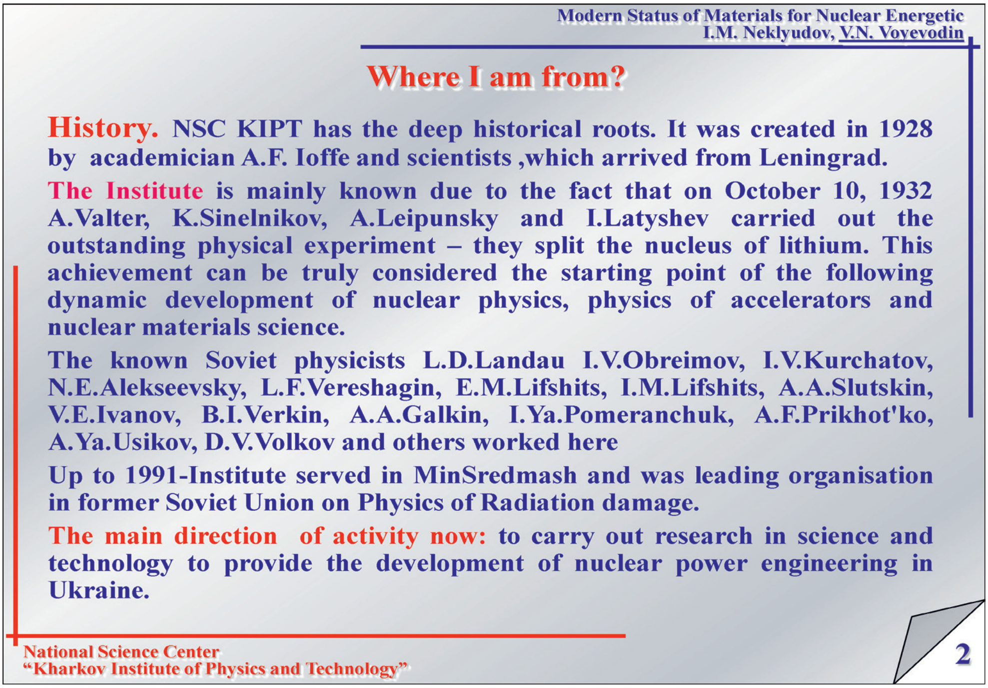
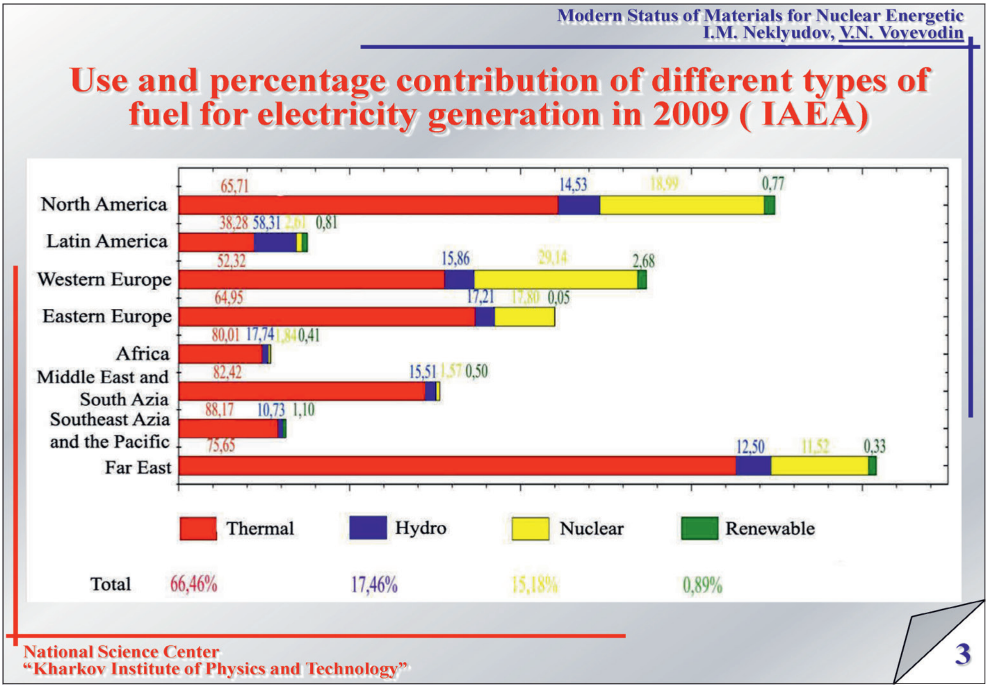
Ivan M. NEKLYUDOV*, Victor N. VOYEVODIN*

MODERN STATUS OF MATERIALS FOR NUCLEAR ENERGETIC



The paper is given in terms of PowerPoint presentation.

* National Science Center “Kharkov Institute of Physics and Technology”, 1, Akademicheskaya Str, 61108, Kharkov, Ukraine


