GEN IV International Forum℠

SCIENTIFIC AND TECHNICAL PROBLEMS OF CLOSED NUCLEAR FUEL CYCLE IN TWO-COMPONENT NUCLEAR ENERGETICS

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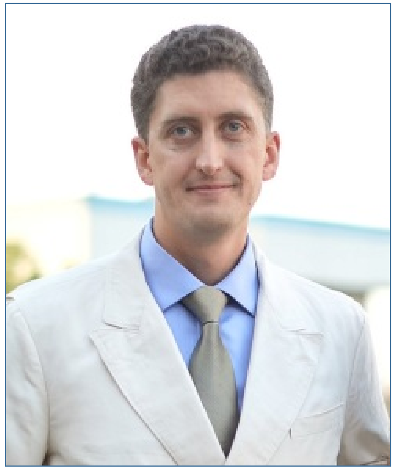
Meet the Presenter

Dr. Alexander Orlov earned his Ph.D. at the MePhI University in Moscow in 2009 and is currently the advisor to Scientific Director of R&D of “Proryv” Project. Since 2012, he has been a member of a team in charge of developing the new technological platform for Nuclear Energetics (NE) consisting of fast reactors with lead and sodium coolants, new type of reactor fuel – mixed U-Pu nitride and technologies to reprocess spent nuclear fuel in order to return it into the fuel cycle. These technologies combined are known as the “Proryv.”



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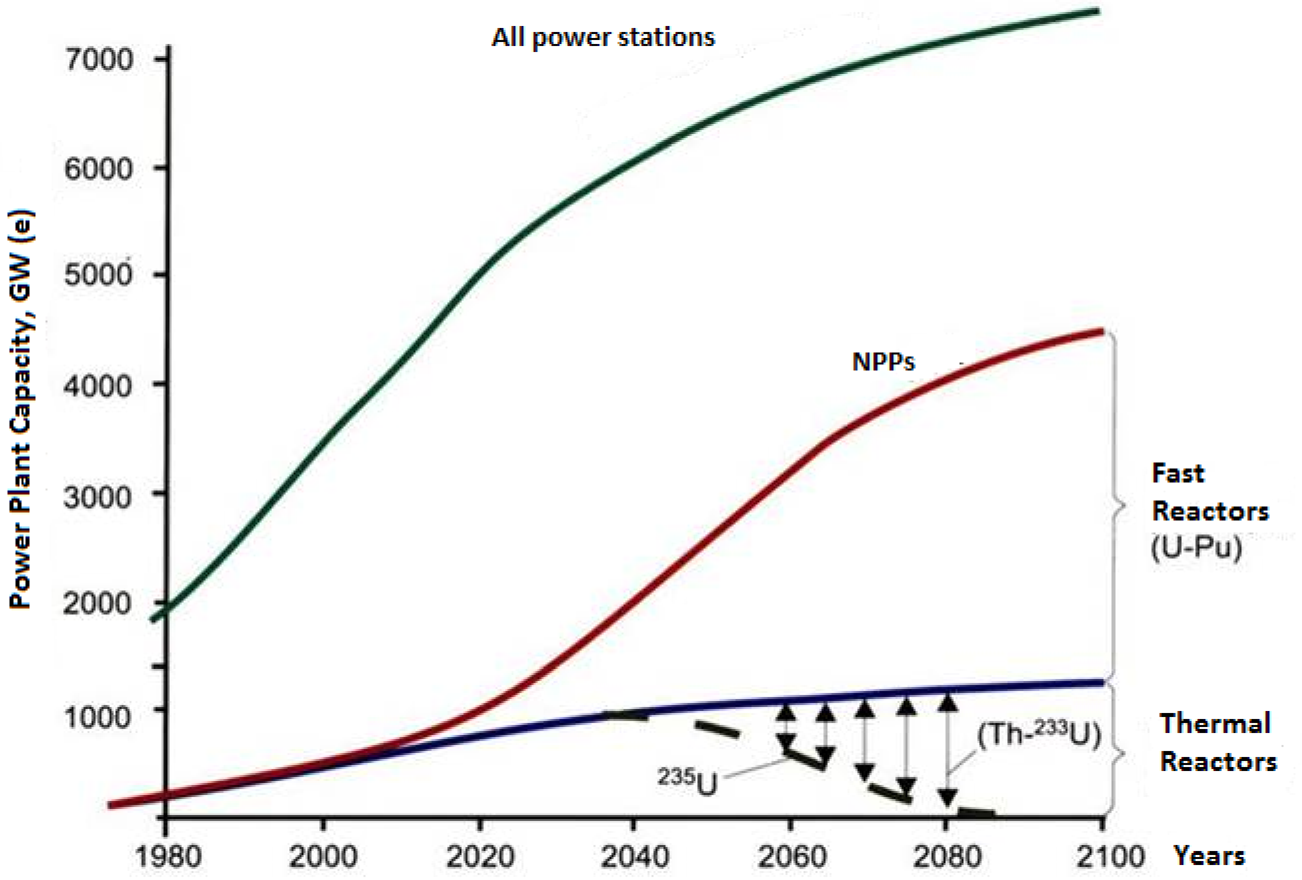
Base expectations

Forecast of World Nuclear Power Growth

Rapid development of Nuclear Energetics (NE), from the first NPP in Obninsk in 1954 (5MW) up to 200 GW in 1980, gave birth to optimistic forecasts for NE development, including those that planned 30% energy production share for NE by 2020. However these forecasts were not destined to happen.



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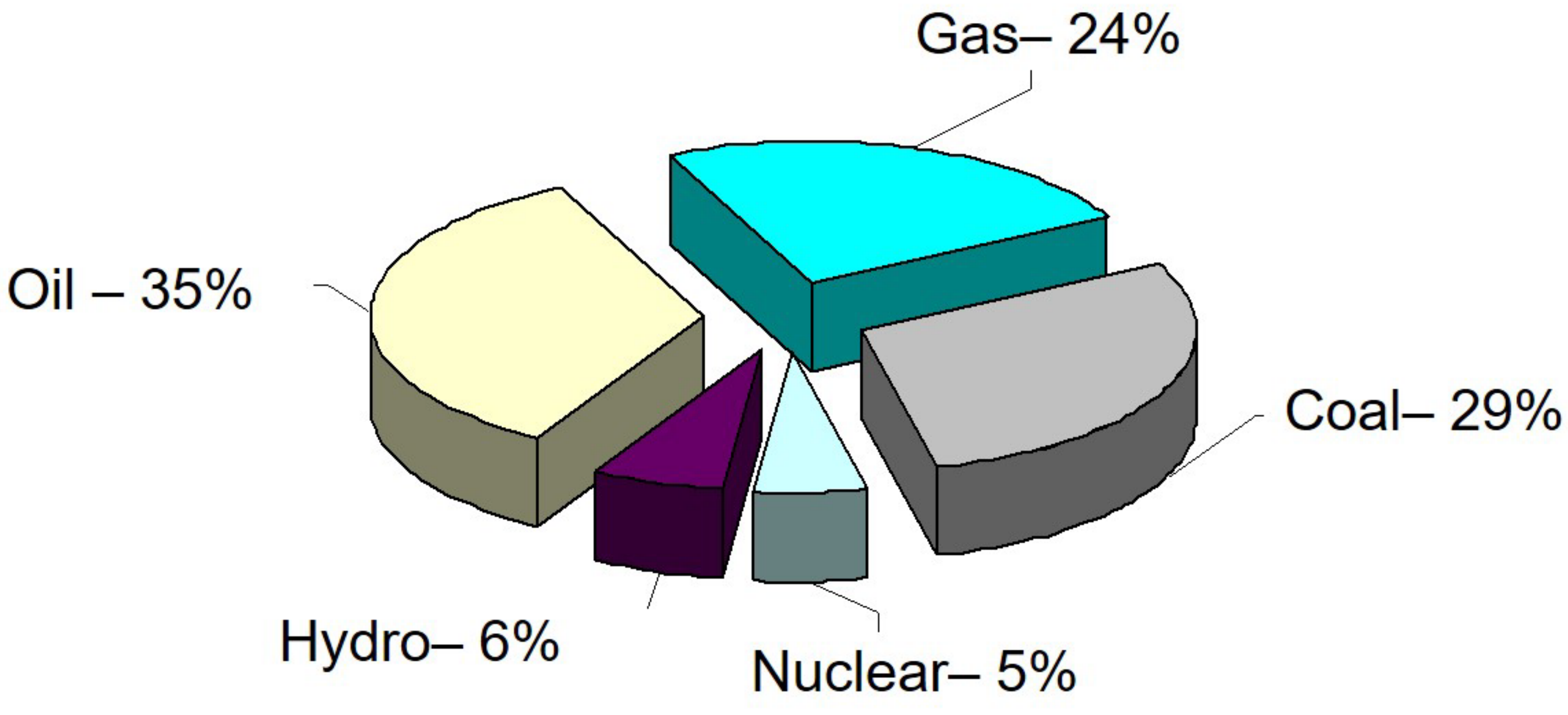
Current state of NE

