler for the heat-protective elastomeric material, but also for reducing the structure net weight of solid propellant rocket.

**Presenting Author*

HIGH TEMPERATURE RESISTANT POLYMER NANO- AND SUBNANOCOMPOSITES

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High performance Cyanate Ester Resins are used in aerospace structures as matrices for carbon-, glass- or organic-containing composites, adhesives, coatings, encapsulants. Improvement of their mechanical performance at high temperatures is the important task to be solved. In this work, three series of high temperature resistant polymer subnano- and nanocomposites have been synthesized by polycyclotrimerization of Cyanate Ester Resins (CER) in the presence of ultralow amounts of different Silica-based inorganic nanofillers as well as using sol-gel method. Dicyanate ester of bisphenol E (Primaset™ LECy, Lonza LTD, Switzerland) was used as initial CER monomer, and epoxycyclohexyl POSS® Cage Mixture (ECH-POSS, from Hybrid Plastics Inc., USA) and amino-montmorillonite (amino-MMT, Nanomer® I.31PS, Nanocor Inc., USA) were used as reactive nanofillers. Additionally, the combination of tetraethoxysilane(TEOS) and γ-aminopropyltrimethoxysilane (APTMS, as a coupling agent) was used for preparing nano- and subnanocomposites by sol-gel method. CER curing process was carried out at increasing temperature up to 300°C resulting in formation of thermally stable densely cross-linked polycyanurate (PCN) network. Due to chemical interaction of reactive, epoxy or amino, or silanol groups of nanomodifiers or forming silica units, with cyanate groups of the growing PCN network, the nanoparticles or subnanometer-sized silica units were chemically incorporated into the matrix forming additional, inorganic junctions in the PCN network. The amount of the inorganic modifiers used was varied from 0.01 to 10.00 wt. %. The molecular structure, nanostructure, molecular dynamics, and thermal/mechanical properties of composites under study were characterized by means of FTIR spectroscopy, STEM/EDXS, Far-IR spectroscopy, DSC, DMA, laser-interferometric creep rate spectroscopy (CRS), and TGA methods.

It was revealed that the most substantial positive impact on PCN dynamics, thermal and mechanical properties was attained at ultralow nano- or subnanofiller contents, e.g., 0.025 - 0.1 wt.%.

It was found that the modifier particles sizes in the best composite samples were 1-3 nm for ECH-POSS, 2 to 3-nanolayer stacks and individual nanolayers for PCN/amino-MMT series, and the SiO_2 nodes of subnanosize (0.5-1.0 nm) were formed in the best samples for PCN/SiO_2 composites obtained using sol-gel method.

The pronounced effect of constraining dynamics over the wide temperature range in the subnanocomposites, due to introducing ultralow silica contents, was observed and confirmed also by increasimg T_g by ~50^0; the displacement of the onset of glass transition range by 80^0 to higher temperatures; increasing activation energy and motional event scale in the glass transition. Strong positive influence of subnano-sized silica nodes on the mechanical properties of PCN was fixed resulting in increasing modulus by ~ 60% at room temperature and its multifold rise at high temperatures. Thus, the upper temperature limit for application of these valuable high temperature materials may be substantially increased in this way.

*Presenting Author

HIGH TEMPERATURE RESISTANT BINDER FOR CARBON PLASTICS BASED ON POLYFUNCTIONAL EPOXIES AND NITRILES

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Structural materials for energy systems are often exposed to extreme operational conditions, especially to high temperatures. The applicability of carbon-, glass- and organic plastics used as structural components or materials in energy systems, for example, engines, working in conditions of high temperature depends on the heat resistance of polymer matrix used as binder in composite material. Sometimes such materials have to withstand the temperature up to 300 oC and even higher.

The novel high temperature resistant densely crosslinked polymer matrix is formed by step-by-step curing in temperature range from 220 to 300 oC of the mixture of polyfunctional epoxide and aromatic nitrile in the presence of specific initiators, catalysts and fillers. The final polymer co-network contains highly thermally stable heterocycles in matrix chemical structure: triazine, isoindoline, phthalocyanine, oxazoline. Changing the binder composition (components ratio) allows widely controlling physical-mechanical and thermal properties of the polymers synthesized and the carbon plastics obtained thereof.

The glass transition temperature, Tg, of the polymer networks obtained varied from 240 to 400 oC (DSC data), the temperature of 10% mass loss, Td10%, varied from 400 to 500 oC (TGA data). The binder developed can be used for preparing carbon plastics as powder or as solution in organic solvents.

Based on the binder developed and the carbon fiber 3606 ("PORCHER") the carbon plastics samples were prepared, the temperature/time schedule was optimized and the physical-mechanical characteristics were measured at different temperatures using testing machine Instron-5582.

The average value of flexural strength, σf, at standard conditions was 837 MPa, and 285 MPa at 300 oC (the retention of strength – 34 %). The average value of tensile strength, σt, at standard conditions was 890 MPa, and 806 MPa at 180 oC (the retention of strength – 91 %), and 690 MPa at 250 oC (the retention of strength – 78 %). Tensile modulus was 95330 MPa at standard conditions and 96660 MPa at 180 oC. The average value of compression strength, σc, at standard conditions was 504 MPa, and 316 MPa at 180 oC (the retention of strength – 63 %), and 142 MPa at 300 oC (the retention of strength –28 %).

**Presenting Author*

CHARACTERIZATION OF HOLD TIME INFLUENCES ON CYCLIC SOFTENING OF FERRITIC-MARTENSITIC STEELS

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Although generally designed for base-load operation, many conventional power plants are now required to match changing power outputs of renewable energy sources. Besides, ever increasing requirements in efficiency demand higher steam temperatures and pressures. Therefore, creep-strength enhanced ferritic-martensitic steels were developed by alloying MX-type carbonitride forming elements what results in good tensile and creep properties at elevated temperatures. However, in addition to creep loadings, cyclic temperature gradients arise on thick-walled structural components due to intermittent operation which lead to fatigue loads. Mechanical properties of ferritic-martensitic steels are remarkably reduced during fatigue loading due to non-saturating cyclic softening.

This degradation mechanism is more pronounced and complex under creep-fatigue loading. Not only additional softening, but also asymmetric peak stresses are observed after introducing hold time to the loading cycle in strain-controlled low-cycle fatigue tests. Also, tests including compressive hold time show significantly reduced lifetime, whereas tests with tensile hold time show a slight increase in cycles to failure. For reliable damage and lifetime prediction, this phenomenon has to be understood.

In the framework of european project MatISSE (Materials' Innovations for a safe and sustainable nuclear energy in Europe), low cycle fatigue tests with and without hold time were carried out on P91 (mod. 9Cr1Mo) ferritic-martensitic steel. Hold times under tension, compression and combined tension and compression were considered. The influence of hold times on softening response of the material was characterized for different temperatures, strain amplitudes and hold time durations. Analysis of resulting hysteresis loops allowed linking of lifetime and hold times' influence on the deformation behavior.

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*Presenting Author

MULTI-SCALE MODELLING OF CARBON NANOTUBE REINFORCED POLYMER COMPOSITES*

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A nanotube can roughly be describedas a rolled-up graphene sheet, which is a two-dimensional hexagonal arrangement of carbon atoms, often referred to as a honeycomb lattice. Carbon nanotubes, much like their parent material graphene, are characterized by high strength, high Young's modulus, durability and tunable electronic behavior. As a result of these superior properties, CNTs have relevant applications in different scientific disciplines like energy storage, mechanical systems, sensing, biological applications etc. In particular, CNT-polymer composites have gained considerable interest in the materials research community in recent years. CNT-polymer composites also have potential usage in aerospace industry,especially in space research, because they are resistant to extreme conditions.

The testing, manipulating and design of viable mixtures of nanotubes and polymers presents challenges from an experimental point of view. For this reason, numerical modeling at the atomistic scale of nanotube-reinforced polymers is crucial for the design of future interfaces.

In this study, we aim to study the elastic properties of a CNT-reinforced PolyEtherEtherKetone (PEEK) matrix. PEEK is a semi-crystalline thermoplastic polymer which has remarkable mechanical properties with a Young's modulus of 3.6 GPa and a rather high melting temperature (370°C). When it is reinforced with CNTs this melting point can reach 390°C. Thanks to these properties, PEEK is suitable for use in extreme conditions, such as nuclear power plants, petroleum and geothermal wells.

We investigate the CNT-PEEK interface at multiple levels of complexity, combining finite-element method (FEM), molecular dynamics (MD) and density functional theory (DFT). In this work, we will first present our benchmark studies regarding the mechanical properties of CNTs of various chiralities under static and dynamic loads. Following this, we will summarize the physical and mechanical properties of PEEK matrix once again in the MD approach. The CNT-PEEK interface will be discussed within both DFT and MD methods, which are found to validate each other. Finally, we will present a comparison of the atomistic level simulations regarding the mechanical properties of the composite system with the finite element method (FEM) results and provide useful insight for its further improvement.

HIGH TEMPERATURE RESISTANT POLYMER NANOPOROUS FILMS

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High temperature resistant polymer nanoporous films are perspective materials for energy systems as membranes. In this work six complementary methods were developed for preparing the nanoporous film systems based on high performance Cyanate Ester Resins (CER), which are transformed to thermostable polycyanurate networks (PCNs) possessing glass transition temperature, T_g, up to 270 ^oC and thermal degradation temperature > 420 ^oC. The networks are characterized by low water uptake and low dielectric loss.

Three methods were based on modification of PCN networks by a reactive porogen (i.e., poly(ε-caprolactone), PCL), which was partially chemically incorporated into the PCN network framework. The porous structures were then created either by extraction of the non-incorporated part of PCL or by partial hydrolysis of PCL followed by removal of the hydrolysis products from the system. Alternatively, a thermal degradation of polyester sub-chains at 250 °C (temperature much lower than the onset temperature of degradation of PCN matrix) also allowed for the creation of nanoporous frameworks. Furthermore, three other original methods of pore generation were developed: (i) the synthesis of PCN networks in the presence of high-boiling liquids (organic phthalates), and their subsequent removal upon extraction, (ii) the synthesis of PCN networks with different degrees of conversion of cyanate groups, followed by the extraction of unreacted monomer or CER fragments non-incorporated into the network structure, and (iii) the preparation of « track-etch » membranes from PCN-based films via irradiation by alpha-particles, followed by an alkaline etching to reveal the tracks created after bombing. Structure-properties relationships for the precursor and porous films obtained were studied using FTIR spectroscopy, DSC, DMA and TGA techniques. The pore sizes and pore size distribution were characterized by using DSC thermoporometry and SEM techniques. The average pore sizes of most of the pores independently of preparing method were found to be between 20 and 80 nm.

Further, the gas transport properties of PCN films were analyzed after the different processing steps, and relationships between the material structure and the main gas transport parameters were established. Interestingly, the nanoporous thermosetting materials demonstrated a significant increase in He permeability after porogen extraction. Moreover, all membranes exhibited higher CO_2 and O_2 sorption abilities and increased He/O_2 and He/CO_2 selectivity factors after porogen desorption. It was shown that both chain mobility and free volumes governed the gas transport properties before porogen extraction, whereas the pore volume content and pore size became predominant factors in the case of the CER membranes obtained.

**Presenting Author*

OPTICAL PROPERTIES OF CARBAZOLE BASED FERROMAGNETIC NANOCOMPOSITE MODIFIED BY UV IRRADIATION

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Materials with combined ferroelectric and ferromagnetic properties or magneto-electric (ME) coupling effects are promising candidates for information technology and device fabrication. Preparation and characterization of multiferroic materials in which ferroelectricity and ferromagnetism coexist attracted much interest in research for functionalized materials and devices. They present a possibility to electrically control magnetic memory devices and, conversely, magnetically manipulate electric devices. In our work, we considered Fe3O4 magnetic NP with and without a protective double-layer coating embedded into the carbazole- based thin film. One of the most severe problems of the Fe3O4 magnetic NP is their fast oxidation. To avoid this harmful process, protective coatings for these NP were developed. In our work we used a SiO2/TiO2 protective coating for the Fe3O4 NP.

The work is focused on development of non-curable low cost ferromagnetic nanocomposite able to be used in printing technologies and the study of possible damages induced by UV irradiation. The main goal of this work is the investigation of the transmission spectra of the synthesized monomer nanocomposite based on carbazole, and the changes induced by UV irradiation.