Modern Status of Materials for Nuclear Energetic
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Use and percentage contribution of different types of fuel for electricity generation in 2009 (IAEA)
North America 65,71 14,53 18,99 0,77
Latin America 38,28 58,31 2,61 0,81
Western Europe 52,32 15,86 29,14 2,68
Eastern Europe 64,95 17,21 17,80 0,05
Africa 80,01 17,74 1,84 0,41
Middle East and South Azia 82,42 15,51 1,57 0,50
Southeast Azia and the Pacific 88,17 10,73 1,10
Far East 75,65 12,50 11,52 0,33
Thermal
Hydro
Nuclear
Renewable
Total 66,46% 17,46% 15,18% 0,89%
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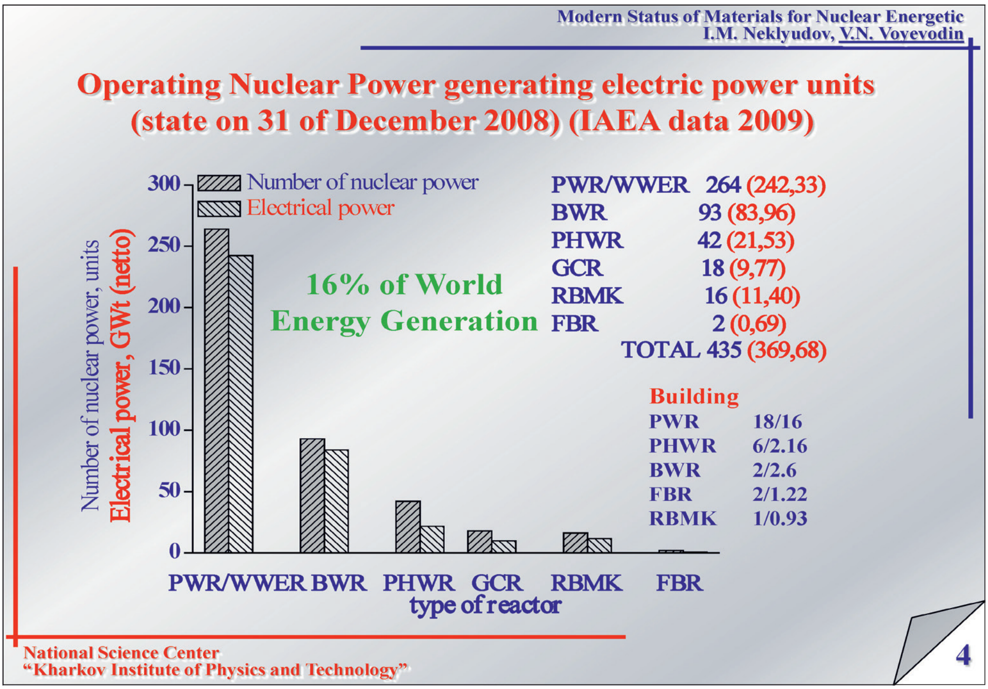
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Operating Nuclear Power generating electric power units (state on 31 of December 2008) (IAEA data 2009)
Number of nuclear power
Electrical power
16% of World Energy Generation
PWR/WWER 264 (242,33)
BWR 93 (83,96)
PHWR 42 (21,53)
GCR 18 (9,77)
RBMK 16 (11,40)
FBR 2 (0,69)
TOTAL 435 (369,68)
Building
PWR 18/16
PHWR 6/2.16
BWR 2/2.6
FBR 2/1.22
RBMK 1/0.93
Number of nuclear power, units
Electrical power, GWt (netto)
300
250
200
150
100
50
0
PWR/WWER BWR PHWR GCR RBMK FBR
type of reactor
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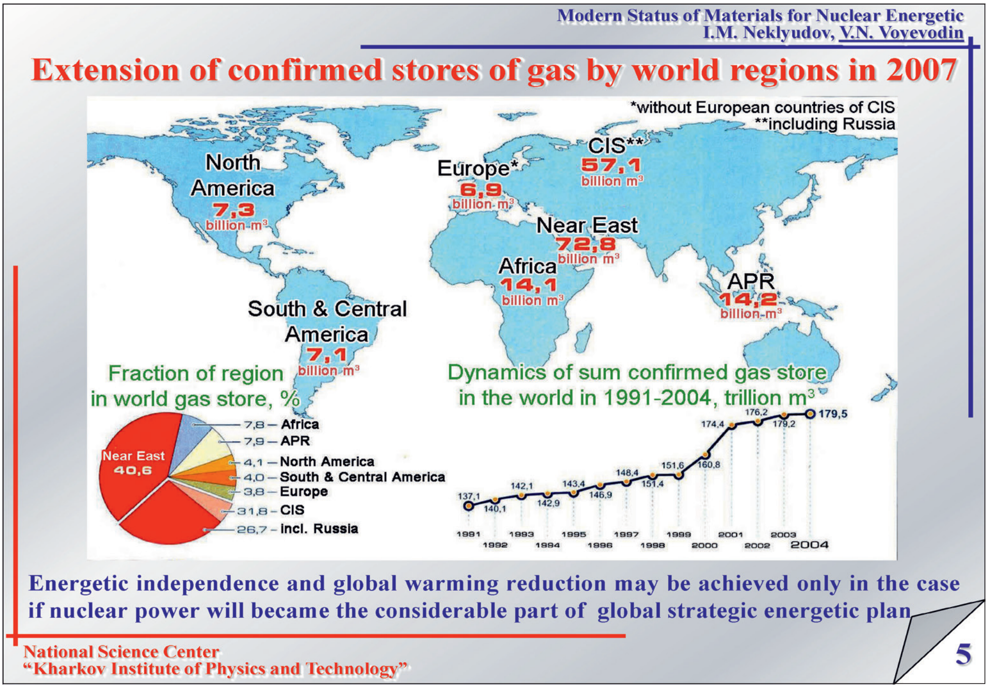
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Extension of confirmed stores of gas by world regions in 2007
*without European countries of CIS
**including Russia
North America 7,3 billion m³
Europe* 6,9 billion m³
CIS** 57,1 billion m³
Near East 72,8 billion m³
Africa 14,1 billion m³
APR 14,2 billion m³
South & Central America 7,1 billion m³
Fraction of region in world gas store, %
Near East 40,6
7,8 – Africa
7,9 – APR
4,1 – North America
4,0 – South & Central America
3,8 – Europe
31,8 – CIS
26,7 – incl. Russia
Dynamics of sum confirmed gas store in the world in 1991-2004, trillion m³
137,1
140,1
142,1
142,9
143,4
146,9
148,4
151,4
151,6
160,8
174,4
176,2
179,2
179,5
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
Energetic independence and global warming reduction may be achieved only in the case if nuclear power will became the considerable part of global strategic energetic plan
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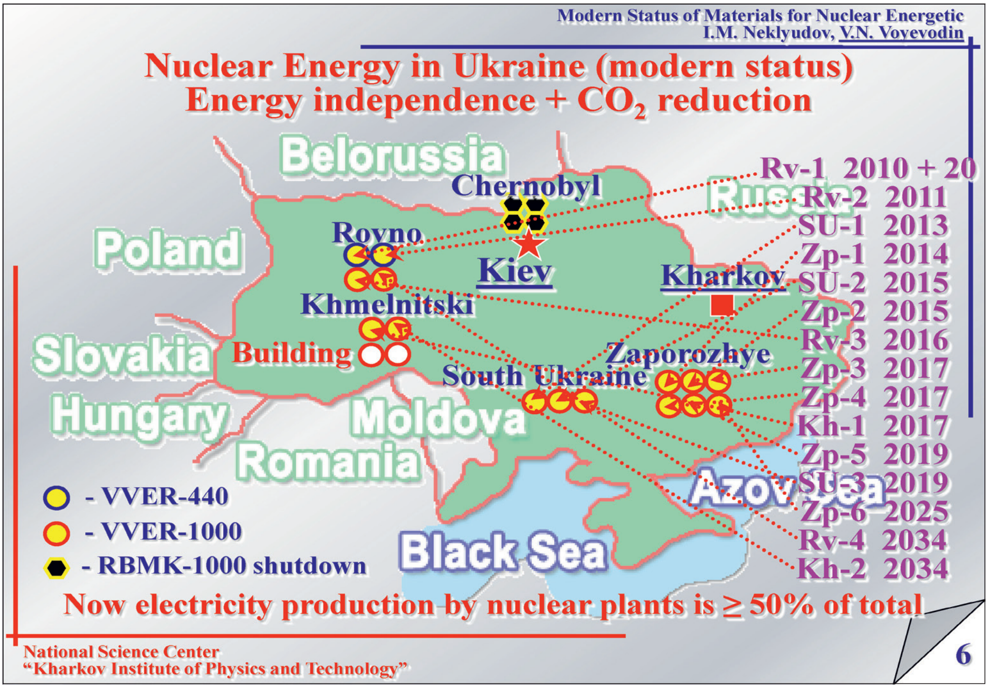