Current NE Position in the World



Energy production in 2015

Scale of NE Development in Total Electric Power Generation in Russia (INEI-2016 forecast), TW*h

	2013	Probable scenario					Critical scenario 2040	Preferable scenario 2040
		2020	2025	2030	2035	2040		
Total	1058	1099	1170	1235	1310	1380	1290	1510
Oil	9	5	4	3	2	2	1	2
Gas	518	498	533	561	582	586	543	679
Coal	162	147	150	151	149	143	132	165
NE	173	221	223	229	250	280	245	294
Hydro	181	198	208	215	222	222	222	222
Bio	3	3	3	4	6	8	8	9
Other renewables	12	26	49	72	99	139	138	139

- Three scenarios have been developed for Russia that carry on the logic of world scenarios. Probable scenario includes all the ground lines of world scenario combining them with preservation of current economy and energy sector performance of Russia. Russian economy in this scenario will reach after 2020 moderate growth rates of 2,2–2,4 %
- Energy balance structure by means of generation will be kept intact in Russia
- Thermal Power Plants will remain the foundation of electrical power generation providing in all scenarios appr. 62% of generation by 2040.

Scale of NE Development in Total Electric Power Generation in the World (INEI-2016 forecast), TW*h

	2013	Probable scenario					Critical scenario 2040	Favorable scenario 2040
		2020	2025	2030	2035	2040		
World	2478	3117	3423	3886	4184	4433	4154	4718
USA	822	886	921	899	869	870	858	896
EU	903	872	779	836	793	762	688	803
China	153	389	585	805	994	1147	1080	1207
Russia	173	221	223	229	250	280	245	294
India	34	79	120	159	195	229	203	257

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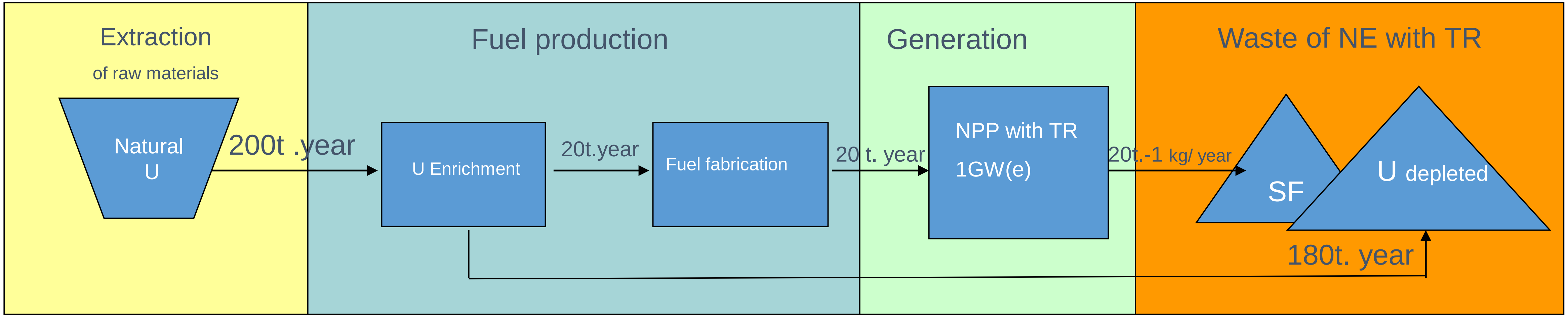
Why?

Modern Nuclear Energetics

The basis of modern world Nuclear Energy are thermal reactors (TR) with uranium fuel in an open nuclear fuel cycle (ONFC).
TR use natural uranium containing 0.7% of the fissile uranium isotope (U-235) as raw material. Nuclear fuel is produced from enriched uranium containing up to 4-5% U-235. In ONFC the resulting waste of nuclear energy generation is spent nuclear fuel (SNF) depleted uranium generated from enrichment.

Annual flows of nuclear materials in open nuclear fuel cycle, 1GW (e)

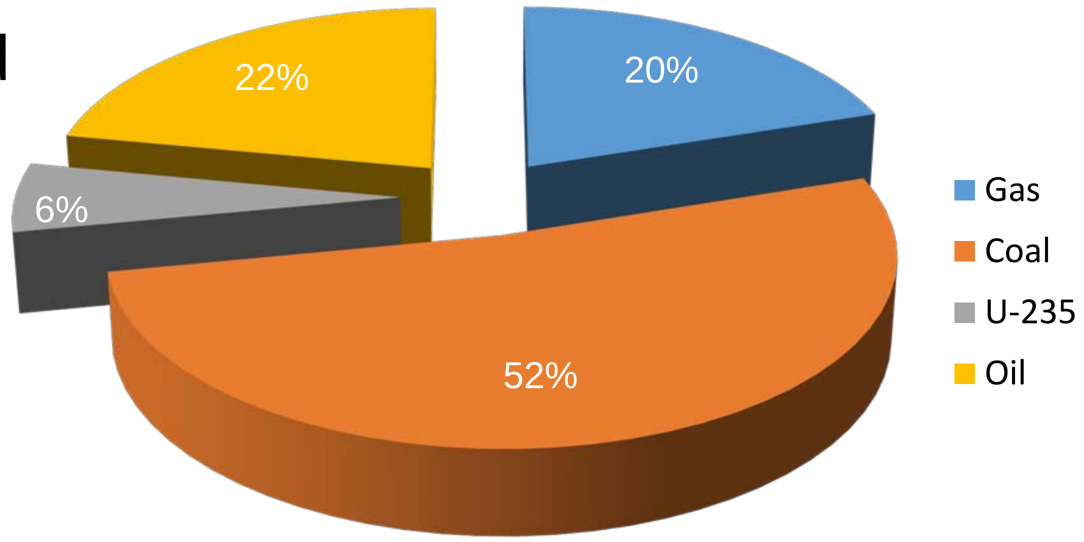


Growth Limits for NE on “old” Technological Basement

LWR technology, which is the basis of the world nuclear energetics, is sufficient for the projected (up to 2050) scale of nuclear energy development. But its potential in solving long-term energy problems is limited due to lack of compliance of its technical safety with the basic requirement for large-scale nuclear energy - excluding accidents requiring evacuation of the population Three Mile Island - 1979, Chernobyl - 1986, and Fukushima – 2011.