NANOINDENTATION STUDY AND PHOTO-INDUCED EFFECTS IN AMORPHOUS ($As_2Se_3)_{1-X}$: Sn_x and $(As_4S_3Se_3)_{1-X}$: Sn_x CHALCOGENIDES

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Amorphous materials represent a new class of advanced materials exhibiting attractive combinations of properties such as high strength/hardness and excellent wear/corrosion resistance. For the development of modern nanotechnologies, nanostructured and functional materials, chalcogenide glasses (ChG) present a big interest. The amorphous films of ChG have been served as a base of many applications in photonics and optoelectronics, especially as inorganic photo-resists for sub-micron technology, optical diffractive elements, sensors and photonic crystals. Special interest is connected of doping of chalcogenide glasses with metal impurities, which alter optical, photoelectrical and transport properties of the host material.

In this paper the experimental results on some mechanical properties, of thermally evaporated amorphous of $(As_2Se_3)_{1-x}$:Sn_x and $(As_4S_3Se_3)_{1-x}$:Sn_x (x=0□10 at.% Sn) glasses and amorphous films (d~2.0 □m) are presented. It was established that the addition of such amounts of tin (x=0□10 at.% Sn) don't leads to essentially changes in the glass physical properties, such as values of the stress and Young's modulus related to the modification of the density and compactness. Investigation of photoplastical effect was performed *in-situ,* during illumination the bulk and thin film samples during indentation, as well as their indentation after illumination with green laser (λ = 532 nm) with power P = 50 mV/cm^2. The hardness

was calculated from load-displacement curves by Oliver-Pharr method. A sharp increasing of hardness is registered when the tin concentration exceed the value of 3% ÷ 4% Sn. The hardness H of $(As_2Se_3)_{1-x}$:Sn_x films varies between H=115□130 kg/mm^2. It was established that the hardness H of amorphous thin films is generally higher than the hardness of bulk samples of the same chemical composition.

EFFECT OF ANNEALING ON THE MICROSTRUCTURE AND HARDNESS OF IRRADIATED TUNGSTEN

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The European Spallation Source (ESS) will be the world's most powerful neutron source facility built in Lund, Sweden. The neutrons are produced through a spallation process in tungsten which has high neutron production rate due to its high atomic number. Tungsten is an environmentally friendly material compared to other target materials, and its use in helium environment avoids corrosion issues related to water cooling. However, it has low ductility and a high ductile-to-brittle transition temperature. Tungsten is the most critical non-structural material and it must operate reliably and predictably for the planned lifetime of the target. In order to estimate the target life, reliable data is needed on the mechanical properties of tungsten after irradiation.

To examine the behavior of tungsten under representative operational conditions, the microstructure of pure tungsten irradiated to 1.4 and 3.5 dpa at below 110°C in a target of the Swiss spallation neutron source was studied. The annealing effect on the microstructure of tungsten irradiated at 1.4 dpa was investigated after annealing the specimen at various elevated temperatures (at 500 °C, 600 °C, 800 °C and 900 °C) for 1 hour. After each annealing step, hardness measurement and transmission electron microscopy (TEM) observations were performed. Microstructural features such as dislocations, defect clusters, dislocation loops and helium bubbles were observed by TEM. The images were obtained in different areas of the samples to obtain quantitative information of the dislocations and defect clusters. There was a significant change in the microstructure of the tungsten after irradiation and post-irradiation annealing. The results show that hardness increases due to annealing, while defect clusters increase in size but decrease in density. No bubbles are detectable at annealing temperatures below 800°C. The results of all these investigations should help us to better understand the hardening effect contributed by defect clusters and helium bubbles in tungsten.

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**Presenting Author*

DISPERSION REINFORCED ALLOYS FOR OPERATION UNDER EXTREME CONDITIONS OF HIGH TEMPERATURE PLASMA

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The rapid technology progress raise the need in development of new materials that would operate in harsh conditions of extremely high temperatures and oxidizing environment impacts. The need in such materials is especially noticed in space-rocketry field for development of heat resistant structures of re-usable spacecraft and nuclear engineering for manufacturing of the nuclear chain reactors casing.

Dispersion reinforced powder alloys could become that kind of materials, which can stand extreme conditions for quite a long time.

The goal of this work was to study the alloys based on nichrome with aluminum reinforced by yttrium bioxide obtained by powder technology.

It was analyzed the cyclic heat resistance of dispersion reinforced alloys based on two nichrome alloys. It was found that the oxidizing pace gradually decreases that is a result of formation of steady protective oxide film. At the initial stage of film formation, the oxidizing process goes in kinetic mode that leads to quite fast samples weight gain. Then the system transfers to diffusion interaction field when the processes of ions transfer through the oxide layer controls the heat resistance. The study of weigh change behavior at every oxidizing cycle shows quite monotone character having the fading of increase and practically end of interaction with atmospheric oxygen.

It is shown that in case of oxidation of nichrome obtained by traditional metallurgical treatment as a result of dissolution and creation of nonhomogeneous solid solution, there is accumulation of almost the whole spectra of metal oxides that are presented in alloy. The nichrome oxide accumulates in a big quantity, as well nickel oxide and spinel $Ni_2Cr_2O_4$ are presented. Obviously, presence of different oxides result in foil delamination and cracks creation due to different thermo mechanical properties.

In case of oxidizing of alloy with 5,95 % of aluminum, the accumulation of aluminum oxide takes place within a thin film. The diffusion through aluminum oxide that is referred to one of resistant in thermic and thermodynamic relations, as a rule, is absent. By this way, the heat resistance of such alloy is explained.

The developed material can be applied in structures that operates during the long period under the extreme conditions of high temperature flow impacts, such as: heat resistant structures of re-usable spacecraft or casings of nuclear chain reactors.

The work is carried out within the Grant Agreement № 607182 of the Seventh Framework Programme of EC (FP7/2011-2014), abbreviation «Light-TPS».

RECENT RESEARCH AND DEVELOPMENT OF ODS STEELS AS MATERIAL FOR EXTREME CONDITIONS

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In Generation IV nuclear power plants substantial increase in operating temperature and pressure compared to current boiling water reactor BWR and pressurised water reactors (PWR) designs, e.g. ~630°C peak cladding temperature, raises challenges which need to be solved.

Oxide-dispersion-strengthened (ODS) steels have been in the focus of different research organization around the globe for the last five decades as potential material to be used at temperatures up to 800°C. ODS steels were developed through microstructural modification of the Cr steels with highly stable yttrium oxide dispersoids, which are known to enhance creep properties of these steels.

The ODS steels are also considered as potential cladding material for accident tolerant fuel (ATF). However, it is also a very interesting material for harsh environments, e.g. fusion, space industry and niche products in high-temperature applications.

In VTT Ltd, research work on these materials is done using multiple perspective approach, experimental work on characterization (mechanical, corrosion and microstructural) of materials produced and available through collaborations within EU frameworks from one side; and on optimization of manufacturing root and own developments on production of ODS steels from the other side. The both research areas remain active up to date.

The supercritical water reactors (SCWR) conditions were simulated using autoclave facilities to determine corrosion properties of selected materials including ODS steels. In addition, creep testing of thin-walled tubes of ODS steel was performed using the pneumatic loading apparatus (PLA), where the axial load is produced utilizing pneumatic loading units called bellows. Because ODS steels cannot be welded, a mechanical plugging method for testing of ODS tubes under internal pressure was developed at VTT and has been successfully applied in a MATISSE EU-project for 9%Cr and 14%Cr ODS fuel cladding tubes. The test rig has also the capability to superimpose axial loading and internal pressure. Also small punch test method will be used for characterizing the mechanical properties of ODS steels.

Development and optimization of the alternative fabrication routes toward ODS steels include production of experimental heats of the steel using powder metallurgy methods, from which internal oxidation method proved to be the optimal route for further development.

Advanced electron microscopy methods are used through all the research and development process for characterization of produced heats of the steel and coupling of mechanical properties of the ODS steel samples with their microstructure.

Main achievements and the latest available results are to be presented in more detail during the workshop.

**Presenting Author*

STRUCTURAL MATERIALS CROSS-CUTTING ISSUES BETWEEN GENIV AND GENII/III FISSION REACTORS AND FUSION ENERGY SYSTEMS

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In order to continue to deliver safe low-carbon nuclear energy for the present and the coming centuries, with a commitment towards even higher safety standards and sustainability, the following phases are foreseen: 1) safe extended operation of existing GenII/III nuclear power plants, 2) subsequent deployment of advanced GenIV fission reactors including cogeneration systems and 3) gradual insertion of fusion systems in the energy production market. These three phases are overlapping and contain a number of common issues that must be resolved, in particular concerning qualification and development of structural materials and the approaches to be applied in this endeavour. This paper addresses some of these cross-cutting issues, identifying them in the development of methods/models to define robust design rules, extrapolating materials' data to the required long service period (up to 60 years), standardization of testing/characterization of materials under various aggressive environments of advanced coolants (from water to molten salts and liquid metals or high temperature gases) and advanced material development (i.e. new F/M steels, HT materials), their standardization, joining, qualification and codification. The common denominator of these issues turns out to be the development of advanced models that describe the behaviour of materials and the extensive use of advanced microstructural characterisation techniques, which are the main focus of the present symposium.

**Presenting Author*

MATHEMATICAL MODELLING OF IRRADIATION SWELLING OF THE REACTOR WWER-1000 CORE BAFFEL

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The core baffle is main element of the reactor VVER-1000 internals, which determines and possibly sharply reduces the service life of reactor. Core baffle is operating in conditions of high neutron irradiation and temperature gradients. The service life of core baffle is primarily determined by its unallowable shape-changing (distortions), caused by radiation swelling and radiation creep processes.

The baffle is made of austenitic steel Cr18-Ni10-Ti, which has high corrosion and crack resistance, good weldability, high plastic properties, which provides its wide use for responsible structures, including nuclear power, where this steel is the main material of the reactor internal elements, operating at high radiation exposures.

Intense radiation is a factor that reduces the stability of the austenitic microstructure, leading to a sufficient changes in the properties of the steel, especially in resistance to corrosion cracking and a tendency to brittle failure (fracture). Under the influence of intense radiation exposure, austenitic steel swells - an irreversible process of increasing the volume, which can lead to a significant change in the stress-strain state in the elements of the internals structures. Long-term heating and irradiation can also cause the phenomenon of radiation creep in the material of the internals elements.

During last decade the physical models of swelling and changes in the properties of Cr18-Ni10-Ti steel under the influence of radiation exposure and temperature were obtain on the results of experimental studies, as well as measurements of the deformations of the inner surface of real baffles after a long operation for about 30 years were conducted. These allow to become advisable to use mathematical modeling methods taking into account the processes of radiation swelling and creep of Cr18-Ni10-Ti steel for the analysis of the general stressed-deformed state of the internals elements and the estimation of their service life. The question of the influence of technological heredity, as well as welding residual stresses, on the stress-strain state of the internals elements is also of interest of modelling.

Numerical estimation of the temperature fields in the core baffle during operation conditions were carried out taking into account gamma-heating, prediction of strains and stresses - due to nonuniform heating and radiation swelling. A comparison of the calculated results of the baffle distortions with experimental data showed good agreement.

The conducted studies revealed a significant influence of the input data on the distribution of the accumulated dose of gamma radiation and the corresponding heat release across the section of the baffle on the accuracy of the results of modeling the stress-strain state in the elements of internals. In connection with this, the actual task now is to obtain updated data on the fluence and heat distribution for each VVER-1000 reactor baffle, taking into account the characteristics of each fuel campaign.

THE EFFECT OF NEUTRON IRRADIATION HARDENING ON THE RESULTS OF FAST FRACTURE EVALUATION

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The problems of the assessment of RPV residual lifetime from the point of view of the resistance against fast fracture are considered. The effects of the base metal hardening on the results of fast fracture evaluation are investigated. It is shown that the conservatism of the type of the approach to the fast fracture evaluation (linear elastic or nonlinear elastic-plastic analysis) depends on the base metal mechanical properties values. Change in these values could be the reason for the change of critical PTS scenario, the most dangerous point on the crack front and the conservative form of the crack geometry. To demonstrate these effects the results of the calculation for South Ukrainian NPP unit 2 residual lifetime are presented. The model scenario has been generated in such a manner to be close to the LOCA scenario, namely "Leak from cold leg with equivalent diameter 32 mm (with respect to antisymmetric cooldown), considered for South Ukraine NPP unit 2. It is shown that the effect of neutron irradiation hardening is a very important argument for the additional lifetime support.

Some very important conclusions can be derived from the presented results.

1. The effect of material hardening due to neutron irradiation is very important for the fast fracture calculations. This effect gives the possibility to additional residual lifetime extension.
2. The crack with the ratio a/c=0.7 can be more dangerous than the crack with the ratio a/c=0.3. So, both the cracks must be taken into account in the analysis. Note, that the Russian code RD EO 0606-2005 prescribes the postulation only the cracks with the ratio a/c=1/3.
3. The effect of cladding residual plastic strains can't realize if the fully elastic model of the material behavior is used. So, the results of fully elastic calculations can be less conservative.