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Nuclear Energy in Ukraine (modern status)
Energy independence + CO₂ reduction
Belorussia
Russia
Poland
Slovakia
Hungary
Moldova
Romania
Chernobyl
Rovno
Kiev
Kharkov
Khmelnitski
Building
South Ukraine
Zaporozhye
Azov Sea
Black Sea
Rv-1 2010 + 20
Rv-2 2011
SU-1 2013
Zp-1 2014
SU-2 2015
Zp-2 2015
Rv-3 2016
Zp-3 2017
Zp-4 2017
Kh-1 2017
Zp-5 2019
SU-3 2019
Zp-6 2025
Rv-4 2034
Kh-2 2034
- VVER-440
- VVER-1000
- RBMK-1000 shutdown
Now electricity production by nuclear plants is ≥ 50% of total
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Situation with Nuclear materials in Ukraine
In Ukraine now are exploited 15 NPP-13 VVER-1000 and 2 VVER-440,
2 VVER-1000 must be finished
Ukraine has sources of own U, Zr, Be, etc
Agreement with RF about building of plant for fabrication of nuclear fuel was signed (2010)
Energy strategy - in a future - attempt to close nuclear fuel cycle -Ukraine is ready to participate in any aspects of material research for reactors -R&D of radiation resistant structural materials, claddings production etc.
♦Now in Ukraine principal of alternative supplies begin to realize
Russia → anybody else!!! Candu-?
Process of confirmation of mixed fuel suppliers using is now done:
1 unit of SU NPP → 6 FS (Westinghouse) → 42FS.
♦Now Ukraine is preparing to production of components of own fuel assemblies (stainless steels, Zr-base alloys etc).
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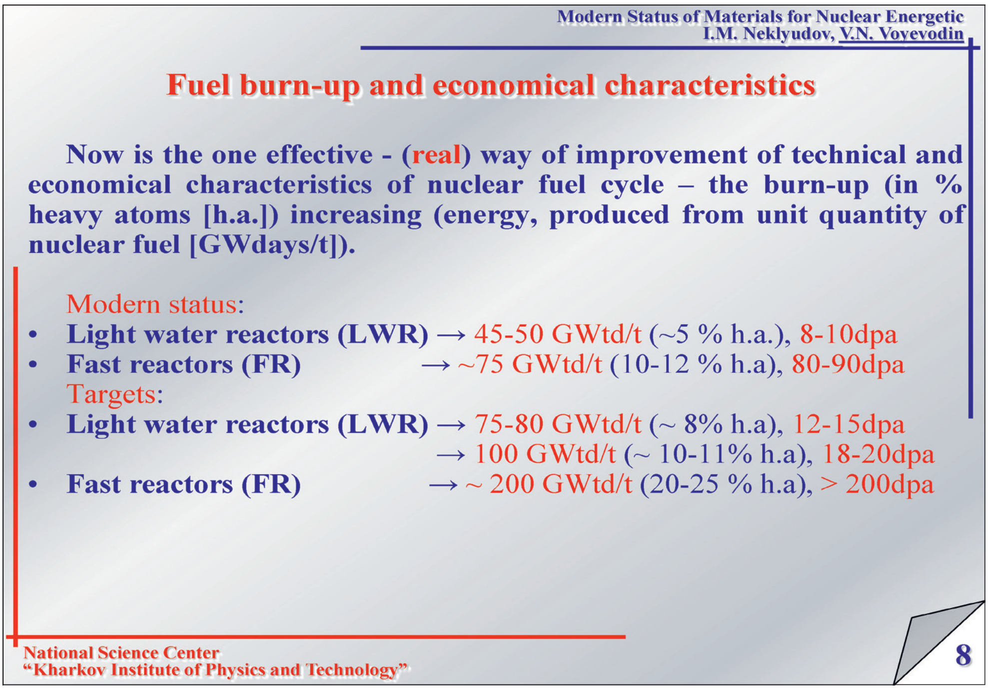
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Fuel burn-up and economical characteristics
Now is the one effective - (real) way of improvement of technical and economical characteristics of nuclear fuel cycle – the burn-up (in % heavy atoms [h.a.]) increasing (energy, produced from unit quantity of nuclear fuel [GWdays/t]).
Modern status:
• Light water reactors (LWR) → 45-50 GWtd/t (~5 % h.a.), 8-10dpa
• Fast reactors (FR) → ~75 GWtd/t (10-12 % h.a), 80-90dpa
Targets:
• Light water reactors (LWR) → 75-80 GWtd/t (~ 8% h.a), 12-15dpa
→ 100 GWtd/t (~ 10-11% h.a), 18-20dpa
• Fast reactors (FR) → ~ 200 GWtd/t (20-25 % h.a), > 200dpa
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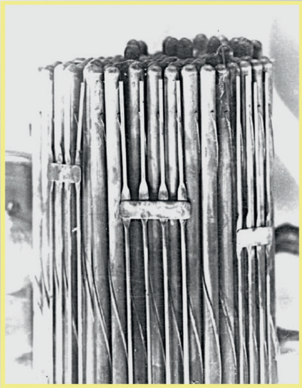
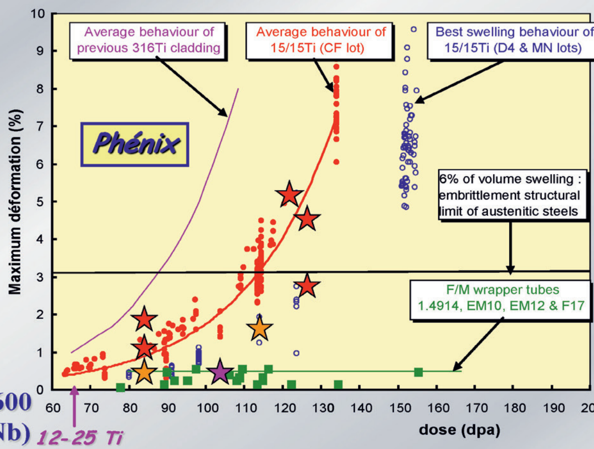
The examples of degradation phenomena