Systemic Problems of the “Old” Technological Basement of NE

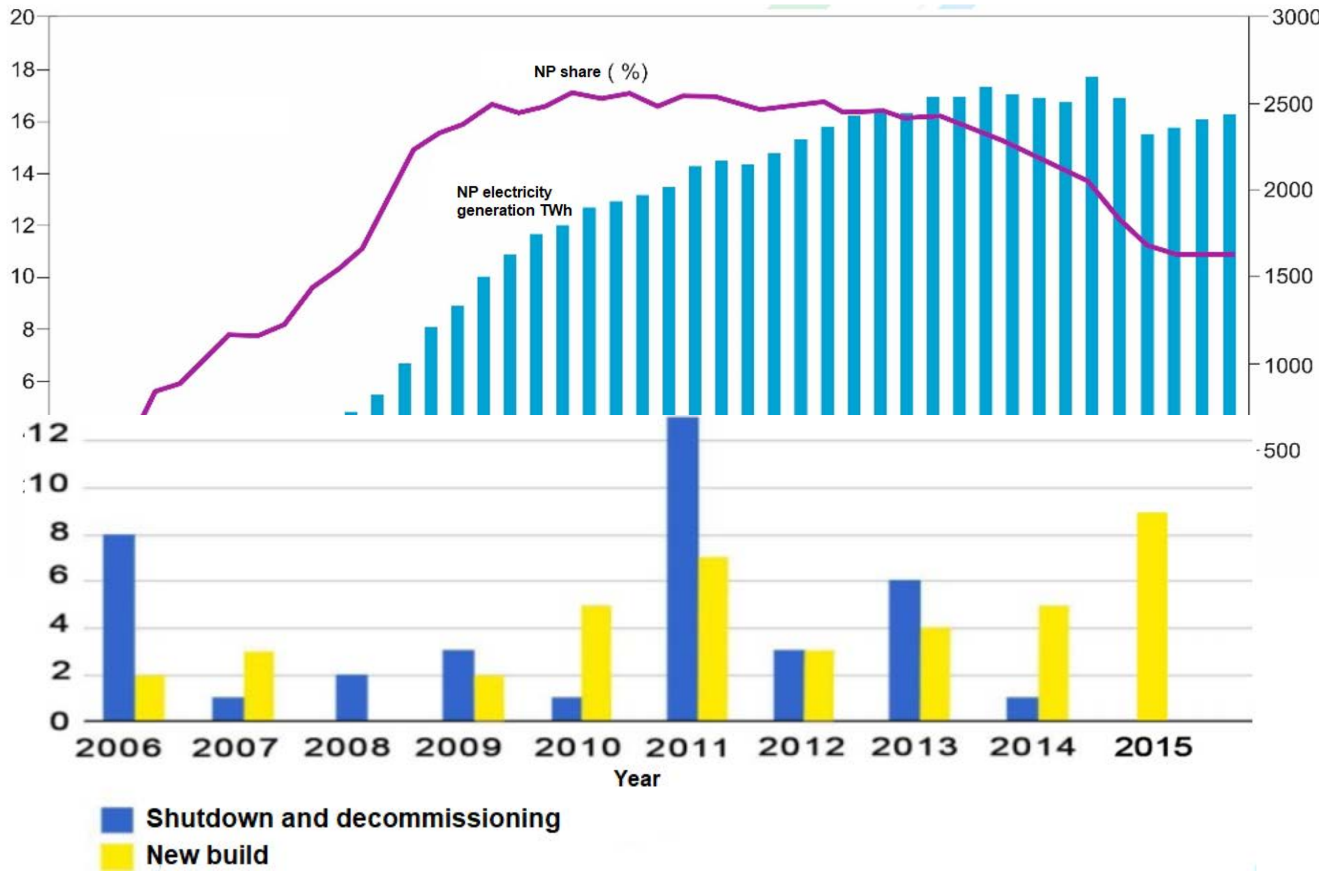
- Low utilization efficiency of the extracted natural uranium
- Lack of environmentally acceptable treatment of the long-lived high-level radioactive waste (minor actinides, etc.)
- Proliferation concern



Relative energy potential of natural resources of the World
(for organic fuel: BP data of 2008, for U-235: RAR 3,3 m.t - IAEA - TECDOC-1629, 2009)

Barriers for NE Development

- The maximum share of nuclear power plants in global electricity generation of 18% was reached in the early 90's. For today it has dropped to 10.7%. Forecasts show further decrease of this share.
- The main obstacle to the development of modern nuclear power is the problem of competitiveness, which rests on the safety problem.
- Attempts to solve the safety problem by creating additional active protection means led to a decrease in the competitiveness of nuclear power in comparison to organic energy sources.



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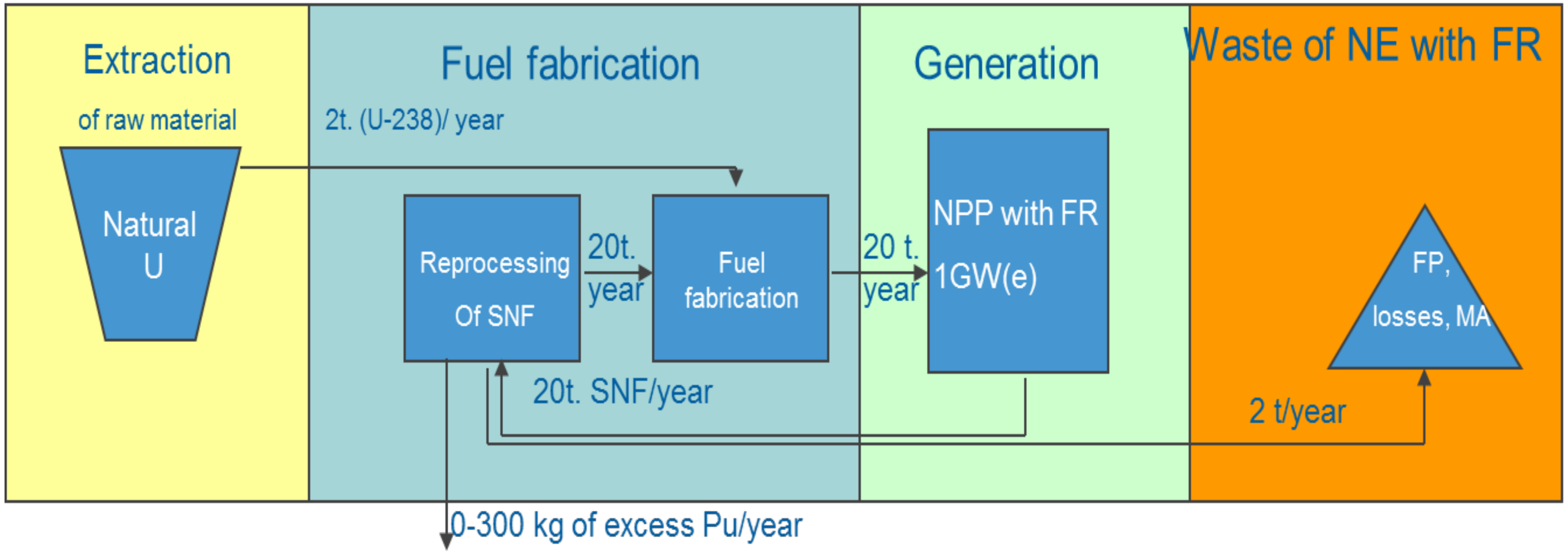
The need for NTP of NE

The Need for the New Technological Platform (NTP): CNFC with FR

- One of the best options for FR fuel is a mixture of natural U-238 and Pu. The physics of FR is such that in the process of fission of Pu in FR there goes a parallel process of capture of excess neutrons by the nuclei of natural U-238 and new Pu is accumulated in fuel in an amount equal to or greater than the burnt out initial Pu.
- The reprocessing of SNF and the recovery of accumulated Pu and unburned U into the fuel cycle of the FR allows us to reduce the need for natural U up to 100 times and the mass of heavy nuclei in high-level waste (HLW) up to 10 times.