THE INFLUENCE OF IN SITU REACTIONS ON STRUCTURE AND MECHANICAL PROPERTIES OF ULTRA-HIGH-TEMPERATURE ZRB2-SIC AND ZRB2-SIC-C CERAMICS

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Ultra-high-temperature ceramics (UHTC) based on zirconium boride and silicon carbide demonstrate a combination of high melting point of ZrB_2 (>3000°C) and high temperature oxidation resistance provided by silicon carbide ability to form continuous SiO_2 film at high temperature. The composites are of particular interest in high temperature engineering. However, high melting points of both phases cause considerable difficulties for the material synthesis: in order to create bulk ZrB_2-SiC ceramics one needs to provide a hot pressing process at a temperature in excess of 2000°C for 60 minutes. Besides, high hardness limits production to only simple geometries.

The presented work investigates possibility of hot pressing process when chemical reactions between zirconium carbide and boron carbide during sintering process allow reducing the furnace temperature and sintering time.

The sample series were prepared with their initial compositions according to the following equation $x(2ZrC + B_4C + 3Si) + (1-x)ZrB_2 \rightarrow (x+1)ZrB_2 + 3xSiC$ (1)

with $x = 0 \div 1$, and $2ZrC + B_4C + ySi \rightarrow 2ZrB_2 + ySiC + (3-y)C$ (2)

with $y = 0 \div 3$.

The investigation of structure and mechanical properties of sintered samples shows that:

- in situ reactions considerably improve the densification kinetics of ZrB_2-SiC-based materials and produce fully densified (non-porous) UHTC ceramics with mechanical characteristics of: H_v = 23GPa and K_{1C} = 6.2MPa·m$^{1/2}$;
- ZrB_2-SiC structure has 3 – 15μm evenly distributed grains of both phases containing submicron intragranular inclusions of SiC in ZrB_2 and ZrB_2 in SiC (See Fig. 1).

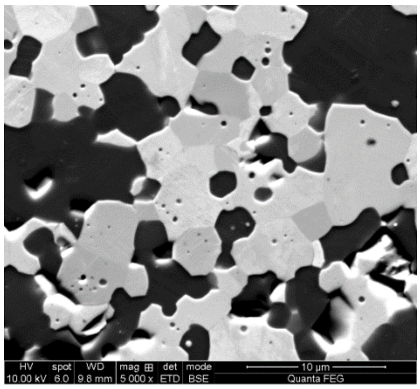

Fig. 1. Electron backscatter contrast on ZrB_2-SiC polished surface

- Hot pressing of ZrC-B_4C-Si system with silicon deficiency results in ZrB_2-SiC-C heteromodulus composites formation with soft phase (graphite). The obtained UHTC can be a machinable material.

- The above properties are achieved after synthesis for 10min at 1800°C and 30MPa pressure.

**Presenting Author*

GRAPHENE SEALS FOR NUCLEAR POWER PLANTS

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Nuclear power in Ukraine provides over 50% of electricity generation in the country. Essential elements of security of nuclear power plants are ring seals of many detachable connections, including tubes and hatches of the nuclear reactor. Previously, these seals were made of copper or nickel rings with subsequent their compression to deformation. In the last decade graphite seals have been widely used, in particular, obtained on the basis of thermally expanded graphite (TEG).

The sealing elements on the basis of this material are characterized by significant advantages compared to traditionally used materials, primarily, due to the great and permanent elasticity, unlimited shelf life and opportunities for multiple use (the number of operations the "assembly-disassembly" up to 50). Materials from TEG at high temperatures and the need of elasticity and electrical conductivity do not have competitive analogues for comparison. TEG also has resistance to chemical and radiation.

The Gas Institute of NAS of Ukraine together with NNEGC "Energoatom" conducted research on the creation of such seals from graphene (FLG-Few Layers of Graphene). The Institute has its own TEG-FLG experimental manufacturing. The technology is based on the thermal expansion of intercalated graphite in the core of the flame combustion.

Thanks to the developed "know-how" we have managed to significantly improve heat flow and increase the residence time of the TEG particle in the reaction zone, which in turn promotes further calcination of the material and improves its quality. Reduced TEG density (3 g/l) improves its plastic properties at subsequent pressing. Performance of the created pilot unit – 3-6 m^3/hour on TEG. Combustion products of natural gas, propane-butane and liquid fuel could be used as a source of heat carrier.

In addition, the Institute has its own pilot production of multi-walled carbon nanotubes (MWCNTs) with purity not lower than 90%. Nanotubes are produced by CVD method. To synthesize MWCNTs we apply products of an oxidative conversion of hydrocarbons on plate catalyst, developed at the Gas Institute of NAS of Ukraine.

As a result of research we managed to develop a springy, ring seals from FLG graphene reinforced by MWCNTs. Their strength is higher on 30% than well-known foreign analogues. There have been designed tooling systems for seals obtaining of different diameters (currently – up to 800 mm). Elastic properties of the seals significantly reduce the tighten force of pins of detachable connections.

APPLICATION OF FRICTION TECHNIQUES TO MANUFACTURING ADVANCED STRUCTURAL MATERIALS

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Metal bonding technologies are increasingly adopting new methods of termo-mechanical plasticization of metal by using the heat generated at friction point of the rotating tool and pressed against the metal surface. These are friction stir welding (FSW) and friction stir processing (FSP) techniques. The first one is particularly suitable for bonding similar or dissimilar structural materials with different mechanical properties, the materials that are difficult to be welded by traditional methods or to create multilayer structures with multifunctional applications. In turn, the FSP technique is used to modify the properties of the surface layer members by alloying with elements as well as relaxing residual stresses and changing the surface roughness.

Literature data and own researches indicated that new structural materials received or modified by applied frictional techniques often display better properties than the original ones.

Own researches on this subject was carried out for typical S235 and S355 mean carbon structural steel under cyclic tension (R=-1, R= -0.2) in LCF and HCF range, for three states of the materials, as follows:

- the steels in the starting state,
- the steels with the surface layer modified by frictional-mechanical treatment,
- the steels after frictional-mechanical treatment and additionally alloyed with chromium or nickel,

under normal conditions in air and in artificial sea water environment at 20°C, as well.

After application of frictional techniques both steels showed significant grains' refinement in the surface layer, better mechanical properties, higher fatigue strength, higher resistances for: cracking, corrosion, wear and cavitation than the original ones.

OBTAINING OF NANOSTRUCTURED ZIRCONIUM AND ZR-1%NB ALLOY AND ITS PROPERTIES

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Pure zirconium and Zr-1%Nb alloy were obtained in nanostructured and ultrafine-grained UFG states by severe plastic deformation methods (extrusion, "compression-extrusion" and drawing). Evolution of the texture and structural parameters during the various methods of severe plastic deformation was investigated.

After the drawing of preliminary extruded zirconium sample (Zr «01» series) nanostructured state was formed (at $\varepsilon = 5.6$ average grain size was equal to d_{av} = 104 nm) with equiaxed and homogenous structure and strong fiber texture $<10\bar{1}0>$ (pole density $P_{10\bar{1}0} \approx 21$). At early stages of drawing process the average subgrain size reduced quickly, but then it slowed down and saturated at high deformation degrees.

After the drawing of the recrystallized rod (Zr «0» series) the average grain size was about 100 nm, as in the case of Zr «01» series. During the deformation process reorientation of grains took place and more weakly fiber texture $<10\bar{1}0>$ was formed (the pole density value was $P_{10\bar{1}0} \approx 11$).

It can be seen that, despite the difference of the initial grain size, after the drawing the final grain size turned out to be almost identical and, apparently, reached the limiting value that can be realized by this SPD method. Moreover, regardless of the initial grain size, fiber texture $<10\bar{1}0>$ was formed, which means that the same deformation mechanism was realized (dislocations slip). It should be noted that this strong crystallographic texture does not correspond to the metallographic texture (i.e. samples had an essentially equiaxed grain microstructure).

Warm "compression-extrusion" deformation of samples (Zr «02» series) at a temperature of about 500 °C led to effective grain grinding up to submicrocrystalline values. But this method did not allow obtaining nanostructured zirconium even at high true strain rates (average grain size at $\varepsilon = 11$ was d_{av} = 320 nm). In the case of "compression-extrusion" at room temperature the minimum achieved grain size was about 250 nm. Texture investigations of those deformed samples showed that "compression-extrusion" deformation leads to a weakly textured state.

Combination of "compression-extrusion" and drawing almost three times reduced the average grain size of Zr «02» samples ($d_{av} \approx$ 120 nm), but obtained value was a bit more larger corresponding value of Zr «01» series.

Thus, the drawing and the combination of drawing and "compression-extrusion" method are more optimal techniques to obtain zirconium in homogeneous nanostructured state.

MODIFICATION OF ZIRCONIA CERAMICS FOR OPERATION IN EXTREME CONDITIONS

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The amazing wears resistance, thermal stability and high corrosion resistance of ceramics based on zirconia ensures a long service life of parts. Along with materials based on beryllium, zirconia is used as retarding and reflecting materials in nuclear reactors. Ceramic materials based on zirconia can withstand extreme temperatures and mechanical loads, so they can be used in the field of power engineering - in engines and turbines of power plants, wind power and hydroelectric stations, sensors of electronic devices. However, for the use of ceramics based on zirconia in power systems under extreme conditions, it is necessary to significantly increase the crack resistance and wear resistance, as well as to prevent dangerous degradation in a humid environment and T <300 ℃ due to the tetragonal-monoclinic transition.

The present study is devoted to the problem of enhancing fracture toughness of ZrO_2 ceramic materials through the modification of zirconia nanopowders by addition of Al_2O_3 and NiO and formation of composite structure based on it. We had analyzed the general and distinguished features of microstructure of both composite materials and its influence on fracture toughness. In this paper we used the XRD, SEM with EDS methods for determination of granulometric, phase, and chemical composition of sintered materials. The peculiarities of dependence of fracture toughness from dopant concentration and changing the Y^{3+} amount in zirconia grains allow us to assume that at least two mechanisms can affect on the fracture toughness of ZrO_2 ceramics. Crack bridging/deflection processes with the "transformation toughening" affect on the dependence of K_{1C} from the dopant concentration. Crack deflection mechanism is affect on the K_{1C} under low concentration of the dopant. The transformation toughening is affect on the K_{1C} when the dopant concentration begin to have an impact on microstructure reorganization–redistribution of Y^{3+} ions and formation of Y^{3+}-depleted grains with high ability to phase transformation.

The proposed method of ceramic composites creation is significantly differs from the traditional method of mechanical mixing of matrix components and filler. The method is based on the synthesis of oxide nanoparticles of the matrix component, the modification of their surface by a low concentration of slightly soluble oxides (<5%), the usage of processing of powder blanks with high hydrostatic pressure and subsequent sintering. The method allows to genetically control the process of formation of interfaces in nanoparticles ensemble and, thus, to control the properties of composites of a new type.

On the example of tetragonal zirconia doped with alumina and nickel oxide an increase in the fracture toughness in 1.8-2.0 times and wear resistance in 1.5 times compared with materials obtained by standard technology of mechanical mixing is showed. The used approaches are completely prevent the possibility of degradation of ceramics in wet conditions and temperatures below 300 ° C.

**Presenting Author*

LOW THEMPERATURE HEAT CAPACITY OF $Gd_2Hf_2O_7$ AS A PROMISING MATERIAL FOR IMMOBILIZATION OF NUCLEAR WASTE

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There has been substantial interest in the use of minerals, especially pyrochlore, $A_2B_2O_7$ (A=rare earths; B=Ti, Zr, Sn Hf), for the immobilization of actinides, particularly plutonium, both as inert matrix fuels and nuclear waste forms. Last systematic studies of rare-earth pyrochlores have led to the discovery that certain compositions (B=Zr, Hf) are stable to very high doses of α-decay event damage.

Studies into the fundamental thermodynamics of actinide substitution into pyrochlore phases have begun to provide a basis for technically sound solutions to the issue of a safe, secure and environmentally acceptable waste material. Low temperature heat capacity measurements combined with high temperature oxide melt solution calorimetry allow the accurate modeling of the phase relationships, chemical durability and fabrication parameters needed to optimize compositions of these materials and provide a full understanding of energetics of their formation.

A recent series of papers have been reported that $Gd_2Hf_2O_7$ is found to be more radiation tolerant than its titanate equivalent $Gd_2Ti_2O_7$.

According to literature data the formation enthalpies and enthalpy increment measurements (from 980 to 1740 K) have been carried out on $Gd_2Hf_2O_7$. There is no information on research into the low temperature heat capacity of $Gd_2Hf_2O_7$.

The objective of the present study is to investigate the isobaric heat capacity of $Gd_2Hf_2O_7$ from 80 to 300 K.