Swelling and deformation of austenitic materials



Assembly P-34, 35 dpa, BN-600
EI-847 steel (16Cr15Ni3MoNb)

(S.Porollo,et al., 2008)



(P.Dubuisson, 2008)

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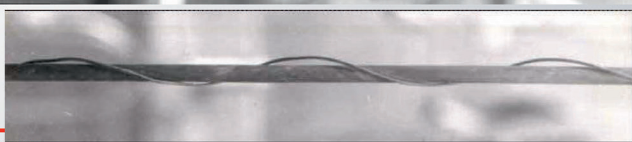
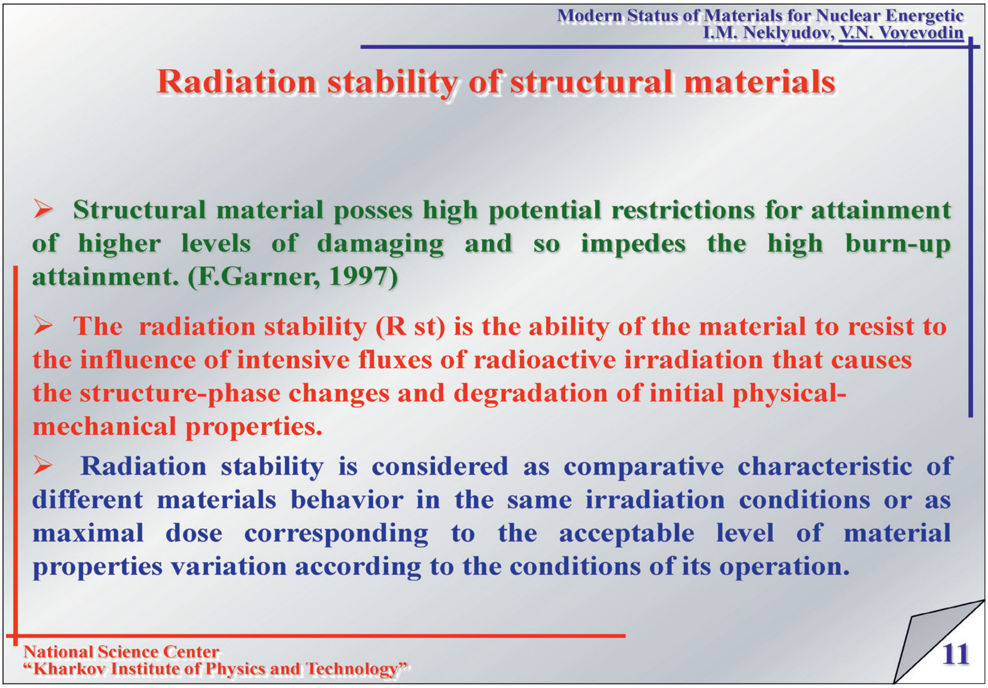
Consequence of wire swelling more than cladding
Chuev, Lanskykh, Ogorodov, Sheikmann, Sergeev, 2004