Annual flows of nuclear materials in closed nuclear fuel cycle



Advantages of Closed Nuclear Fuel Cycle (CNFC) vs. Open Nuclear Fuel Cycle (ONFC):

- In minimization of fuel and RAW flows
- In lowering stored SNF quantities
- In lowering stored Pu quantities

Parameter	ONFC	CNFC
Yearly consumption of U per 1 GW·year (e)	170 tons	1 ton
U consumption for 60 years per 1 GW(e)	10 000 tons	60 tons
Max power of NE with 600÷700 thousand tons of natural U	60÷70 GW for 60 years	600÷700 GW for 1000 years
SNF, HAW (actinides) per 1GW·year	17 tons	Reprocessed SNF
RAW as fissile particles per 1GW·year	1 ton	1 ton

Current NE position in the World

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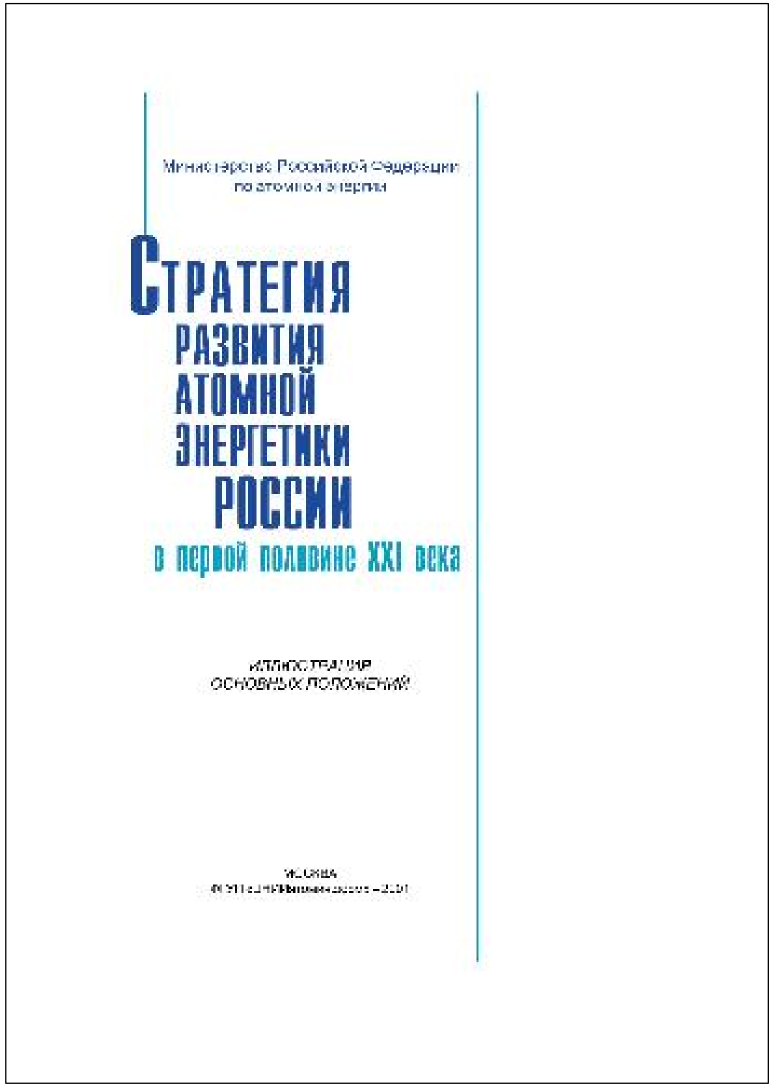
Formalization of approaches to NTP of NE

"STRATEGY-2000"



The requirements aimed at overcoming the problems of modern Nuclear Power in the fields of safety, raw materials, nuclear waste, nonproliferation and economy were first worked out in Russia at the end of the 20th century and presented in the "Strategy for the Development of Nuclear Energy in Russia in the First Half of the 21st Century," approved by the Government of RF (further "Strategy-2000")

CNFC with FR – a World Trend

- Within the framework of the largest international forum GENERATION-IV, organized at the beginning of the 21st century, nuclear technology developers elaborated requirements for the new generation of reactors. Among the six technologies chosen for joint development, four are different technologies for FR and CNFC.

- In the framework of another major IAEA-INPRO international project, user requirements for innovative nuclear power systems that meet the principles of sustainable development have been formulated. INPRO research also confirmed the importance of the development of FR and SNFC technologies especially for countries with large NPP park or for those planning a large-scale development of nuclear power. At the same time, many countries with a small NPP park prefer TR of generation 3+.

Major Milestones for the Development of the Concept of CNFC with FR in Russia

- 2000 - Strategy for the development of Nuclear Energy in Russia in the first half of the 21st century.
- 2010 - FTP "Nuclear energy technologies of new generation for the period of 2010-2015 and for the future up to 2020."
- 2012 - "PRORYV" Project (within the framework of FTP "Nuclear energy technologies of new generation for the period of 2010-2015 and for the future up to 2020").

Current NE Position in the World

6 Requirements for NTP of NE

NTP Requirements

- Technical safety of Nuclear Energy - elimination of accidents that require evacuation of the population
- Environmental safety of the nuclear fuel cycle - solving the problems of LLHLW (long-living high active waste) handling and SNF accumulation
- Sustainable fuel supply for Nuclear Energy - CNFC can become the basis for long-term provision of nuclear fuel (for thousands of years) with fuel raw materials
- Competitiveness of Nuclear Energy

6.1 Technical safety

Technical Safety of NTP

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GOAL

ELIMINATION of accidents at nuclear power plants and other nuclear fuel cycle facilities that require EVACUATION OF THE POPULATION

WAYS TO REACH THIS GOAL

- Eliminate reactivity accidents (acceleration on instantaneous neutrons), which may lead to the need for evacuation of the population.
- Eliminate accidents with loss of heat removal, which can lead to the need for evacuation of the population.
- Exclude fires and explosions at nuclear power plants, which may lead to the need for evacuation of the population

Technical Safety of NTP

MEANS TO REACH THE GOAL

- Dense fuel in reactor core with zero reactivity margin for burnup
- Lead coolant
- Air heat exchanger;
- Natural circulation of coolant with heat removal through the air heat exchanger
- Fires and explosions at the reactor unit with the release of radioactivity should be excluded by the physical and chemical properties of the coolant and structural materials that do not enter into an explosion or fire hazard interaction with the environment (water and air) with evolution of hydrogen