Gadolinium hafnate was synthesized by the method of thermal decomposition of conjointly crystallized nitrates. X-ray diffraction analysis ($Cu_{K\alpha}$-radiation with Ni-filter) showed the typical pyrochlore pattern, without any impurities. The cell parameter 1.0522 nm is in good agreement with literature data.

The $Gd_2Hf_2O_7$ heat capacity was measured for the first time using the adiabatic calorimetry technique with periodic heat entry. The error of the heat capacity measurements was smaller than 0.4 % in temperature interval from 80 to 300 K.

Over the entire temperature range, C_p of gadolinium hafnate increases monotonically, no anomalies being observed. The heat capacity, entropy, enthalpy and reduced Gibbs energy of $Gd_2Hf_2O_7$ were determined for the first time at standard conditions.

**Presenting Author*

DEVELOPMENT OF DIMENSIONALLY STABLE STRUCTURE OF DRAWTUBE OF OPTICAL DEVICE MADE OF COMPOSITE MATERIAL

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Development of dimensionally stable structures for the space application which meet the requirements of the modern developmental level of aerospace technology is almost impossible without composite materials. Nowadays, Yuzhnoye SDO is working on the dimensionally stable structures design, manufacturing and testing.

One such example is development of dimensionally stable structure of drawtube of the CFRP optical device.

This drawtube is a supporting structural element for optical mirrors. The primary objective of the drawtube is to maintain the dimensional stability during spacecraft operating cycle to keep the pre-defined position of optical mirrors and ensure the quality of optical-electronic equipment.

The main feature of this work is application of analytical method of designing dimensionally stable structure. This method is the basis for the design engineering procedure for shell cylindrical structures made of composite materials. Applicability of the procedure was confirmed by calculations of the strength of structure by finite element method and dimension-stability tests of cylindrical test samples (with different layup schedules), as well as dimension-stability tests of the structure of the drawtube. Such procedure allows to optimize the physical-mechanical properties of composite structure and shows the ways to reduce weight and overall dimensions of the structure.

The drawtube rational design is examined in this paper. Presented analytical design method allows approximately calculations of the required physical-mechanical characteristics of the structure at the design stage. Analysis of the influence of processing technique is examined. The analysis permits to expand the allowable angle of fiber orientation without great impact on the thermal-dimensional stability and strength properties of the structure and to simplify the technological requirements. The features of performing dimension-stability test for measuring the coefficient of thermal expansion and the tests results analysis are presented. The paper also provides a comparison of the desired, calculated and measured physical-mechanical characteristics of the structure.

DETERMINATION OF HYDROGEN IN ZIRCONIUM ALLOYS BY VACUUM HOT EXTRACTION USING GAS CHROMATOGRAPHY

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Numerous techniques are used to investigate the amount of hydrogen in metals. Conventional techniques (hot extraction, vacuum fusion, inert gas fusion, thermal desorption spectroscopy) with the resulting gas mixture analyzed by a spectrograph or a mass spectrometer are competing with differential scanning calorimetry, electrochemical, NMR and even nuclear microprobe methods. For the first step, the development of a vacuum hot extraction and gas-carrier method with gas chromatography registration, which could be used in routine analysis, was chosen.

The self-made setup was developed by now for the thermal extraction of gas components from solid materials. This setup is supplied with the commercial gas chromatograph "SELMICHROM-1". The system provides full automatization of experiment, processing and visualization of data about nature and total content of extracted gases. Previously it has been used for the examination of carbon oxides in different materials. Currently the technique was adjusted and tested for the analysis of zirconium alloys charged by hydrogen. Such alloys are the first safety shield of the nuclear reactor. These are put in the harsh conditions such as elevated temperature, high pressure, high flux fast neutron irradiation, water/steam corrosive environment, etc.

Detection of gases evolved during thermal extraction and their concentration evaluation is conducted by a gas chromatograph equipped with a thermal conductivity detector. Heating of a sample, temperature stabilization at the heating points, qualitative registration of gas content are controlled by a personal computer using the special software package.

The amount of hydrogen desorbed from the materials within the investigated temperature range is obtained by the integration of the plot of hydrogen signal intensity versus time. Certainly, the calibration curve must be applied, and a normalized weight of sample must be used to obtain quantitative data.

Evaluation of concentration of the evolved gas is carried out via a conversion of H_2 peak into its volume. Volume of evolved hydrogen is converted to the weight of 1 gram of the studied sample by the following equation:

$$Vx_{1gr} = Vx / Mx, \qquad (1.1)$$

where Vx is a gas volume measured at the heating point; Mx is a mass of a sample.

The series of preliminary experiments were conducted to find the optimal conditions (temperature and time of gas extraction, atmosphere: inert gas or vacuum, etc).

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**Presenting Author*

SINTERING KINETICS OF TETRAGONAL ZIRCONIA NANOPOWDERS. THE SILICA ADDITIVE IMPACT

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It is known the ceramics based on tetragonal zirconia nanopowders (3Y-TZP) has excellent mechanical properties, such as high fracture toughness, strength, hardness et al. It has become an important structural ceramics material and it is widely used in optical fiber connectors, grinding media, precision parts. Zirconia ceramics also applied in orthopedic surgery because of good biocompatibility. The mechanical properties of 3Y-TZP strongly depend on the microstructure which can be controlled by applying the sintering-acceleration effect of different additives and by changing obtaining conditions of nanopowders [1].

To develop high-performance nanopowders, it is necessary to clarify the effect of various additives on the sintering mechanism of 3Y-TZP.

The sintering behavior of 3Y-TZP with and without a small amount of SiO2 has been investigated to clarify the silica effect on sintering kinetics and identify mass transfer (diffusion) mechanisms. For definition of predominant sintering mechanisms at the initial sintering stage has applied a constant rate of heating (CRH) method [2-3].

It was found that 0.2 wt % SiO2 additive on depending from methods of dopant addition have different effects on sintering kinetics and mass transfer mechanisms of zirconia nanopowders as can be seen on the table 1. It was shown the small amount of silica additive is a reason for the changing of predominant diffusion mechanism from volume to grain boundary diffusion in case of the nanopowders obtained by co-precipitation.

Table 1. The parameter n of diffusion mechanism and activation energy Q of sintering.

Nanopowders	Obtaining method	n	Q (kJ/mol)
3Y-TZP	*co-precipitation*	1/2	667
PM8-3Y-TZP	*co-precipitation with milling for 8h*	1/2	804
3Y-TZP-0.2 wt % SiO2	*co-precipitation*	1/3	830
PMM8-3Y-TZP-0.2 wt % SiO2	*powder mixing and milling for 8h*	1/2	660

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MODELING AND DIAGNOSTICS OF THE BEHAVIOR OF NUCLEAR MATERIALS UNDER NORMAL OPERATING CONDITIONS AND THE ACTION OF EXTREME FACTORS

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The development of nuclear materials for the next-generation nuclear facilities assumes their predictive behavior under operating conditions and the availability of a reserve of resistance to the influence of extreme factors under the conditions of emergency loads. These problems consist of several components: conducting testing effects on structural nuclear materials using high-intensity radiation fluxes. In order to achieve this purpose we used a high-current accelerator of relativistic electrons with the following parameters: electron energy 0.35 MeV, beam current 2 kA, pulse duration 5 μs.

The influence of this radiation flux on various alloys was studied: stainless steel, aluminum alloys, zirconium alloy, titanium alloys. It should be noted that such an impact might be interesting both from the point of view of the repetition of the action of extreme factors and the possibility of modifying effects on the surface in order to improve performance. Confirmation of the possibility of improving the performance characteristics are the results of a study of the mechanical characteristics of a number of materials. Another problem is the modeling of behavior under conditions of extreme impacts on rocks, considered as candidate materials for the disposal of radioactive waste. We tested the behavior of granite materials under the influence of a high-current relativistic electron beam. The action of this beam is able to simulate, in addition to factors of radiation exposure, the action of factors such as seismic impact, lightning strike. Specific features of the change in the elemental composition in the zone of the beam effect were established. An express technique was proposed for determining the influence of the beam on the subsequent regime of radiative heat exchange of irradiated materials and their moisture permeability. Express methodology is based on the use of thermographic control of the state of irradiated surfaces with subsequent numerical processing of the dynamics of the temperature field change. This method is under development and approbation for monitoring the condition of equipment and structures of Zaporizhzhya NPP. The state of the surfaces of valves of industrial water pipelines of responsible consumers, the state of the structures of splashing pools, pumping equipment were studied.

NUMERICAL PREDICTION OF RESIDUAL STRESSES IN THE PRESSURE VESSEL SHELL OF REACTOR WWER-1000

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Reactor pressure vessel (RPV) is one of the most important components for long-term operation of nuclear power plants. Technological residual stresses significantly influence on the structural integrity assessment of RPV because of high tensile stresses caused by the operational loads and residual stresses result in high stress intensity factor when crack is postulated.

For the RPV shell VVER-1000 the nozzle zone and butt girth weld joints are most dangerous areas related to crack initiation and growth during the pressurized thermal shock events. To validate extending of the safe long-term operation of reactor vessel the residual stresses in consequence of technological operations of welding, corrosion-resistant cladding and post welding heat treatment (PWHT) must be considered.

A significant complexity of experimental measurement of residual stresses in existing RPV prevents taking them into account in the structural integrity and lifetime assessment. Currently for these purposes for RPV VVER-1000 rather approximate data contained in the recommendations of the procedures, such as Russian MPK-CXP-2000 and European VERLIFE are used.

Significant progress in computer technology and simulation of welding stresses and their interaction with temperature and operational loads using modern mathematical methods create preconditions for more precise evaluation of non-relaxed technological residual stresses in RPV VVER-1000 taking into account the real parameters of all technological operations.

The Finite Element (FE) models for numerical simulation of the residual stresses in butt girth weld joint and cladding of nozzle zone of the RPV WWER-1000 were developed in The E.O. Paton Electric Welding Institute. The model of girth weld joint includes tracking of the history of stress formation during multipass butt welding, stress redistribution due to PWHT, following anticorrosive cladding on the inner surface of the RPV shell and final PWHT operation. The nozzle zone model considers only anticorrosive cladding and PWHT operations.

The developed models are based on thermal-elastic-plastic-creep FE analysis considering microstructural phase transformations and associated changes in volume and yield strength in the melting zone and heat affected zone for welding of 2.5Cr-Mo-V steel (15H2NMFA). Implementation of calculation algorithms according of the developed model is possible as in general three dimensional as in reduced two dimensional formulation using the assumption of axial symmetry within the plane strain hypothesis in order to save computer resources and time of calculation.

The comparison of the calculated distribution of residual stresses in zone of the weld joint of the RPV VVER-1000 with recommendations of procedures VERLIFE and MPK-CXP-2000 is presented. Despite the general character of distribution through thickness of the shell, these data are noticeable different in values. The variation of numerical results of residual stresses for three different reactors VVER-1000 due to the differences in chemical content of RPV steel and technological parameters according to their producer passports are obtained.

**Presenting Author*

MODELING OF CONSTRAINED IRRADIATION-INDUCED SWELLING OF UC PELLETS IN FUEL RODS

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Uranium monocarbide is an attractive alternative to uranium dioxide as a fuel material because of its higher uranium density and thermal conductivity. One of the drawbacks of this fuel is comparatively high swelling rate under irradiation. Fuel swelling, ultimately, leads to direct contact between pellet and cladding resulting in constrained creep of the fuel, bulging and failure of the cladding.

Presentation is devoted to the results of finite element modeling of cladding-constrained UC irradiation swelling and stress development both in the cylindrical pellet and SiC cladding in the course of fuel burnup. It is shown that swelling is non-uniformly distributed in the pellet volume because of temperature gradient across the pellet radius and high sensitivity of UC creep to temperature. Cladding stress assessments are obtained for different reactor powers and degrees of burnup. Modeling parameters corresponds to GA EM^2 modular reactor.

RADIATION RESISTANCE OF $MgAl_2O_4$- SPINELS: EFFECT OF 3d IONS ON DAMAGE RESPONSE

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Magnesium aluminum spinel ($MgAl_2O_4$) generally presents double oxides with a melting temperature of 2135 ºC. Due to its a high radiation resistance to radiation damage, $MgAl_2O_4$ was proposed as a very promising material for RF windows in a fusion reactor. On the other hand, it is well known *that dopants* play a key role in different radiation sensitivity of solid state materials.

The present work summarizes our experimental studies of fast neutron-irradiation of pure and doped (Mn^{2+}, Cr^{3+} etc) $MgAl_2O_4$ single crystals.