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Radiation stability of structural materials
➢ Structural material posses high potential restrictions for attainment of higher levels of damaging and so impedes the high burn-up attainment. (F.Garner, 1997)
➢ The radiation stability (R st) is the ability of the material to resist to the influence of intensive fluxes of radioactive irradiation that causes the structure-phase changes and degradation of initial physical-mechanical properties.
➢ Radiation stability is considered as comparative characteristic of different materials behavior in the same irradiation conditions or as maximal dose corresponding to the acceptable level of material properties variation according to the conditions of its operation.
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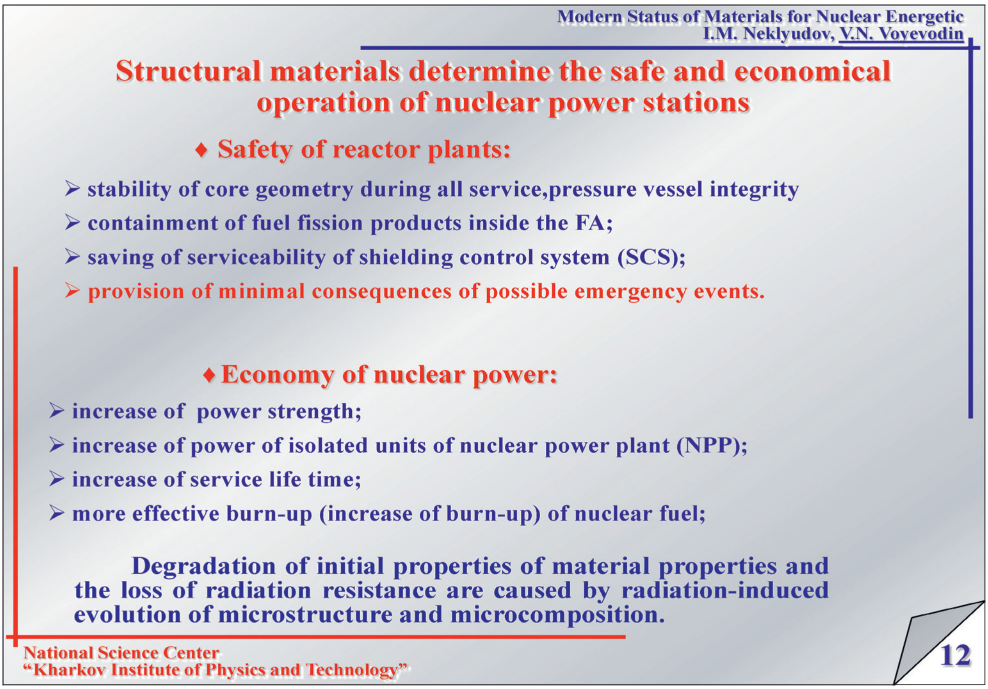
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Structural materials determine the safe and economical operation of nuclear power stations
♦ Safety of reactor plants:
➢ stability of core geometry during all service,pressure vessel integrity
➢ containment of fuel fission products inside the FA;
➢ saving of serviceability of shielding control system (SCS);
➢ provision of minimal consequences of possible emergency events.
♦ Economy of nuclear power:
➢ increase of power strength;
➢ increase of power of isolated units of nuclear power plant (NPP);
➢ increase of service life time;
➢ more effective burn-up (increase of burn-up) of nuclear fuel;
Degradation of initial properties of material properties and the loss of radiation resistance are caused by radiation-induced evolution of microstructure and microcomposition.
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Conditions of materials irradiation in reactors

Reactor	Material	T°, C	F, n/m²sec (E_n>0,1MeV)	k, dpa/c	He, appm/year	H, appm/year	Lifetime, dpa (years)
PWR Westinghouse pressure vessel	Low-alloyed ferritic steels	290 – 315	$1 \cdot 10^{15}$	$8 \cdot 10^{-11}$	$1 \cdot 10^{-3}$	$8{,}85 \cdot 10^{-2}$	0.2 (60 years)
WWER-1000 pressure vessel	Ferritic-perlitic steels	290 – 315	$5 \cdot 10^{15}$	$4 \cdot 10^{-10}$.	$5 \cdot 10^{-3}$	$4{,}4 \cdot 10^{-1}$	0.1 (40 years)
PWR Westinghouse Fuel element cladding Z_5=3,2%; 99тUO$_2$	Zr alloys	345 – 420	$4 \cdot 10^{17}$	$3 \cdot 10^{-8}$	$3{,}3 \cdot 10^{-1}$	$2{,}9 \cdot 10^{-1}$	4 (5 years)
WWER-1000 Fuel element cladding Z_5=4,4%; 66,3тUO$_2$	Zr alloys	345 – 420	$4{,}4 \cdot 10^{17}$	$3{,}2 \cdot 10^{-8}$	$3{,}6 \cdot 10^{-1}$	$3{,}2 \cdot 10^{-1}$	8 – 10 (3 years)
WWER-1000 PVI (buffle)	Austenitic steel	300 – 410	$2 \cdot 10^{17}$	$3 \cdot 10^{-8}$	30	60	55 (30 years)
FBR Fuel element cladding	Austenitic steel, fer.-mart.steel	450 – 650	$2 \cdot 10^{19}$	$1 \cdot 10^{-6}$	20 – 30	–	150 – 200 (4 years)

It is calculated for 1 astronomical year= $3{,}1557 \cdot 10^7$ sec ; 1 ef. year = 7000 hours=$2{,}52 \cdot 10^7$ sec
Due to difference lifetime calculation is performed for 1 astronomical year

Modern Status of Materials for Nuclear Energetic
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Executive Summary

- **Ion-beam materials research can accelerate the development of two critical materials areas for nuclear energy**
  - The development of *radiation tolerant materials* is the big scientific/technical goal that is specific to the success of sustainable nuclear energy
  - Similarly, the development of high and ultra-high burn-up fuels is critical to the development of advanced fission and FFH systems
- **Energy independence and the reduction of global warming will be realized as a result of nuclear energy being a significant part of the global strategic energy plan**
  - The long time (~20 years) for materials development, testing, licensing, and insertion is a scientific and technological challenge if not an imperative.