6.2 Environmental safety

Environmental Safety of NTP

GOAL

PUBLICLY ACCEPTABLE TREATMENT OF THE LLHLW (MA, ETC.) AND AVOIDANCE OF SNF ACCUMULATION

WAYS TO REACH THE GOAL

- Prohibition of disposal of radioactive waste containing ecologically significant amounts of LLHLW
- Reduction of the quantity of TR SNF stored and exclusion of FR SNF accumulation
- Isolation of radioactive waste

Environmental Safety of NTP

MEANS TO REACH THE GOAL

- Processing SNF of TR and FR
- MA transmutation
- Disposal of radioactive waste

6.3 Stable fuel supply

Resource Stability of NTP

GOAL

Long-term provision of nuclear fuel (for thousands of years) with raw materials

WAYS TO REACH THE GOAL

- Full reproduction of fissile nuclides in the core
- Transition to a closed NFC

Resource Stability of NTP

MEANS TO REACH THE GOAL

- Fast reactor with BR ~ 1
- SNF reprocessing
- Fabrication of nuclear fuel from SNF reprocessing products and natural (or depleted) uranium

6.4 Competitiveness

Competitiveness of NTP

WAYS AND MEANS TO REACH THE GOAL

- Elimination and simplification of a number of NPP safety systems
- Reduction of construction material consumption by simplifying the design of the reactor
- Reduction of the fuel component
- Reduction of transportation costs - the on-site Nuclear Fuel Cycle

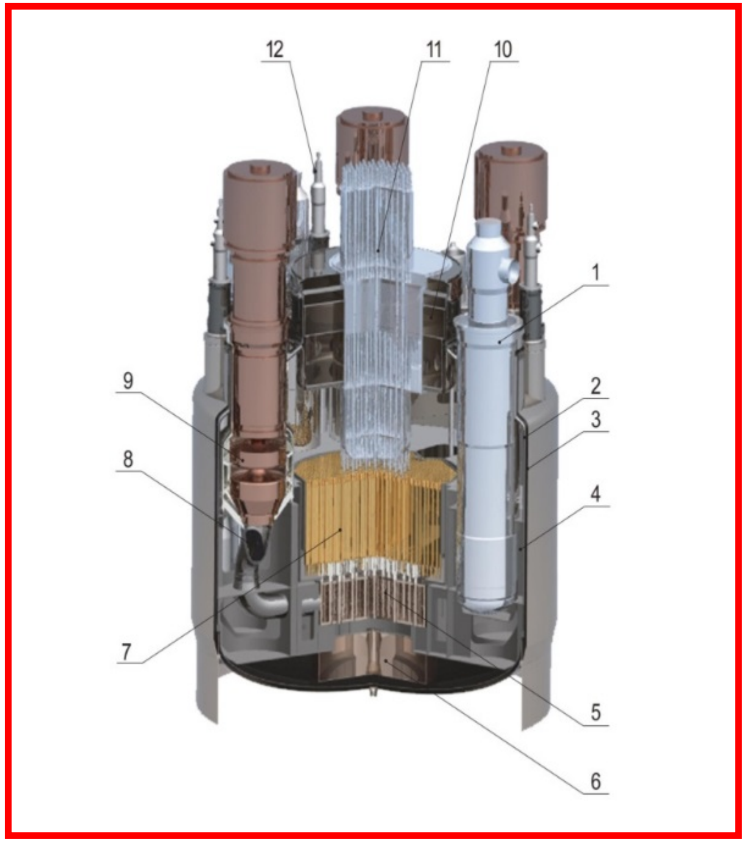
7

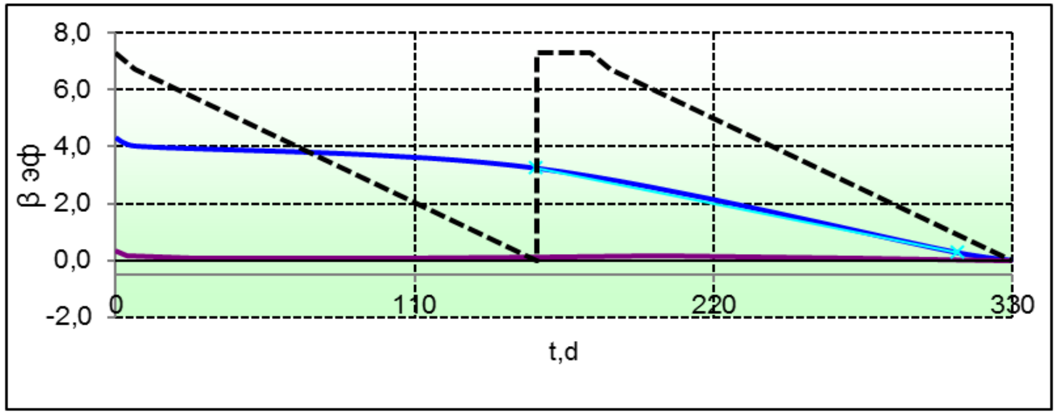
Main results of “Proryv” Project

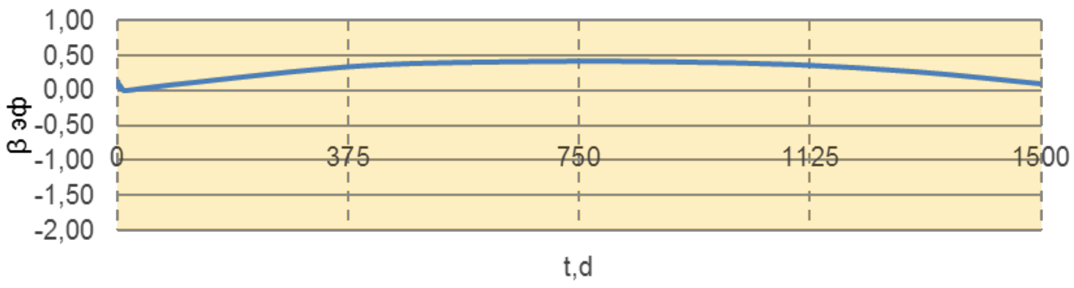
7.1 TECHNICAL SAFETY OF NTP

“Proryv” Project: Elimination of Accidents with Loss of Heat Removal and Fast Neutron Acceleration

Integral layout of the reactor unit - allows localizing coolant leaks in the bulk of the reactor body and ensuring conditions for efficient natural circulation







Equilibrium dense fuel– It’s shown that equilibrium condition of a core in terms of reactivity is reached fairly quickly (5-8 years).

Reactivity margin in BREST with Mixed U-Pu nitride (MNIT) fuel. Special measures allow stabilizing reactivity for the whole life cycle of Reactor Unit.

Lead Coolant Technology

- The technological regulations for the operation of Lead Coolant Technology System (LCTS) for BREST-OD-300 reactor installation have been developed.
- Designs of the equipment of the LCTS (oxygen activity sensor (OAS), mass transfer device, coolant filter, hydrogen sensor in gas, aerosol filters) have been developed.
- The means of quality control of the coolant (OAS) passed the acceptance tests.
- The full-scale model of the gas dispersant was successfully tested.