In particular, it was found:

1. Fast neutron irradiation of $MgAl_2O_4$ leads to the decrease of the lattice parameter.

2. In stoichiometric $MgAl_2O_4$:Mn^{2+} single crystals, fast neutron irradiation leads to occupancy change of Mn^{2+} ions from tetrahedral to octahedral coordination position in the crystal lattice.

3. Fast neutron irradiation also leads to F^+ (oxygen vacancy with one trapped electron) lattice defect creation. Using the pulse EPR technique of hyperfine sub-level correlation spectroscopy indicates that an electron from an F^+ centre reveals hyperfine interaction only with neighbouring octahedral coordinated ^{27}Al nuclei.

4. Fast neutron irradiation leads also to the significant broadening of R- and N-luminescence lines of Cr^{3+} impurity ions in both stoichiometric and non-stoichiometric $MgAl_2O_4$. Furthermore, at low fluences ($\sim10^{16}$ cm^{-2}) an increase in the intensity ratio of N- to R-lines by 5–20% was clearly observed, while at higher fluences ($\sim10^{20}$ cm^{-2}), the fine structure of R and N zero-phonon lines is not anymore resolved and the total yield of Cr^{3+} luminescence is decreased.

WIND ENERGY: MATERIALS DEVELOPMENT AND REQUIREMENTS

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The drastic expansion of the renewable energy sector is an important precondition for achieving the fossil fuel independency in Europe, and to achieve 20% electricity supply from renewable sources by 2020. The EU offshore wind energy capacity is expected to grow by 21% annually, and this requires the installation of large wind turbines (10 to 20 MW and higher values) standing in wind farms of several hundred MW. Wind turbines (WT) with blades up to 80 … 110 m should sustain a combination of extreme mechanical and cyclic multiaxial loading of variable amplitude, with environmental and thermal/high humidity/erosion effects. Wind turbines experience a relatively high rate of unexpected failures, with resulting downtimes, loss of revenue, increased operational and maintenance costs, also with view on the decreased accessibility of off-shore parks. Even the currently planned lifetimes of turbines of 20…25 years are not always secured. The potential costs of repair and replacement of damaged WTs (including costs for helicopter flights and personnel to repair a blade) are huge. In order to create a basis for successful development and expansion of wind energy in Europe, the reliability of large offshore WTs should be drastically increased to ensure 30 years and more lifetime of turbines, by increasing the stiffness, durability and strength of WT materials under complex mechanical (fatigue, impact) and environmental loading.

In this presentation, the research studies of wind energy materials are summarized [1-4]. The development of lighter carbon fiber based composites, hybrid based composites, nanoengineered composites [3], testing and manufacturing technologies of the materials are discussed. The perspectives of the development of materials for wind energy both for large wind turbines and small low cost alternatives [5] are presented.

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FRACTAL NATURE OF WIND ENERGY

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The fluctuation of wind speed is known to be proportional to the cube of wind speed. Also, the wind energy systems exhibit extreme instability which is their main disadvantage. However, an accurate prediction of wind speed and dynamics is essential for improving performances of wind energy systems. The priceless importance for this prediction is analysing fractal characteristics of the wind speed time series. An improved fractal interpolation prediction method is proposed to predict the wind speed series. According to the self-similarity characteristic and the scale invariance, the fractal extrapolate interpolation prediction can be performed by extending the fractal characteristic from internal interval to external interval. This process can be automatized by implementing all input combinations (roughness lengths, and wind speed at certain height) in order to find the most optimal input combination for wind speed prediction at according to fractal analysis. The reliability of the computational models analyse is based on simulation results and using Pearson correlation coefficient, coefficient of determination and root-mean-square error.

**Presenting Author*

NANO INDENTATION CHARACTERIZATION OF T91 AND EUROFER STEELS FOR NUCLEAR APPLICATIONS

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Instrumented nanoindentation technique has become commonly used method for determining the materials hardness and elastic modulus. It has also tremendously contributed to the understanding of the elasto-plastic mechanics of the studied systems. In the field of nuclear materials analysis, nanoindentation is gaining importance to estimate the structural integrity of materials, in particular to study radiation induced mechanical property changes. Therefore, implementation of this technique helps to assess the component lifetime.

In recent years, various nanoindenter instruments have been commercialized. Each of them is equipped with its own, original data analysis software to determine material properties and characteristic operation mode. This variation leads to a need for establishing common procedures for the measurement and analysis of results in order to obtain equivalent results. This triggered a collaboration between some contributors to EERA JPNM with the primary objective of establishing common procedures to evaluate micro and nanomechanical properties of ion- and neutron-irradiated materials by using nanoindentation technique.

Within the EERA-JPNM nanoindentation group, CVRez has been part of a Round-Robin exercise to estimate indentation hardness and elastic modulus of Eurofer-97 ant T-91 at room temperature. Our results show that measured mechanical properties of Eurofer 97 and T91 steels are relatively similar, and good agreement between the results of load control and depth control measurement methods was achieved. Sample preparation, test methods (load/depth control) and data analysis procedures will be presented. As well, a preliminary comparison of data with three of the laboratories involved will be also debated, together with some first observations and main issues encountered for reliable data comparability.

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*Presenting Author

ZrB2 – BASED CERAMICS AND THERMAL SPRAYED COATINGS ON CARBON COMPOSITES

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ZrB_2- based dense ceramics with different sintering agents were obtained by the hot pressing and vacuum hot pressing modes. The principles of UHTCs structure and properties formation have been developed. It was determined that structure formation at sintering and shrinkage kinetics are determined by the formation of diffusion zones in the interface. In these areas the processes of phase transformations which determine the adhesion take place. Adhesive characteristics determine microstructure (grain-boundary) strength which was identified by us by the indentation method for the first time. Fracture toughness, tension strength and compression strength have been determined, as well. This grain-boundary strength determines mechanical and service properties. Correlation dependences of microstructure strength on other mechanical characteristics (fracture toughness, tension strength, compression strength) allow to create materials with necessary properties.

The dense ceramics were subjected to oxidation at 1550 and at 1650°C for 15 minutes and repeated 1-3 times in a bottom-loading furnace. It revealed that method of obtaining influences oxidation resistance of the ceramics. Herewith, ceramics obtained by vacuum hot pressing showed higher resistance to oxidation compared to the other ceramics obtained by hot pressing, retaining the pristine ZrB_2 under a thin outermost SiO_2 glassy layer. Among the investigated materials, none showed oxide spallation and the best results were achieved when ZrB_2 was sintered with solely $MoSi_2$ or simultaneous addition of $MoSi_2$ and CrB_2.

ZrB_2- $MoSi_2$ composite powders have been obtained by carbo-thermal synthesis on a specially designed equipment and coatings were applied on C/C substrates by shrouded plasma spray method. The regimes of deposition and the optimal powders size have been determined. Some mechanical properties were measured by indentation method (hardness, fracture toughness, tension strength, compression strength, as well as microstructural (grain-boundary) strength).It was shown that the coating has relatively high hardness values, which are typically characteristic of zirconium boride ceramics. Herewith, a transition layer between the carbon and the coating has lower hardness values and it can be associated with its complex composition. The absence of differences in the length of the cracks from the corners of the prints propagating along the interfaces between the various layers and perpendicular to them indicates that the resistance to cracks propagation along and perpendicular to the interfaces for the investigated layers and interfaces is isotropic. It points out that the strength of the interfaces is the same as that of the materials adjacent to these boundaries and the absence of significant internal stresses or their relaxation. It testifies the stability and availability of such coatings application. The applied coatings were subjected to ablative testing with HHO flame. It has been determined that the coating increses the resistance of C/C composite to ablation.

MULTILEVEL MODELING DEFECT STRUCTURE FORMATION IN PURE ZIRCONIUM UNDER PARTICLE IRRADIATION

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Structural, electronic and energetic properties of pure Zirconium with isolated vacancies and their clusters are studied. The lattice constant change in pure Zirconium with different concentrations of isolated vacancy and different configurations of di- and tri-vacancy is discussed. Stability of small vacancy clusters is analyzed. It is shown that with an increase in the concentration of isolated vacancy the lattice constant decreases, whereas single vacancy formation energy increases indicating that isolated vacancies will tend to form clusters. It is shown, that if the distance between vacancies in a cluster does not exceed the first-neighbour distance, the corresponding vacancy cluster will be stable. In the opposite case, the interaction between vacancies in di-vacancy promotes formation of isolated vacancies, whereas the tri-vacancy will de-compose into di-vacancy and isolated vacancy or three isolated vacancies, depending on distances between vacancies in tri-vacancy.

Cascade formation, development and annealing in pure zirconium crystals irradiated at different irradiation conditions are studied. Statistical and geometric properties of cascades are examined in detail by varying sample temperature, energy of primary knocked atoms and direction of their motion. It was shown a possibility of channelling at cascades development, resulting in formation of crowdions. A change in statistical properties of the crystal during cascade development and relaxation time of cascades is calculated. A possibility of formation of different type of defects after cascades annealing is discussed.

Spatial self-organization of an ensemble of point defects in α-Zr irradiated by fast neutrons by using reaction rate theory is studied. In our consideration we take into account elastic properties of the medium due to defects presence and sink density dynamics. We consider dynamics of the system with uniform point defects distribution and spatially extended system in two and three dimensions, separately, at different irradiation regimes (by varying irradiation temperature and dose rate). It was found that point defects patterning accompanied by a formation of vacancy clusters; their morphology changes are governed by irradiation temperature and damage rate. Vacancy clusters occupation densities and distributions over their sizes are studied in details. Obtained results are in good correspondence with theoretical ones and experimental observations for α-Zr subjected to sustained irradiation.

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*Presenting Author

MINIMIZING THE RADIOACTIVE LEAKAGE INTO THE REACTOR CIRCUIT UNDER EXTREME CONDITIONS OF NORMAL OPERATION

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It is proposed to improve the safety-efficiency balance of future nuclear energy systems operated constantly under extreme conditions, by means of ensuring the hermeticity of fuel rod claddings based on the creep energy theory method (CET-method), in order to minimize the radioactive leakage through fuel claddings into the reactor circuit.

Project idea: as cladding damage parameter $\omega(\tau)$ is an integral characteristic of the microcracks growth, we can minimize the radioactive leakage through fuel claddings into the innovative PWR circuit, for extreme conditions of normal operation including variable loading modes, by minimization of $\omega(\tau)$. So, the project idea is to use the CET-method for minimization of the rod cladding fracture due to damage accumulation under reactor variable/constant loading and, as a result of the intrinsic features of the method, to take into account the loading history of any fuel assembly as well as the distribution of damage para-meter among fuel rods of any fuel assembly.

The main aim of the project is working out physical grounds of improved controlling t heprospective reactor fuel properties, in order to enhance the reactor competetive ability, espe- cially by minimization of microcracks growth in rod claddings influencing the radioactive pollution of the reactor circuit.

The structure of the CET-criterion made it possible to propose a generalized method for fuel rod behavior control. Using this generalized method, the probability of failure of fuel rod claddings in the whole core can be considerably decreased. Based on the CET-method, in the frame of the project, an innovative technology for future reactor fuel cladding tightness control will be worked out in detail. Though the method is based on the experimentally proved creep energy theory, there are the actual tasks to be solved in the frame of the project:

1. Verification of the CET-method by means of its application to a real case in which cladding failures and reactor power cycles are known.
2. Based on the CET-method, development of know-how for ensuring the maximum tightness of claddings in prospective nuclear reactors operated constantly under extreme conditions.

**Presenting Author*

NEUTRON DIFFRACTION STUDY OF IN-SITU STRAINED MARTENSITIC/FERRITIC OXIDE DISPERSION STRENGTHENED STEELS

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Oxide dispersion strengthened (ODS) steels represent a materials class being considered as structural materials for advanced future nuclear fission plants, such as the gas-cooled very-high-temperature reactor (VHTR) or for cladding material being exposed to elevated irradiation dose in fast neutron reactors, such as the sodium cooled fast reactor (SFR). The mechanism providing the advanced high temperature behavior is the pinning of dislocations through the dispersoids, which also persists at high temperatures. The advanced resistance to irradiation comes from the additional interface to the dispersoids, providing condensation space for the helium and point defects, potentially depleting the matrix from such detrimental features.

In this study, two 9Cr-ODS and one 12Cr-ODS steels are studied by in situ Neutron diffraction during tensile test at room temperature. The peak shifts and broadening of diffraction spectrum on several low index planes ({110}, {200}, {211} and {310}) are monitored. The material exhibits a particular behavior of the lattice strain after plastic deformation. The presentation will show detailed results from neutron diffraction experiments, giving an insight into the deformation mechanism in the dispersion modified ferritic steel, which understanding is crucial before this advanced material class can be introduced in nuclear applications.