Radiation tolerance and high burn-up are science challenges with strong technological implications.

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Advantage of ion and electron simulation

Why accelerators are needed?

- Higher damage rate (10^{-4}–10^{-2} /accelerator/ vs 10^{-6}–10^{-10} dpa/s /reactor/)
- Good control of experimental parameters (temperature, flux and environment), possibility of parameters separation
- Ideally suited for optimizing minor alloying composition
- Irradiated specimens are not radioactive, unlike reactor specimens which are highly radioactive and may have to be handled only in hot cells
- Only one possible choice in the absence of high flux neutron irradiation facility.
- Many nuclear facilities are shut down now ((FFTF, EBR-II, RAPSODIE, SUPERPHENIX, PHENIX(2010) DFR, PFR, BR-10, BN-350, MONJU, JOYO etc)

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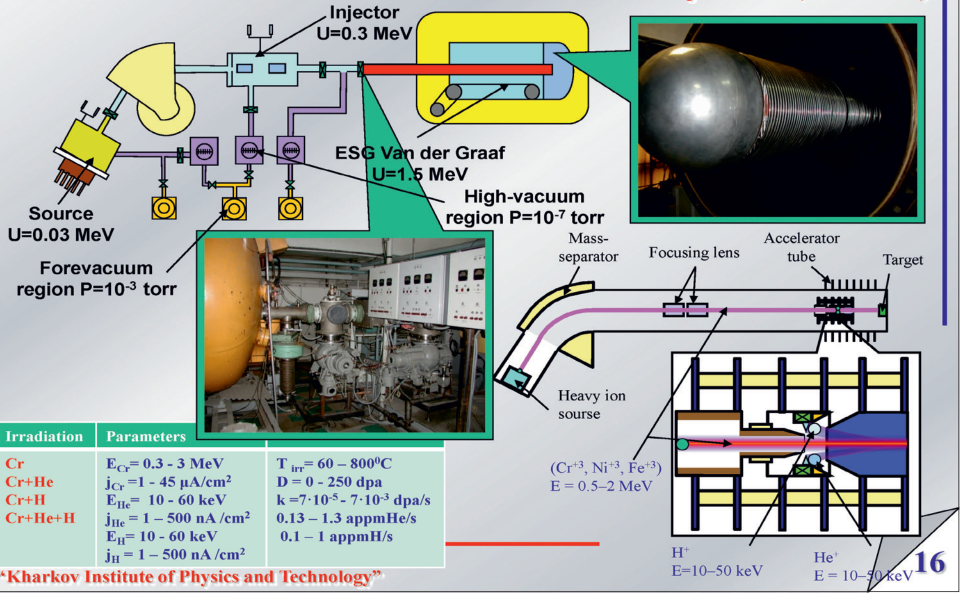
Electrostatic Accelerator with External Injector (ESUVI)



Irradiation	Parameters	
Cr Cr+He Cr+H Cr+He+H	E_{Cr}= 0.3 - 3 MeV j_{Cr} =1 - 45 μA/cm² E_{He}= 10 - 60 keV j_{He} = 1 – 500 nA /cm² E_H= 10 - 60 keV j_H = 1 – 500 nA /cm²	T_{irr}= 60 – 800⁰C D = 0 - 250 dpa k =$7\cdot10^{-5}$ - $7\cdot10^{-3}$ dpa/s 0.13 – 1.3 appmHe/s 0.1 – 1 appmH/s

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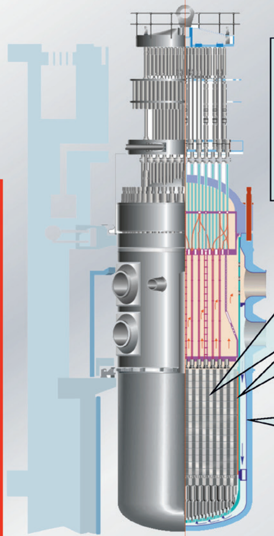
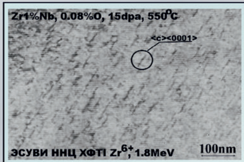
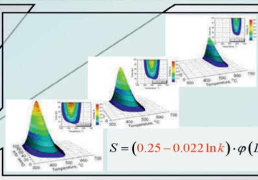
Radiation damage in VVER materials





Claddings (Zr-1%Nb)

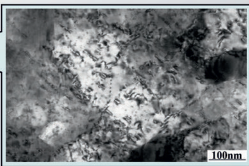
Suppression of radiation growth Increasing of oxygen(0,08–0,19%) leads to reduction of <c>- loops size, which are responsible for radiation growth.



PVI (18Cr10NiTi)

Prediction of swelling in wide range of doses, irradiation temperatures and rate doses.

$$S = (0.25 - 0.022\ln k)\cdot\varphi(D - 103 + 0.1T - 2.6\ln k)\cdot\exp\left\{-\frac{(T - 690 - 15.5\ln k)^2}{2\cdot(12.3 - 1.9\ln k)^2}\right\}$$



Vessel (2Cr-Mo-V)

Express irradiation simulates correctly mechanisms of pressure vessel material hardening. Yield strength increases at the expense of fine dislocation loops formation.