List of Software Codes Used for BREST-OD-300 Verification

Area of application	List of codes	State of verification and licensing
Neutron-physics calculation of the core	MCU-BR FACT-BR	Verified, ongoing licensing
Thermal mechanics of fuel rods and bundles	ДРАКОН ANSYS	Submitted for licensing-2018 Licensed for form deformation of fuel bundles
Thermal hydraulics of the core and circuits	HYDRA-IBRAE/LM/V1 ПУЧОК-ЖМТ CFD-codes: FLOW VISION, ANSYS(FLUENT)	Verified, ongoing licensing Verified
Radiation parameters of fuel, defense, fission products, environment influence	POM Containment Code System (COCOSYS) КАСКАД-С-3.0 КАТРИН-2.5 ТАРУСА-9	Verified Verified Verified, ongoing licensing
Rigidness	ЗЕНИТ-95 ANSYS	Licensed
Probabilistic Safety Analysis	RiskSpectrum PSA 1.10	Licensed
Normal operation failure and accidents	DINAR ЕВКЛИД/V1	Verified

Laboratory and Pilot Manufacturing of MNIT Fuel

Research of MNIT fuel and testing of its manufacturing technology are carried out on laboratory facilities at the following sites:

- VNIINM - samples, fuel and fuel elements for BN-600, MIR, BOR-60
- VNIITF - samples, fuel and fuel elements for BOR-60 (start of production - 2016)
- NIIAR - samples with MA, fuel, fuel rods and EFA (experimental fuel assembly) for BOR-60

Manufacturing of fuel elements and EFA for BN-600 (up to 12 FA / year) is performed at pilot plants located at the SKhK:

- CEU-1 – experimental technology of MNIT fuel (up to 200 kg / year)
- CEU-2 - mastering of industrial technology of MNIT fuel (from 2016)

Reactor Testing of Experimental Bundles with MNIT Fuel

BN-600 18 EFB (experimental fuel bundles) placed for testing, of which:

- 6 EFB with BN-600 and BN-800 fuel rods
- 6 EFB with central and peripheral fuel rods for BN-1200
- 6 with central and peripheral fuel rods for BREST

Completed irradiation of 10 EFB (КЭТВС-1, КЭТВС-2, КЭТВС-3, ЭТВС-4, ЭТВС-5, КЭТВС-6, КЭТВС-7, ЭТВС-8, ЭТВС-9, ЭТВС-10)

All bundles remained sealed

BOR-60 9 disassembly EFB, of which:

- 5 EFB (ОУ-1 –ОУ-4, ОУ-8) with BREST fuel rods
- 2 EFB (ОУ-7 и ОУ-9) with BN-1200 fuel rods
- 2 EFB (ОУ-5 и ОУ-9) with new materials

Finished irradiation of 5 EFB (ОУ-1, ОУ-3, ОУ-5, ОУ-7, ОУ-9).

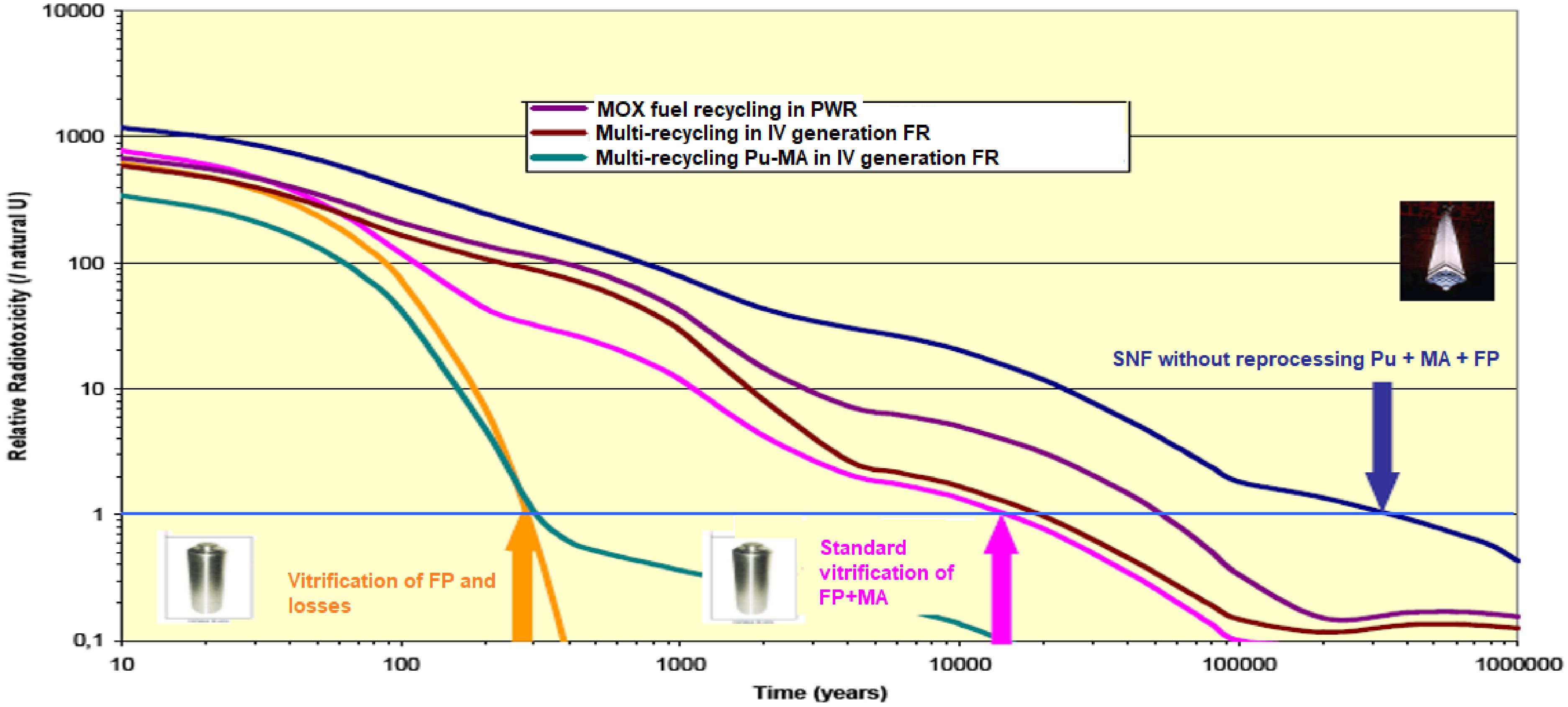
Instrumental assembly of 7 fuel rods, with sensors for in-reactor temperature control of the fuel center, gas pressure under the shell and fuel column extension have completed irradiation in the MIR reactor.