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*Presenting Author

THE PROSPECTS OF CREATING NUCLEAR ENGINEERING BASED ON HELIUM-3

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Depletion of material and energy resources of the Earth leads to serious energy crisis. According to experts, at the present rate of economic development their reserves will be enough for 50 years. Therefore, the search for alternative sources of the Earth's energy resources is an up-to-date issue and, of course, the most efficient is nuclear energy.

We talk about thermonuclear energy of the future and new ecological type of fuel that cannot be produced on the Earth. First of all, it is about extraction of helium-3.

Helium-3 that has a unique atomic structure promises fantastic prospects. The usage of helium-3 in thermonuclear reactions will provide a tremendous amount of electricity, without drowning in dangerous radioactive waste produced by nuclear power plants. The main advantage of helium-3 is not even its energy value, it is unique ecological safery of the energy based on it. Unlike most nuclear reactions, the reaction with helium-3 proceeds with release of protons, but not neutrons, which penetrate deeply into the surrounding structural materials, making them radioactive and destroying them at a time. Protons do not penetrate deep inside and does not induce radioactivity. Therefore, materials can work for decades. No problems with radioactive waste disposal arise.

Helium-3 is fatally limited on the Earth, but it is available in sufficient quantities on the Moon. The researchers suggest that the reserves of helium-3 would provide the Earth's energy consumption, even increased compared with modern life in several times (up to 6000 GWh) for up to 1000 years.

Development of technology for mining lunar raw materials and the creation of an initial structure of the lunar industry are ongoing challenges. The main determining factor of the technology – economic feasibility of lunar rocks processing on the Moon.

The aim of this study is development of technology for mining lunar raw materials with the use of open type mining equipment (quarry) that has a number of advantages (compared to the explosive method): many years of experience on the Earth; ready prototypes of this equipment; the possibility to upgrade for use in aggressive environments; the possibility of equipment automation.

Yuzhnoye SDO works under the development of technology for helium-3 obtaining from regolith, as well as searches for mining equipment and equipment, which is needed for the processing of gases for creation of a closed production cycle.

The problem of finding new energy resources is international, therefore taking into account Yuzhnoye SDO experience of participation in the European framework programs FP-5, FP-6, FP-7 we see it reasonable to consider the question of creation of a consortium of interested EU countries and solve this energy problems in the framework of Horizon 2020 program.

THE SELF-POWERED NEUTRON DETECTOR WITH THE EMITTER OF HAFNIUM FOR DETECTING THERMAL AND RESONANCE NEUTRONS IN THE NUCLEAR REACTORS OF THE 2-3 GENERATIONS

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At the present time, to control the neutron-physical parameters of the reactor core of nuclear power plants, the rhodium emission sensors of the direct charge (Self-Powered Neutron Detector –SPND), placed in the channels of neutron measurements of the fuel assemblies, are traditionally used.

The disadvantages of rhodium as the emitter material of SPND is its high burn rate (57% after 300 days of operation in the thermal neutron stream of 5.3×10^{13} l/cm$^2\times$s and 14.6% in the stream of 1×10^{13} l/cm$^2\times$s), and its very high cost ~ $ 225 per gram.

The purpose of the described work is the development and manufacturing of emitters for SPND of hafnium as a replacement material for rhodium. We see it possible and necessary to develop a technology for the manufacture of new emitters of Hf and the entire structure of the internal assembly. The development and the implementation of the Hf-based SPND will ensure monitoring and maintenance of the optimal modes of operation of nuclear reactors and increase their reliability.

The rare metal hafnium is produced in Ukrainian companies. In recent years, they started using hafnium as the material for the elements of the reactors' control rods. The pioneer of this development in the Ukraine is the National Science Center "Kharkov Institute of Physics and Technology" (KIPT). At KIPT, a unique processing technology to obtain a wide variety of nomenclature of hafnium rods, sheets, wires was developed. The cost of hafnium is $ 3 per gram, which is considerably lower than that for the noble metal rhodium.

The natural hafnium is composed of 6 stable isotopes from ^{176}Hf to ^{181}Hf, out of which ^{181}Hf creates secondary electrons during the interaction with thermal neutrons. The rest of the isotopes generate electrons as a result of the scattering of gamma rays emitted during the radiative capture of neutrons. Both mechanisms allow the use of Hf for the SPND emitters.

Currently, there is no detailed calculation of the transformations of Hf isotopes due to neutron irradiation in literature. Our preliminary calculations show that, within 300 days of exposure, only ~3% of ^{181}Hf will burn out in the thermal neutron flux of 5.3×10^{13} 1/cm$^2\times$s. Moreover, due to the nuclear reactions in Hf during irradiation, the ^{181}Hf isotope concentration increases, that is, a continuous renewal of the emitter material will occur during the internal assembly operation.

**Presenting Author*

AN ESTIMATION OF RADIATION EMBRITTLEMENT FOR WWER-1000 RPV WELD METAL USING THE CHARPY IMPACT AND FRACTURE TOUGHNESS TEST DATA

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The surveillance tests were performed for weld metal of WWER-1000 reactor pressure vessels using the Charpy V-notch and fracture mechanics (pre-cracked Charpy) specimens. The four welds with the different content of nickel and manganese are included in the analysis. The specimens were irradiated within the neutron fluence (E > 0,5 MeV) range of $(4,5 \div 82,9) \cdot 10^{22}$ m^{-2}. The radiation embrittlement of weld metal has been estimated using the Charpy impact and fracture toughness test data. A comparison of the shifts of the critical brittleness temperature, T_K, and reference temperature T_0, due to irradiation has been done with respect to the estimation of embrittlement rate.

The analysis has shown that in most cases the test data derived according to the different approaches results in practically the same estimates of embrittlement rate with some scatter. Furthermore, it has been found that the radiation embrittlement coefficient A_F is higher than a design value for the RPV weld which has simultaneously high nickel and high manganese content. The maximum shifts of Charpy and fracture toughness curves for this weld are 113°C and 98°C respectively.

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*Presenting Author

OVERVIEW OF THEORETICAL AND EXPERIMENTAL STUDYING OF CRYSTALLINE CERAMICS IN SI IEG NASU

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As a result of the previous and ongoing nuclear power programmers, Ukraine accumulates substantial amounts of spent fuel and radioactive wastes. In accordance with the Ukrainian regulatory requirements, liquid waste must be immobilized to a stable physical and chemical form. The engineered barriers the glass waste forms of actinides are not reliable for long-term (i.e.,□□10^5 years) storage under conditions in geological repositories. Ceramics are the most durable actinide waste forms; however, they are still not generally adopted by the nuclear industry.

Direct incorporation of HLW into ceramic hosts has been the topic of extensive study over many years and a number of reviews are available. Adapting of this experience in Ukraine were involved specialists of the SI IEG NAS of Ukraine and the NSC "Kharkiv Institute of Physics and Technology" NAS of Ukraine. Since 1997 the Department of Nuclear Geochemistry of the Institute of Environmental Geochemistry has developed several different types of crystalline host-phases acceptable for immobilization of high level wastes [1,2].

A, was established by the IAEA in 2011 to encourage cooperative research, thereby contributing to the solution of existing and anticipated future problems in these areas. In Coordinated Research Project, entitled Processing Technologies for High Level Waste, Formulation of Matrices and Characterization of Waste Forms, single phase hollandite ceramic was made in Ukraine (IEG NASU) aimed at Cs immobilisation, an isolated fraction of HLW generated by the reprocessing of spent nuclear fuel. Hollandite matrix is a good candidate because of its high cesium incorporation ability and its excellent chemical stability. The works have been done in Institute in recent years is devoted to the synthesis and micro structure ceramic matrices characterization [3].

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**Presenting Author*

NANOSIZED ZIRCONIA AS A MEDIUM FOR CREATION OF HIGH-CAPACITY ENERGY STORAGE SYSTEMS

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At the present stage of the development of technology the problem of electric energy preserving becomes extremely urgent. Due to the ability of quickly receive and deliver a large amount of electric charge, ionistors or superionic capacitors are a promising direction for solving this problem. However, in order to its successfully usage, it is necessary to realize capacity densities of order $\delta\rho C \geq 100$ μF / mm^3 and satisfy a number of additional requirements for their functionality. Thus, the task of developing of solid-state high-temperature nanoionic storage devices with high density of capacity is arises.

One way for solving this problem is to use dielectrics as working material of a device. In the near-surface layer of a dielectric with a large dielectric permittivity it is possible to obtain electric fields which comparable to fields of a crystal lattice 10^8-10^9 V/m and, correspondingly, ultrahigh densities of electrical energy. In this case, a nanostructured analog of a conventional flat capacitor is obtained.

In this paper we study electrical properties of concentrated dispersed systems based on ZrO_2-3mol% Y_2O_3 nanopowders in order to elucidate the possibility of using them as submicroscopic nanoionic storage devices.

The effect of accumulation of an electric charge of density up to 100 μF / g after exposure in an electric field (100 ÷ 10000 V / m) by a system of high-pressure compressed zirconia nanoparticles at a temperature of 300 K was established. The effect has a dimensional nature. The dependence of the accumulated voltage from a size of nanoparticles, pressing pressure and charge voltage was studied; the electrical properties of this device were investigated by using the methods of electrochemical impedance spectroscopy.

It is shown that the mechanism of the phenomenon is caused by tunneling effect during a chemical interaction of surface of oxide nanoparticle with an adsorption ion atmosphere. Electric charge layer that formed in the near-surface zone of a material of nanoparticles with an opposite charged adsorption layer that localized on the surface of nanoparticles are formed an electric capacitance.

Established effect opens the possibility of creating solid state capacitors of ultrahigh density of capacity (> 100μF / g), which in terms of technological level of production and operational characteristics will significantly exceed the basic analogues of a planar design. Temperature stability of the dielectric material widens the operating temperature range of a device. It is possible to miniaturize the device to microscopic dimensions.

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REINFORCING BASALT FIBER IN THE MANUFACTURE OF WIND TURBINES

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Georgia produced the basalt fiber. In the town of Rustavi is located enterprise "Basalt Fibers" that produces fiber, woven from it fabric and basalt wool. The company uses basalt deposits of Marneuli region, which in chemical composition is one of the best in the world for the production of basalt fiber. This is alkaline basalt. It has a high chemical resistance that is several times higher than chemical resistance of glass fiber. Along with this, the strength of basalt fiber is up to 20-25% higher than the strength of glass fiber.

With these preliminary data on basalt fiber, we in the Department of Engineering Mechanics of Georgian Technical University decided to start study of manufacturing technology of wind power plant rotors. For this we manufacture the moulds of blades in length L = 1800 mm, for diameter of the rotor D = 4 m, L = 2300 mm for rotor diameter D = 5 m and L = 4800 mm for rotor diameter of D =10 m. The moulds in length L = 1800 mm and L = 2300 mm are made from wood and the mould of length L = 4800 mm is made from sheet steel with internal heating. In the moulds is laid woven fabric made from basalt fibers, each of them is coated (impregnated) building polyester. In the timber moulds the polymerization was performed by catalysts (initiator and accelerator) and in metal moulds was used thermal polymerization. Thermal polymerization facilitates the production of blades with equal weight. We have also carried out tests on the tensile strength and bending strength of multilayer samples from basalt woven fabrics.

Our tests are at an early stage. They showed that with application of basalt fiber is possible to produce rotors of wind turbines. Based on the properties of basalt fibers such rotors should be lighter than the rotors from glass fiber and most importantly, they will have a higher chemical resistance. This fact makes effective use of such rotors on the shores of seas and oceans.

It should also be noted that the process of manufacturing of the basalt fiber is much shorter than the technological process of manufacturing of glass fiber. Basalt rocks with dimensions 80-100 mm were placed in a furnace where they are melted at a temperature of 1200-1300 ℃. Under the furnace bottom is platinum radium filler. In the filler are 250 small holes from that are derived basalt yarns. The manufacturer applies fillers with a hole diameter up to 10 μm, 12 μm or 14 μm. The strength of 250 assembled filaments makes up to 16 000 MG.PA (for 10 μm), 14 000 MG.PA (for 12 μm) and 13 000 MG.PA (for 14 μm). Several bundles each from 250 filaments are collected together and produce roving. The roving measured by Tex. Tex is weight of 1 km length roving. The manufacturer produces from 300 Tex up to 2700 Tex. In the production of glass fibers are necessary several operations for glass fiber manufacturing technology. This circumstance will lower the price of basalt fiber in the future.

We strive to give start to the possibility of using in wind power of a relatively new reinforcing material that will withstand extreme operating conditions and will be much cheaper than carbon fiber. In small wind turbines, instead glass fiber will be possible to use basalt fibers.