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Zirconium alloys-status and prospects

Now burn-up of FE of reactors WWER-1000 constitutes 45-50 GWt d/t (8-10 dpa)

Prospects

- Need of provision of FE burnup to 75-80 GVt d/t U. Increase of the resource from 30000 to 46000 eff.hours (45 – 75 GVt d/t U)
- Increase of the temperature of FE claddings to 358 C and vapor content into coolant to 13% mass.
- Power manoeuvring
- Undoubted provision of safety criteria

Chemical composition of zirconium alloys

Alloy	Content of elements, %					
	Nb	Sn	Fe	O	S	C
E-110	0.9-1.1			≤ 0.1		≤ 0.02
E-125	2.4-2.7			≤ 0.1		≤ 0.02
M5	0.8-1.2		0.015-0.06	0.09-0.18	≤0.0035	0.0025-0.012
Zy-2		1.2-1.7	0.07-0.2	0.1-0.14		≤ 0.027
Zy-4		1.2-1.7	0.18-0.24	0.1-0.14		≤ 0.027
E-635	0.9-1.1	1.0-1.5	0.3-0.5	≤ 0.1		≤ 0.02
Zirlo	0.9-1.1	0.9-1.1	0.09-0.11	0.1-0.14		≤ 0.027

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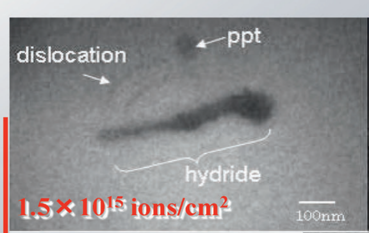
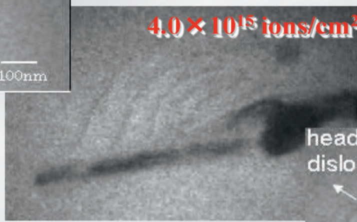
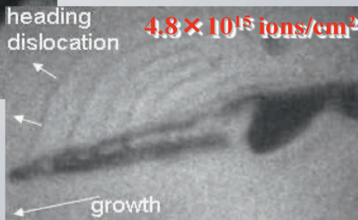
Microscopic evolution of Zr hydride in Zircalloy-4 [Y.Shinohara et.al., 2007]

The dynamic process of the formation of Zr hydrides accompanied with dislocations around hydrides was observed.







Growth of a intra-granular Zr hydride in Zircaloy-4 under 150 keV H_2^+ irradiation, B=z=[0001], g = [1010]

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Reason for the consideration of new generation of reactors of IV generation is the following

- Low efficiency (~33-34%) of nuclear reactors in comparison with thermal power station with fossil fuel (~45% and higher, up to 55% - expected, is building in Europe).
- Introduction of "passive safety system" on the level of nuclear reactors design, excluding the elements of electrical automatic equipment (due to its failures) and the minimizing of operator influence on the nuclear reactor operation (so-called human factor).
- Specialization of nuclear reactors according to their industrial use:
  - for production of electrical power;
  - for production of high efficiency heat;
  - for production of hydrogen fuel and use in the chemical industry.

It is caused by that analysis of the electrical power use round the world had showed that ~ 50% of electrical power is converted into the heat.