7.2

ENVIRONMENTAL SAFETY OF NTP

Environmental Safety of NTP RAW Burial

The reprocessing of spent nuclear fuel for the recycling of unburned uranium and plutonium opens the possibility for solving the problem of waste of NE, provided that optimal approaches to handling various components of LLHLW are selected



7.3 ROBUSTNESS OF NTP

Three Major Technical Solutions for CNFC

- Pyro-chemical reprocessing of FR SNF to reduce the duration of SNF retention before its reprocessing and to exclude the separation of pure plutonium during its processing
- No blanket design of fast reactors to exclude the production of weapon-grade plutonium
- Transmutation of minor actinides in FR to enforce balance between extracted fuel RAW (radioactive waste) materials and buried RAW

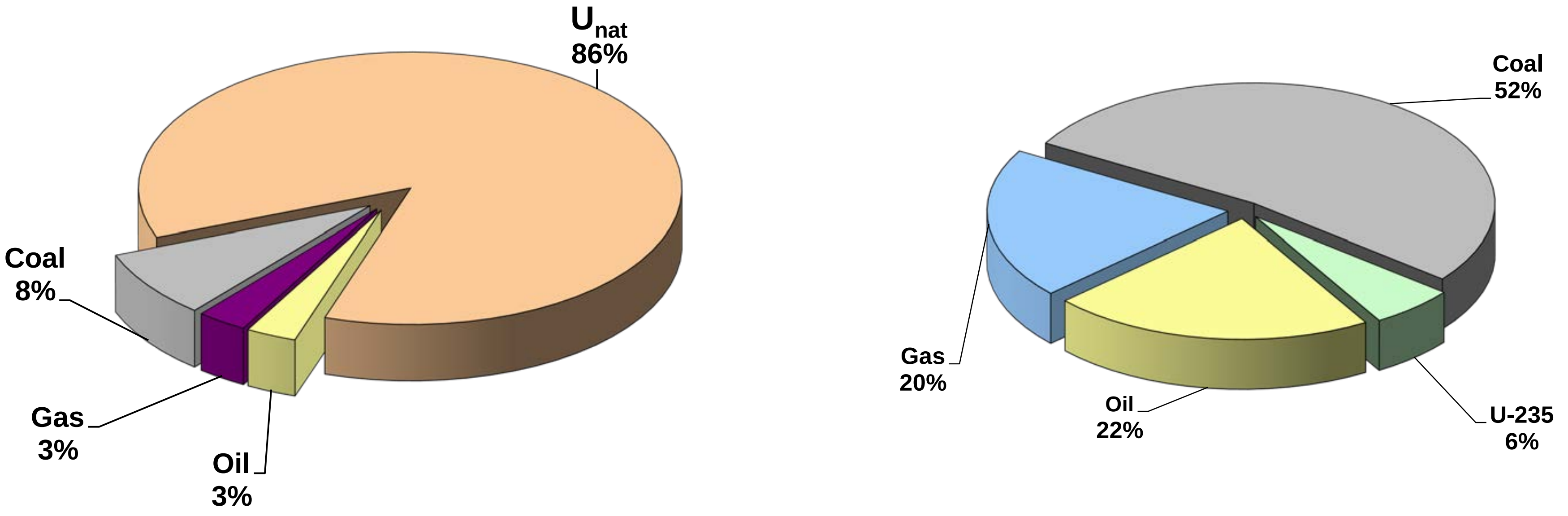
7.4

RAW MATERIAL STABILITY OF NTP

Raw Material Stability of NTP-Transfer to Closed NFC

All types of FR in CNFC allow changing the raw material base of Nuclear Energy from limited U-235 (0.7% of natural U) to practically unlimited U-238 (99.3%). FR per 1 GW consumes 0.7 t of U per year, compared to 160 t of natural uranium for WWER. Such raw material base opens prospects for large-scale use of NE for solving problems of sustainable development.

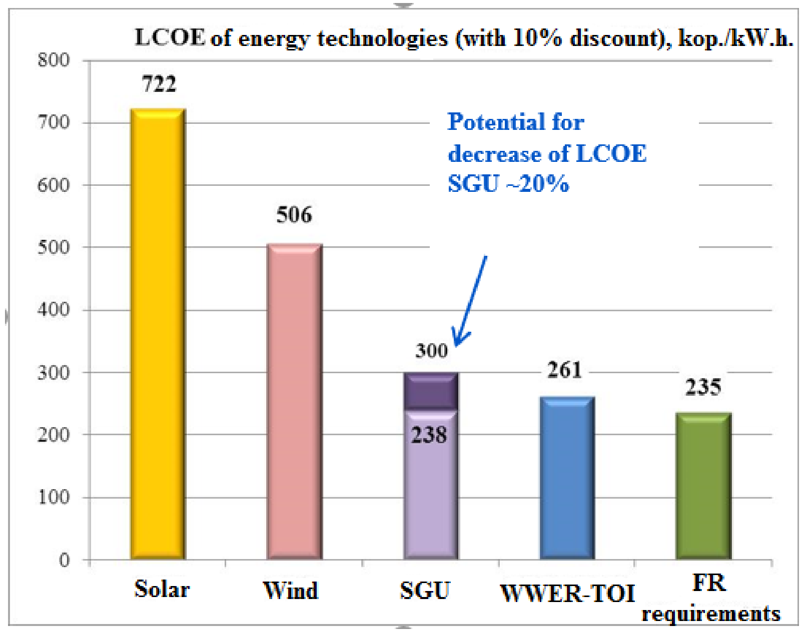
Energy potential of various types of raw material resources in Russia



7.5 COMPETITIVENESS OF NTP

Competitiveness Requirements of "Proryv" Project

Parameter	Requirement as for 2017 prices
Unit power, MW(e)	1220
C. read, %	93
Normal mode ratio.p/MW(e)	0.3
Self cons. of electr., %	5.0
Capital costs, th. RuR./kW	81.3
Capital costs, billion RuR (without VAT)	198.5
Manufact. of fuel, th.RuR./kg t.m.	131.9
Treatment of SNF/RAW, th.RuR./kgt.m.	81.4



The decomposed requirements of competitiveness of the "PRORYV" Project, are developed in accordance with current local regulations of the State Corporation Rosatom, agreed with corresponding structures of SC Rosatom and competent outside organizations (INEI RAS, INES). These requirements are stated in the Terms of \Reference for "PRORYV" Project (approved in 2015), Terms of Reference for development of conceptual design (CD) for IEC (Industrial Energy Complex) with BN-1200 reactor, Terms of Reference for development of conceptual design for IEC with BR-1200 reactor (both approved in 2016), terms of reference for development of CNFC conceptual design based on BR-1200 and BN-1200 (approved in 2017). Confirmation of achievability of the set economic requirements is planned on the basis of the development results of IEC conceptual design with BN-1200 and BR-1200.

8

EXTERNAL PROBLEMS of NTP with FR and CNFC

Future of Nuclear Energy

Analysis of approaches in Russia and other countries to the future of nuclear energy shows the presence of two main trends:

1. Development of nuclear power on the basis of thermal reactors with open nuclear fuel cycle.
2. Development of closed nuclear fuel cycle with the introduction of reactors that provide simple or extended nuclear fuel reproductions ($BR \geq 1$).