NOVEL THERMOSTABLE NANOPOROUS POLYMER FILMS OF CYANATE ESTER RESINS DESIGNED BY USING IONIC LIQUIDS AS POROGENS

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Cyanate ester resin (CER) offer a variety of excellent thermal and good mechanical properties, which commend them for use in high performance technology (e.g. as matrices for composites for high speed electronic circuitry and transportation). For the electronics market, attractive features of CER are their low dielectric loss characteristics, dimensional stability at molten solder temperatures (220-270°C), high purity, inherent flame-retardancy (giving the potential to eliminate brominated flame retardants) and excellent adhesion to conductor metals at temperatures up to 300°C. Nevertheless, engineering porous CER thermosetting films still remains challenging. The interest in ILs arises from their specific properties, including negligible vapour pressure, wide liquid-state temperature range, excellent thermal and chemical stability, easy synthesis, and good stability to oxidative and reductive conditions. In this work, the novel nanoporous CER films were generated by polycyclotrimerization of dicyanate ester of bisphenol E in the presence of varying contents of 1-heptylpyridinium tetrafluoroborate as a porogen with the further elimination of the latter. Thermal stability of nanoporous materials was estimated using TGA technique, and the values of the degradation temperature onset ($T_{d\ onset}$), temperature of maximal degradation rate ($T_{d\ max}$), temperature of 50% mass loss ($T_{d50\%}$) and char residue were determined. It was established that the nanoporous films obtained characterized higher thermal stability (T_{d1} increase by 55-84 °C and $T_{d50\%}$ by 86-110°C depending on the initial porogen content) in comparison with respective CER/IL precursors. It should be stressed that the synthesis was carried out without using any additional solvent or specific catalyst and the ionic liquid used potentially being utilized repeatedly. So, these nanoporous CER films are promising materials working under extreme conditions (high temperatures, corrosive media…, for example, as thermostable nanoporous membranes as well as for energy systems.

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A LOW-TEMPERATURE FUEL CELL OPERATING ON HYDROGEN SULFIDE (H2S)

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Hydrogen sulfide H_2S existing in the deep-waters of the Black Sea may become an alternative energy source. Use of the fuel cell for obtaining of electricity from hydrogen sulfide of the Black Sea waters is suggested in the present work.

Studies in recent years show an increased interest for hydrogen sulfide as an alternative fuel in fuel cells. Many researches are carried out in the sphere of use of hydrogen sulfide as fuel raw material, but in all considered works the oxidation of gaseous hydrogen sulfide was realized with the use of expensive catalysts and composition materials at high temperature (800-1000℃), which is not commercially profitable for production.

Dissolved in water hydrogen sulfide exists in Black Sea waters. In many cases elemental sulfur is obtained as end product from decomposition of hydrogen sulfide. But in a fuel cell it is better to convert the sulfide to sulfate ion instead of elemental sulfur, because there is a transfer of eight electrons instead of only two thus obtaining four times more energy.

Present process is low-temperature, expensive and hardly-made catalysts are not used.

Membranes for fuel cells are selected and processes passing on certain electrodes of the fuel cell are studied. The values of current and voltage were measured during the experiment. Current density and power were calculated concerning the visible area of given electrode.

Laboratory and large-laboratory models of the fuel cell were created. The experimental study of these models was carried out on different electrodes. The most efficiently working electrode materials, which have as a function of electrode, so the function of catalyst, are selected. The selected electrode-catalyst was not poisoned by hydrogen sulfide and its oxidation products. The lifetime of spent anionic membrane (Ralex –AM-PP) was established - 320 hours. It was shown, at what conditions of external load (resistance - 1000 ohm) the fuel cell works most effectively, when it has maximal power.

MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AUSTENITIC ODS STEEL AND ODS HIGH ENTROPY ALLOY

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Austenitic steels are widely used in nuclear power and in other technical fields. In comparison with ferritic-martensitic steels they are characterized by higher high-temperature strength but have lower radiation resistance. The problem solution of austenitic steels radiation resistance improvement with simultaneous increasing of high-temperature resistance is possible by producing the nanostructured state in these alloys. This state characterized by the presence of nanosized particles (~2-10 nm) with high density (~10^{15}-10^{16}cm^{-3}) and uniform distribution into the matrix. Thermodynamically stable oxides may serve as such nanoparticles, and steels, strengthened by such particles, are named oxide dispersion-strengthened steels (ODS steels).

Other class of promising radiation-resistant materials for new generation nuclear reactors and future fusion reactors is so-called high entropy alloys (HEA's) or concentrated multicomponent alloys that have simple BCC or FCC lattices. Single-phase HEAs with FCC lattice in recrystallized state have usually very high plasticity with relatively low strength characteristics, particularly yield strength. This fully applies to the "classical" equiatomic five-component FCC alloy CoCrFeNiMn (Cantor' alloy). In this work we proposed to improve the strength characteristics of HEAs by using oxide dispersion-strengthening technique, i.e. creation of ODS HEA's. The realization of this idea is demonstrated on Cantor's alloy.

Commercial austenitic steel 08Cr18Ni10Ti and experimental equiatomic CoCrFeNiMn alloy were used as initial materials. Powders of steel or HEA were mixed with 0,5%wt of oxide nanopowder, produced by DonPhTI NASU, and mechanically alloyed in argon in high-energy ball mill. The oxide nanopowder composition was 80%mol Y_2O_3-20%mol ZrO_2*;* particle size was 16 nm and lattice parameter was a =10.528±8·10^{-3} Å. All kinds of mechanical treatment from powder compacting to rolling of compacted blank were carried out at room temperature. In addition, mechanical treatments were alternated with short-time high temperature annealing. As the result, the tapes of 08Cr18Ni10Ti ODS steel and CoCrFeNiMn ODS HEA 200 µm thickness were obtained. The specimens' structure analysis was conducted by electron microscopy using JEM-100CX and JEM-2100 microscopes. X-ray diffraction studies were performed by DRON-2 diffractometer using Fe-Kα radiation. Mechanical tension tests were conducted at temperature range of 77 – 1000 K.

It was established that the ODS steel after the final thermal treatment had austenitic matrix in which complex oxide precipitates were uniformly distributed. The precipitate's density was 7-8·10^{15} cm^{-3} and their average size was near 10 nm. Strength characteristics of ODS steel were significantly higher than the initial steel ones. Especially substantial gain was observed at high temperatures (1000 K), where the yield strength of ODS steel was 2.3 times higher than for initial 08Cr18Ni10Ti steel.

Also, yield strength of the CoCrFeNiMn ODS HEA at temperature range of 77-800 K was 2.5÷3 times higher than for initial alloys, though average oxide precipitates was bigger and their distribution uniformity was poorer than in ODS steel. Thereby, oxide dispersion strengthening is effective not only for steels but also for high entropy alloys.

THE INFLUENCE OF HE ATOMS ON THE FORMATION OF SMALL VACANCY COMPLEXES IN HCP-BERYLLIUM

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A strong interest in beryllium is due to its practical applications in nuclear energetics as a coverage material for the first wall of thermonuclear reactors, such as ITER, JET, EDA. In the process of neutron irradiation, the induced defects are formed in beryllium matrix, such as interstitial impurities (H, He), atomic vacancies, vacancy clusters, etc. The role of ab-initio DFT modelling in the field of condensed matter physics has dramatically increased in recent decades. Nowadays, not only fundamental, but also applied problems are frequently solved using these methods. In the latter case the results of the modelling are used as forecasts and allow to obtain information about the energetics of the atomic vacancies and vacancy clusters formations. A special interest is given to the study of the influence of interstitial impurity atoms on the processes of vacancy and vacancy complexes formation. In the present work, we use ab-initio methods to study the energetics of small vacancy complexes (2-10 vacancies) formation in hcp-Be. We present a detailed study of the influence of a single He atom on the formation of the vacancy complexes. Calculations were performed using a planewave pseudopotential method, realized in Quantum-ESPRESSO program package [1]. Our results demonstrate that the interaction between two nearby vacancies in hcp-Be shows a repulsive character. The results also show that the formation of small vacancy complexes (2-10 vacancies) is not energetically favorable. This fact is quite unexpected, as in continuous approximation the interaction between nearby vacancies must be of attractive nature. We demonstrate that this effect is due to a substantial reorganisation of hcp-Be electronic subsystem during the formation of the vacancy complexes, and this fact is not taken into account in elasticity theory. However, the situation is completely different if a single He atom is present in Be matrix. Calculations of the formation energies of the vacancy complexes in the presence of a single He atom demonstrate that He induces the effective attraction between the vacancies in hcp-Be. We calculated the energetically favorable positions of He atom by performing a series of calculations with initial He position in one of the vacancy centers, as well as in the center of the whole vacancy complex. We observe that for the 2-vacancy clusters He atoms prefer to stay between the vacancies, while for the 3-vacancy clusters He is displaced from the basal plane containing the vacancies. In the vacancy clusters of larger sizes He atom prefers to sit in the center of the vacancy complex. We also estimated the average sizes of the vacancy clusters in thermodynamically equilibrium state.

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MATERIALS AND PANELS FOR INTEGRATED THERMAL PROTECTION SYSTEMS

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We consider the thermal protection system integrated thermal and structural functions. Typically, it is a set of corrugated core sandwich panels. It is necessary to find the right combination of materials properties and geometric parameters of panels from design point of view such as safety, weight and cost. Here thermomechanical analysis can be useful, in particular at the early stage of the design. For the first, we selected good candidate materials. We used an approximation of maximal bottom temperature of the panel together with search in a materials database. For the second, we carried out coupled thermomechanical analysis of panels buckling. As results, we ranked different combinations of materials and panel's geometry for their further texting and design's improvements.

GRAPHENE: METHODS OF OBTAINING

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Graphene is a two-dimensional allotropic modification of carbon formed by a layer of carbon atoms one-atom thick in sp^2-hybridization and connected via σ and π bonds to a hexagonal two-dimensional crystal lattice. It can be represented as one plane of graphite, separated from a bulk crystal. It is estimated that graphene has great mechanical rigidity and record high thermal conductivity (~ 1 TPa [4] and ~ $5 \cdot 10^3$ $W \cdot m^{-1} \cdot K^{-1}$, respectively).

Imagine a carbon plate that is only one atom thick, but more solid than a diamond, and transmitting electricity is 100 times better than silicon computer chips. The distance between the nearest carbon atoms in graphene is about 0,14 nm. Graphene pieces are obtained by mechanical action on highly oriented pyrolytic graphite or kish-graphite. First, flat pieces of graphite are placed between the sticky tapes (scotch tape) and split one after the other, creating enough thin layers (among the many films one-layer and two-layer films may appear, which are of interest). After exfoliation, the scotch with thin graphite films is pressed against the substrate of oxidized silicon. It is difficult to obtain a film of a certain size and shape in the fixed parts of the substrate (the horizontal dimensions of the films are usually about 10 μm). Found using an optical microscope (they are poorly visible with a dielectric thickness of 300 nm), the films are prepared for measurements. The thickness can be determined using an atomic force microscope (it can vary within 1 nm for graphene) or using Raman scattering.

Grapes can also be made from graphite using chemical methods. First, the microcrystals of graphite are exposed to a mixture of sulfuric and hydrochloric acids. Graphite is oxidized and carboxyl groups of graphene appear on the edges of the sample. They are converted into chlorides with thionyl chloride. Then, under the action of octadecylamine in solutions of tetrahydrofuran, tetrachloromethane and dichloroethane, they pass into graphene layers 0,54 nm thick. This chemical method is not the only one, and by changing organic solvents and chemicals, one can obtain nanometer layers of graphite.

Scientists from the State Association of Scientific and Applied Research of Australia (CSIRO), in collaboration with engineers from Sydney University, Sydney University of Technology and Queensland University of Technology, invented a new method for mining graphene suitable for use in microelectronics. Interestingly, the new technology, called GraphAir, does not require the use of vacuum. The creation of graphene can occur in the open air, and the speed of its production is much higher compared with other existing methods of production. The essence of the method is quite simple: graphene film is extracted from soybean oil in just one cycle of pyrolysis. The oil is heated in a sealed quartz tube for about 26 minutes to 800 degrees Celsius, resulting in the decomposition into carbon "building blocks" necessary for the synthesis of graphene. Due to the limitation of the air flow entering the quartz tube, the resulting carbon is not further transformed into carbon dioxide or other gases. "Blocks" are then rapidly cooled on a nickel substrate, where a thin rectangle of graphene one nanometer thick is formed.

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IMPROVING OF PHYSICO-MECHANICAL AND TRIBOLOGICAL PROPERTIES OF THE Nb-Ti ALLOY BY THERMODIFFUSION OXIDATION

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Nb-Ti alloys are promising for the production of chemical equipment, nuclear power equipment, parts of jet engines. Chemical oxidation can increase the surface hardness and wear resistance of alloys.

The influence of chemical and thermal treatment on structure, physico-mechanical and tribological properties of alloys was analyzed. The following results were obtained.