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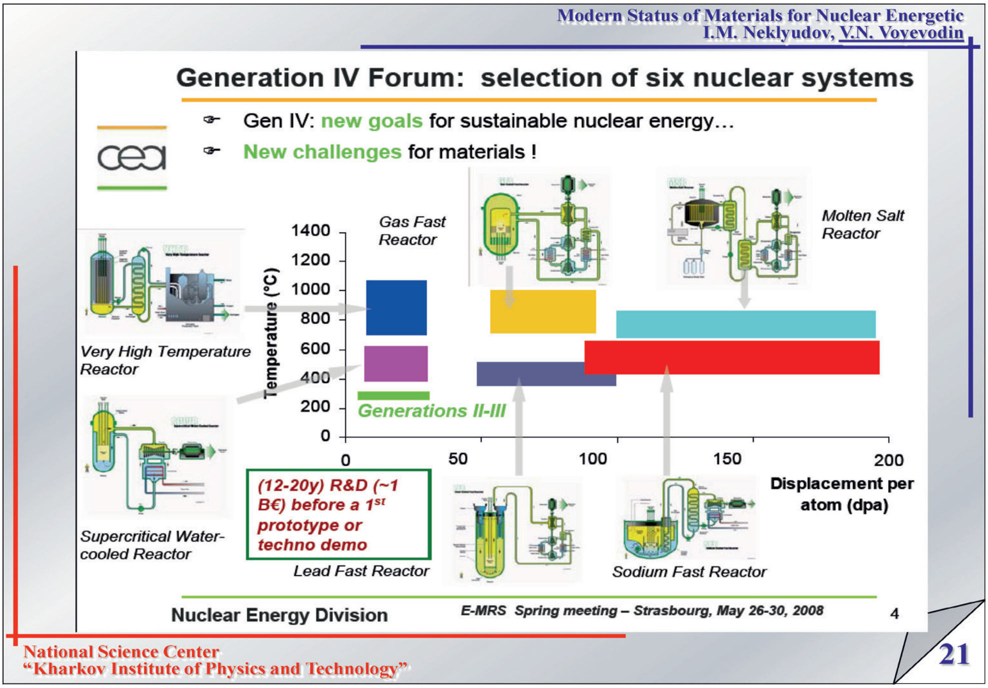
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Generation IV Forum: selection of six nuclear systems
cea
Gen IV: new goals for sustainable nuclear energy…
New challenges for materials !
Gas Fast Reactor
Molten Salt Reactor
Very High Temperature Reactor
Supercritical Water-cooled Reactor
Temperature (°C)
1400
1200
1000
800
600
400
200
0
Generations II-III
0
50
100
150
200
Displacement per atom (dpa)
(12-20y) R&D (~1 B€) before a 1st prototype or techno demo
Lead Fast Reactor
Sodium Fast Reactor
Nuclear Energy Division
E-MRS Spring meeting – Strasbourg, May 26-30, 2008
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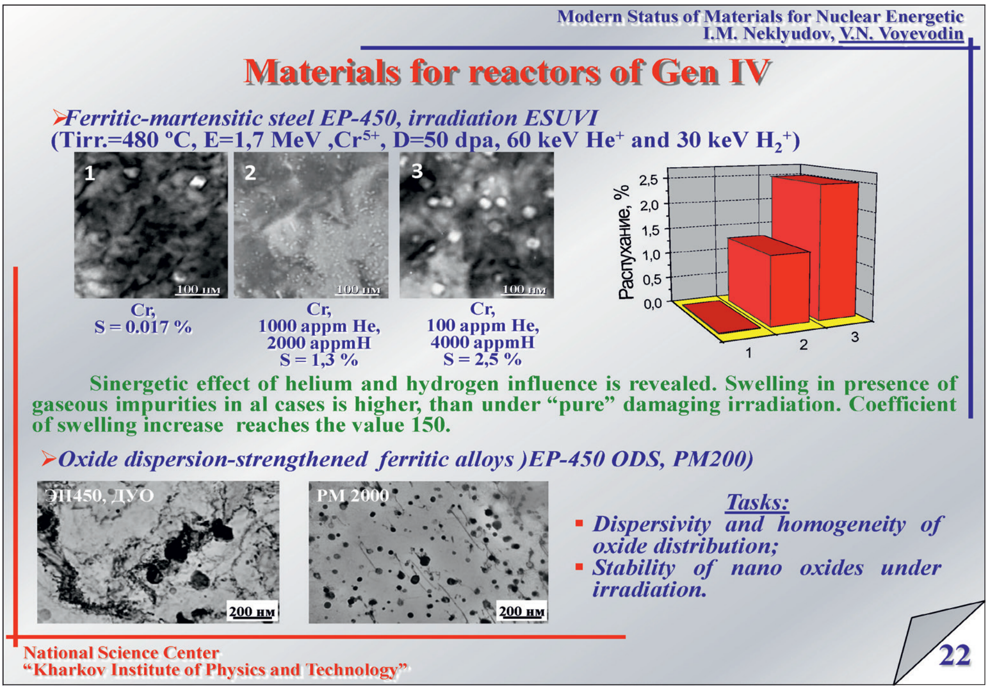
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Materials for reactors of Gen IV
➢Ferritic-martensitic steel EP-450, irradiation ESUVI
(Tirr.=480 °C, E=1,7 MeV ,Cr5+, D=50 dpa, 60 keV He+ and 30 keV H2+)
1
2
3
100 нм
Cr, S = 0.017 %
Cr, 1000 appm He, 2000 appmH S = 1,3 %
Cr, 100 appm He, 4000 appmH S = 2,5 %
Распухание, %
2,5
2,0
1,5
1,0
0,5
0,0
1
2
3
Sinergetic effect of helium and hydrogen influence is revealed. Swelling in presence of gaseous impurities in al cases is higher, than under "pure" damaging irradiation. Coefficient of swelling increase reaches the value 150.
➢Oxide dispersion-strengthened ferritic alloys)EP-450 ODS, PM200)
ЭП450, ДУО
PM 2000
200 нм
Tasks:
Dispersivity and homogeneity of oxide distribution;
Stability of nano oxides under irradiation.
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Integration of science and education on personnel preparation
Ф
Т
Ф
The example of effective collaboration is the long term (since 1948) common working towards preparation of personnel in Kharkov University for National Science Center “Kharkov Institute of Physics and Technology” in the field of theoretical and experimental nuclear physics, radiation material science and other professions.
After 1945 Ukrainian Physical-Technical Institute, later Kharkov Institute of Physics ant Technology (KIPT) was oriented towards the nuclear program of Soviet Union. The nuclear department of physical-mathematical faculty was founded in Kharkov University to supply KIPT with scientific personnel; in 1962 this department was transformed into physical-technical faculty. Since 1962 and until today NSC “KIPT” is the main customer and consumer of University“production”.
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KNU ↔ KIPT
It`s now many years the educational process is carried out via common educational –scientific complex.
The branches of following chairs are founded in KIPT:
➢ experimental nuclear physics;
➢ theoretical nuclear physics;
➢ reactor materials science;
➢ physics of plasma and physical technologies.
The prominent scientists of Ukraine supervise these branches.

Conclusion

- Reaching of nuclear fuel high burn-up and necessary levels of safety are limited by insufficient radiation resistance of structural materials.
- The main phenomena that limit the materials use (embrittlement of pressure vessels, low temperature swelling of austenitic steels, growth and shape changes of zirconium alloys, swelling of cladding and wrappers of fast reactors) are interconnected by general physics of phenomena characteristic for irradiated materials but revealed in specific conditions.
- The presented aim-participation reaching of commercially necessary levels of nuclear fuel burn-up may be realized only on the base of modern scientific ideas about the effect of physical mechanisms of microstructure evolution associated with variation of starting mechanical properties under irradiation.
- Collaboration of nuclear physicists, material science specialists and nuclear power plants operators is the casting factor in the solution of posed tasks.