Large-scale nuclear power is only feasible under the second approach

9 PRELIMINARY RESULTS

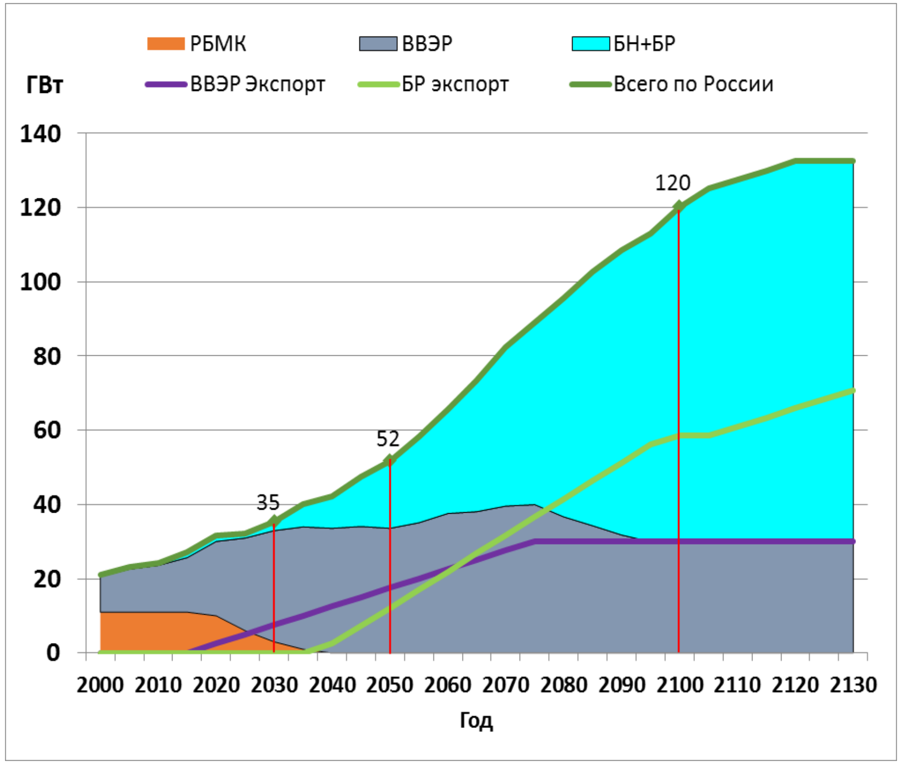
Technological Elements of NTP

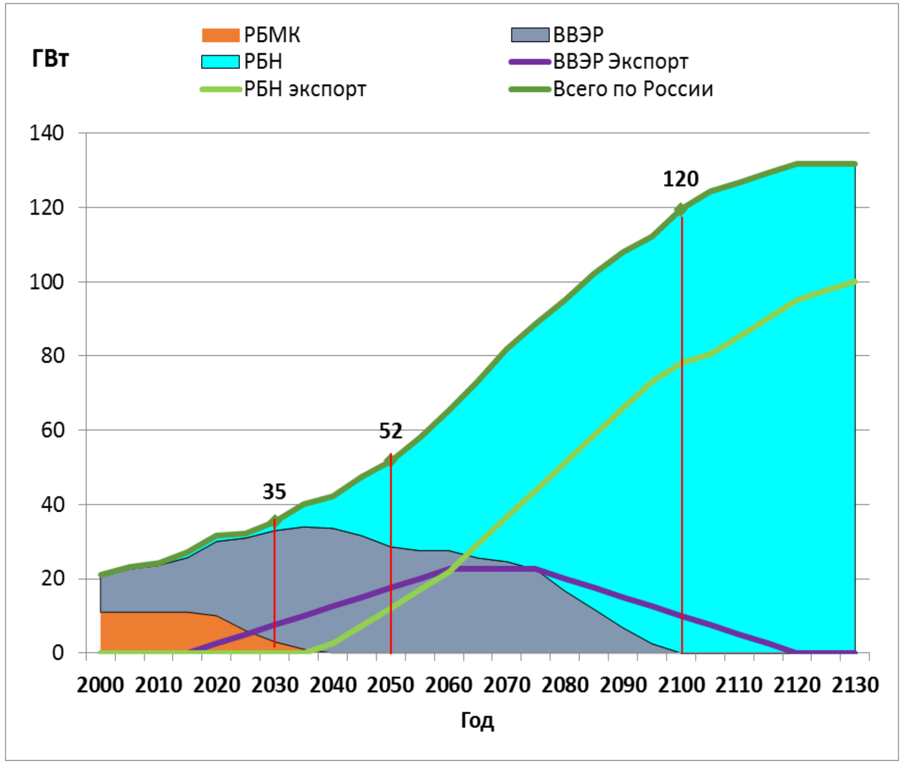
Developed within the “Proryv” framework:

1. Pilot Demonstrational Energy Complex (PDEC):
   - Lead cooled BREST-OD-300 Power Unit
   - Fabrication/refabrication Unit for dense nuclear fuel (FRU)
   - Reprocessing Unit for SNF (RU)
2. BN-1200 Power Unit
3. Design project of Industrial Energy Complex (IEC) with RBN-1200 and CNFC

Possible Development Dynamics of NE Structure in Russia

Total Capacity





A) Shaping of permanent 2-component NE

B) Full transfer to NTP by 2100 with FR domination

Export of NPPs is foreseen at up to 100% level from internal capacity for WWER and 50-100% for FR, fuel, CNFC

Current NE Position in the World

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MAJOR R&D TASKS for “PRORYV” FRAMEWORK up to 2035

Tree of Problems - 2018

	1st level	
1.1.	Lead coolant for BREST-OD-300	One step forward – two back
1.2	MNIT for BREST-OD-300 and BN-1200	Impressive experimental base. Not enough code support LM layer needed!
1.3	Armed concrete vessel for BREST-OD-300	
1.4	Intercircuit leak of for BREST-OD-300 SG	
	2nd level	
2.1	Reactor with BR<1	
2.2	Materials for BR-1200 shell	No clear vector forward
2.3	Pyro-chemistry	Managed to re-start, there is promise
2.4	Competitiveness	Requirements developed by idealists, materialists have to say their word
	3rd level	
3.1.	MA burnout in FR	
3.2.	Radiation migration equivalence when treating RAW	

Further R&D Tasks of “Proryv” Project

R&D of PDEC objects (until commissioning):

- DCS, IM, MM, EM
- BREST: MCP tests, SG, coolant control tech, BFS, mockup core items tests, RU equipment, materials testing.
- CNFC:
- Development of FU equipment (ovens, presses, distant manipulators).
- RU processes R&D: reprocessing of SNF and RAW treatment .
- MNIT fuel:
- Development of fuel testing program: justification of 6% burnout

R&D on ODEC:

- Equilibrium Core physics
- Operating reactor unit with lead coolant
- Optimizing pilot-industrial CNFC tech

R&D of IEC objects :

- Design project – justification of competitiveness of CNFC with FR
- MNIT– experimental verification of 12% burnout and its reprocessing
- BN-1200 – finalizing R&D program
- BR-1200 – fulfillment of R&D program
- CNFC objects– fulfillment of R&D program

General systematic R&D:

- Norms and regulations
- Optimization of 2-component NE with CNFC and FR and TR
- R&D of RAW to implement radioactive-equivalent treatment of FM in CNFC
- Development of software codes for Reactor Unit, CNFC, Safety

CONCLUSION

“PRORYV” Project provides the State Corporation "Rosatom" with leadership in:

- Construction of FR with inherent safety (deterministic exclusion of accidents requiring evacuation of the population)
- Creation of dense MNIT fuel, optimal for Fast Reactors
- Final solution of the problem of SNF accumulation and radiation equivalent treatment of radioactive waste
- Creation of the world's first pilot energy complex with FR and CNFC technologies (PDEC)

The crisis of world nuclear power can be overcome by the creation between 2018-2035 of the first industrial IEC (Industrial Energy Complex) based on Fast Reactors:

- With BN-1200 reactor, if competitiveness with WWER will be confirmed by design project
- With BR-1200, which is competitive with CCGT and RES
- Reduction of natural uranium consumption by 6 times and the growth rate of SNF stocks with the introduction of FR
- Phased introduction of SNF reprocessing technologies when economic feasibility is achieved (price of uranium raw materials and SNF storage)

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Upcoming Webinars

19 February 2019	Safety of Gen IV Reactors	Dr. Luca Ammirabile, EU
20 March 2019	The Allegro Experimental Gas Cooled Fast Reactor Project	Dr. Ladislav Belovsky, UJV, Czech Republic
15 April 2019	European Sodium Fast Reactor: An Introduction	Dr. Konstantin Mikityuk, PSI, Switzerland