Oxidation kinetics of the BH-10 alloy in air at temperatures from 400 to 900°C can be described by a parabolic dependence. The energy of oxidation activation which is 212.5 kJ/mol is evaluated.

Oxidation of the BH-10 alloy in air at temperatures from 400 to 900°C promotes the formation of the gas-saturated surface layer of thickness from 30 до 70 μm. Its maximum microhardness increases from 4.2 to 7 GPa due to step-by-step formation of dispersive oxides NbO, NbO_2, $Nb_xTi_yAl_zO_k$, $TiNb_2O_7$, $Ti_{0,4}Al_{0,3}Nb_{0,3}O_2$, that strengthen the alloy surface layer.

The method of surface hardening of the niobium-titanium alloys is proposed. Combined chemical and thermal treatment of alloys is proposed. As a result of this treatment the oxygen-enrich composite layer is formed of the surface. It consists of the complex oxides inclusions of rutile-type Ti(Nb, Al, V)O_2 in the matrix. In this case the gas-saturated layer with the content of oxide inclusions of 40-50 vol. % is formed. It provides the increased wear resistance of the alloy in about 5 times.

It is shown that the composite oxide layer protects the surface of the alloy against wear in the presence of hydrogen. Both after electrolytic hydrogenation and in gaseous hydrogen the coefficient of oxidized alloy friction decreases in 2.5–4 times.

The mechanism of the oxidized layer wear is proposed and it is show that the friction surface is characterized by a sequential change of oxide inclusions brittle fracture and plastic deformation of the matrix.

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SOFTENING EFFECT AND FEATURES OF AN ELECTRONIC SPECTRUM
OF HIGH-TEMPERATURE Mo-Re, Mo-Re-Nb ALLOYS

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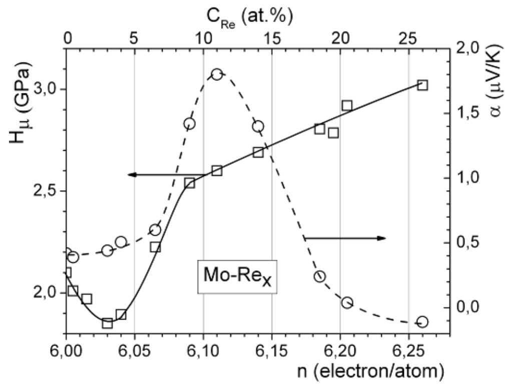
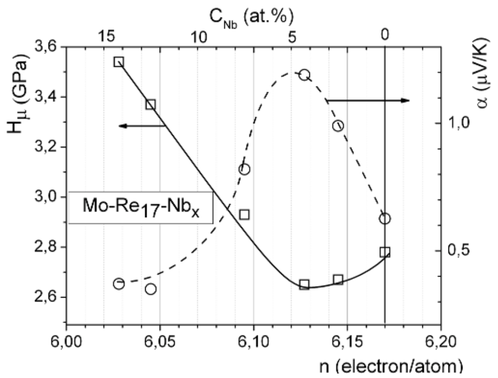
Mo based alloys offer high stability, high creep resistance and high thermal conductivity, and thus are very attractive for many important high-temperature applications (including critical components in missiles, turbines and fusion reactors). At research of superconducting and kinetic characteristics of these Mo_{1-x}-Re_x and Mo_{1-x-y}-Re_x-Nb_y alloys has been established, that rhenium addition (which have one valence electron more than molybdenum) leads to electronic topological transition (ETT) -formation of a new electronic cavity [1]. In the case of niobium addition to alloy Mo-Re, which has less number of valence electrons than molybdenum, this electronic cavity disappears. Extremum in dependences of thermoelectric power $\alpha(n)$ correspond to these ETT there [1], (where $n=6+x-y$ – effective electronic concentration).

The influence of specified alloys composition on their microhardness H_μ at a room temperature is investigated in this work (see figure).





The main feature of the adduced results for binary alloys is minimum presence on dependence H_μ *(n)* that will be agreed with article data [2]. In ternary alloys minimum H_μ also is observed at certain concentration of niobium though it contradicts conclusions of authors [2] about strengthening action of the impurity, which valence is less than molybdenum. Therefore presence of microhardness minimum in ternary alloys can serve as an argument in favor of the electronic nature of the softening effect phenomenon. It is shown [2] that position of a hardness minimum C_{min} of binary alloys changes with temperature decreasing. Dependency extrapolation of $C_{min}^{1/2}(T)$ to zero temperature gives value $C_{min}(0)$ ~10%at rhenium. That corresponds to value C_c - critical concentration rhenium in Mo_{1-x}-Re_x alloy at which ETT is observed at low temperatures.

Availability of a band with large density of states near to Fermi's level and the temperature smearing of a spectrum "involved" this band can have strong effect on mechanical properties by stacking fault energy decreasing. This mechanism disappears while moving from the band edge. Influence ETT can disappear entirely at high temperatures, when topological feature of density of states is completely smearing away. The parameter of attenuation, caused by electron-impurity scattering in an alloy with the critical rhenium content, makes 30K [1]. Therefore, the temperature ~500K at which the softening effect disappears [2], can quite lead to full smearing of topological feature in density of states.

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SPENT NUCLEAR FUEL AND RADIOACTIVE WASTE MAGNETO-PLASMA REPROCESSING

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At present the recycling of nuclear fuel (NF), i.e. its reuse, is implemented by using PUREX-process as a main recycling strategy for nuclear waste management. However, it leads to increase of liquid radioactive waste volume, while the alternative methods of physical reprocessing, in particular plasma ones, do not require chemical reagents, but use only electrical power. Currently, the studies on plasma reprocessing of the spent nuclear fuel (SNF) become of great importance and they are carried out in the United States, Russia, Ukraine. NSC KIPT (Ukraine) carries out studies connected with the development of plasma SNF reprocessing without using PUREX process, but only physical methods, i.e. through the heating, ionization, rotation of plasma with use of non-radioactive simulation media. Such a separation method can lead to the dividing of the SNF volume into two groups of elements: fission products (FPs) and actinides (NF), which can be reused. During irradiation of the uranium oxide fuel in the reactor's stationary conditions a significant consumption of oxygen goes to the oxidation of FPs. When studying heating process of the spent fuel it was shown formation of a lot of ternary compounds too.

The presence of the multicomponent oxide compounds in the SNF complicates the processes of magneto-plasma reprocessing, reduces fission product removal from spent fuel, and hence, it may impact on the environment. For higher quality removal FPs from irradiated fuel in the plasma stages it would be necessary to investigate the properties of different multicomponent oxides for obtaining information on their physical values. Based on the progress made in ACSEPT (Actinide reCycling by SEParation and Transmutation- FP7 EURATOM), a new collaborative project is under discussion with potential partners in order to compare two concepts of recycling strategies for SNF: with and without PUREX process. Magneto-plasma reprocessing is dedicated to the development of non-aqueous SNF reprocessing using plasma methods. It assumes three consequent stages where separation of FPs from actinides (NF) in each stage can be implemented without chemical reagents. The goal is to carry out the studies of the principles on magneto-plasma separation of actinides and fission products from SNF using only physical methods.

A NEW METHOD FOR THE PREDICTION OF WWER RPV METAL CRITICAL TEMPERATURE OF BRITTLENESS

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In the WWER countries the critical temperature of brittleness (CTB) of metal is the main characteristic that used for estimation of brittle fracture safety margin of reactor pressure vessels (RPV). Lifetime of RPV determination based on the prediction of CTB.

CTB value is obtaining by the processing of Charpy impact energy versus temperature data which are obtained as a result of Charpy V-notched (CVN) tests of radiation surveillance specimens (SS) sets.

The paper presents a review of modern codes that regulate WWER RPVs CTB prediction. The peculiarity of these codes is that all of them based on the CTB shift ideology. According to this ideology the CTB is defined as the initial CTB value plus CTB shift due to the radiation plus certain margin. This margin includes the scatter of CTB in the initial state and scatter of CTB shift due to the radiation.

There is a tendency of modern WWER RPV integrity assessment codes to provide maximum level of the conservatism with: choosing the CTB in the initial state for the CTB shifts determination; choosing the CTB in the initial state for the CTB determination; taking into account the scatter of CTB in the initial state and scatter of CTB shift due to the radiation. Such tendency leads to the huge predictive values of CTB which subsequently can lead to formal unfulfillment of brittle fracture criterion for RPVs.

problems related with the CTB definition of RPV are presented and disadvantages of the modern codes are shown.

It is shown, that due to the fact that the method of CTB determination for RPV metal in the initial state (performed on the plant that manufactured RPV) and the method of CTB determination for RPV metal after irradiation (performed using the SS) are different, the most of problems related with the shift ideology was arose. In order to solve the problems the passport data of CVN test of base metal and welds of all Ukrainian WWER RPVs are processed by two above mentioned methods of CTB definition. Using the mathematical statistics the correlation between the methods is obtained.

Paper demonstrates that the usage of actual CTB data obtained directly from impact tests of radiated Charpy V-notched SS, instead of the CTB shift ideology, is the progressive way of adequate RPV metal CTB definition.

“GREEN” CORROSION INHIBITORS BASED ON BIOGENIC SURFACTANTS

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Anticorrosion effectiveness of rhamnolipid biosurfactant and its complex with natural polysaccharide derived from *Pseudomonas* sp. PS-17 bacteria was studied. The biogenic products influence on the corrosion of an aluminium Al-Cu-Mg alloy was examined using electrochemical methods supported by quantum-chemical calculations. It was established that the rhamnolipid based biosurfactants effectively inhibit corrosion of the alloy in fresh water and in technical liquid of cooling systems. The efficiency of inhibition becomes stronger with the increase of biosurfactant concentration however above the critical micelle concentration further improvement in inhibition is minor. It is believed that the mechanism of corrosion inhibition is related to the adsorption of the biosurfactant molecule on the aluminium alloy surface and the formation of a barrier film however, the formation of a complex compound (salt film) between aluminium ions and rhamnolipid on anodic sites of the alloy is not ruled out. In the case of surface mechanical activation of the alloy, the biosurfactant molecule effectively prevents corrosion. Furthermore, addition of the biosurfactants to the corrosion environment increases the re-passivation kinetics of the alloy by 2-4 times as compared with an uninhibited environment.

The biogenic inhibitors can be used alone and in synergistic compositions. They can be added to corrosion environment at low concentrations due to their high activity and this makes them economically beneficial at price equal to synthetic inhibitors. The inhibitors are characterized by low toxicity and ability to biodegradation. The use of new biosurfactant-based inhibitors could be possible in different areas: for the protection of equipment in oil and gas industry, in heat-power engineering, particularly in acid cleaning compositions for boilers in electric power stations, in central heating and power plants, in multi-electrode systems of liquid cooling systems of internal combustion engines and electronic equipment.

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RESEARCH OF GRAPHITE ^{14}C WASTE FROM RBMK-TYPE REACTORS

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Institutions of National Academy of Science of Ukraine are investigating various options for usage of graphite from uranium-graphite reactors during their decommissioning [1-3]. These researches are contributed to number of collaborative projects, including IAEA coordinated research project: "Treatment of Irradiated Graphite to Meet Waste Acceptance Criteria for Disposal" and the EURATOM Project: "CArbon-14 Source Term", **(CAST)**. The objectives of the CAST project are to gain new scientific understanding of the rate of carbon-14 release from corrosion of irradiated steels and zircaloys and from leaching of irradiated graphite under geological disposal conditions.

Graphite is the key component of RBMK-type reactors and aim of this research to develop better understanding of this material to support future waste management options. Exposure to neutron radiation at high temperature induces large amount structural changes over many length scales. Since each grade of graphite has unique structure and texture, its irradiation behavior can be expected to be somewhat different. The research was carried out to investigate the structure and morphology of the surface layer of the samples of graphite stack (GR-280) and the split graphite rings from technological channels (GRP-2-125). Studies of graphite microstructure have been performed, using XRD and SEM to evaluate the graphite's morphological features. Silicon standard was used to determine the peak position and peak broadening. It was shown that the interlayer spacing (d_{00l}) expands in the treated graphite. Based on the diffraction patterns, estimates were made about distance between sheets and the magnitude of the coherent scattering.

Chemical treatments have been investigated in order to decontaminate irradiated graphite waste. Two mechanisms have been identified in the chemical decontamination of graphite: destruction of the binding material and selective removal of the surface layer of graphite. Leaching experiments show that the ^{14}C radioactivity of graphite without oxide layer is less compared to ^{14}C of same graphite samples with oxide graphene layer.

New methods of converting nuclear energy into useful power, such as high temperature gas-cooled reactor (HTGR) with large graphite core will depend of graphite matrix materials.

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