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Nuclear Energy Strategy in the XXI Century: Advance on All Fronts

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Today, Russian nuclear industry suggests a concept of "Atomic Project 2.0" as a new "frontal" stage aiming at sustainable development involving innovative technologies and materials, as well as advanced nuclear power facilities. Such "frontal" expansion aiming to achieve sustainable progress in economy and ecology – rather than addressing internal technology and resource issues – becomes a basic trend of present-day nuclear energy development. Both in Russia and all over the world, nuclear energy relies on pressurized water reactors with capacities exceeding 1000 MW, and there are no reasons to expect any changes of this situation in the foreseeable future. VVER technology is a key instrument for our country to achieve its strategic nuclear energy goals. Large reactors keep evolving, from Novovoronezh-5 (1980), via "small" and "large" series of VVER-1000, to AES-2006 (Russia's largest operating VVER-1200) and VVER-TOI with VVER-1300. At the same time, capacity expansion to encompass small reactors (below 300 MWe as defined by the IAEA) is a long-expected trend of nuclear development. Small and medium NPP deployment prospects that account for electricity demand forecasts and geographical distribution of generating capacities in Russia promise a "new quality" of nuclear generation and a fundamentally different niche in the energy mix. Practical implementation of fast reactor technology to enable fuel cycle closing is beginning today based on BN-800 reactor at Beloyarsk NPP. Revival of the nuclear industry's drive to spread on new energy consumption areas – a trend born together with the start of practical use of nuclear energy, affected by severe accidents from time to time, but never abandoned – may represent the most distinctive sign of the current nuclear energy development stage. Presumably, the nuclear energy strategy that would be worth inclusion in "Atomic Project 2.0" should include hydrogen production, seawater desalination and district heating based on nuclear technology and intended for both Russian and international markets, as well as advanced technologies such as molten-salt or hybrid nuclear systems.

Key Words: nuclear energy strategy, nuclear reactors, technology platform.

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Fundamental and Applied Investigatons of Thermal Hydraulics for Fast Reactors with Liquid-Metal Coolants

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The results of research in the field of hydrodynamics and heat transfer in fast reactors and an accelerator-controlled system with liquid metal coolants are presented. The physical phenomena, effects, regularities and characteristics of the velocity and temperature fields in the flow path and core of fast reactors are analyzed. The data of experimental studies are presented on a single-tube model of a large-module steam generator and on a fragmentary thermohydraulic model of a steam generator of a reactor installation with twisted steam-generating tubes. The results of investigations of temperature and velocity fields on a small-scale water model of a fast reactor vessel are demonstrated temperature stratification with stagnant and recirculating formations, internal waves appear at the stratified boundaries, temperature pulsations, thermal fatigue of structural materials and a decrease in the service life of the equipment. It is shown that the boiling process of liquid metals in channels and assemblies of fuel elements has a complex structure, is characterized by both stable (bubble, annular-dispersed) and pulsation (slug) regimes with significant fluctuations of

parameters, which can cause a crisis of heat transfer. Heat transfer was studied, a cartogram of two-phase flow regimes was constructed during boiling of liquid metals in fuel element assemblies, the effect of the surface roughness of fuel elements on heat transfer and boiling regimes of liquid metal in fuel element assemblies was found. The possibility of long-term stable cooling of the core during sodium boiling was shown for a new technical solution — "sodium cavity" above the reactor core. The characteristics of the degradation process of the simulator of the fuel assembly of the fast reactor core during the thermal interaction of uranium-containing simulators of fuel with static sodium and their dependence on the parameters and design of the system are determined. The problems of thermophysical research for high-temperature sodium fast reactor for the production of hydrogen.

Key Words: hydrodynamics, heat transfer, fast reactors, accelerator-controlled systems, liquid metal, reactor vessel, core, collector systems, mixing chamber, steam generator, stratification, boiling, regime map, thermal interaction

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Problems and Prospects for Engineering Small-Group Calculations of RBMK-1000 Reactors

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The paper presents an approach that makes it possible to expand the range of solved operational neutron-physical problems due to the possibility of combining various models of neutron transport (multi-group with a detailed description of the geometry and two-group with a homogeneous description) in separate parts of the computational domain. The approach is implemented in the high-precision engineer program MNT-CUDA (version 2.0) which is focused on full-scale reactor calculations by the group Monte Carlo method with the possibility of a detailed description of neutron transport in the entire system or its individual fragments and uses the technology of parallel computations on GPUs. The article demonstrates new features of the program. The research results on the accuracy of combined calculations are presented and analyzed.

Key Words: small-group engineer calculations, Monte-Carlo method, combined calculations, MNT-CUDA program.

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Cross-section Libraries Approximation by Machine Learning Methods and Neural Networks in a Small-Group Neutron-Physical Cross-Sections Library for RBMK-1000 Calculations

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The article describes in principle new library of small-group neutron-physical cross-sections CNET, intended for calculating the RBMK-1000 reactors neutron-physical characteristics. The CNET library uses neural network technology to approximate cell (nodes) constants tallied in a large set of various reactor states full-scale calculations. The article discusses the problems that arise when approximating neutron cross sections using machine learning methods and, in particular, neural networks. A description of the approaches to solving these problems used in JSC "All-Russian Research Institute for Nuclear Power Plants Operation" in the development of a new CNET library is given. The verification results of the increased accuracy code MNT-CUDA with the CNET library are presented.

Key Words: neutron cross sections, neutron cross sections approximation, machine learning methods, neural networks.

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The KIR2 Software Complex for Simulation of a Stationary and Non-Stationary Particle Transport by Monte Carlo Method

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The KIR2 software complex for simulating neutron-physical stationary and non-stationary processes in reactors based on the Monte Carlo method [1, 2] is discussed. The paper presents a brief description of the software complex being developed, its key opportunities and features of architecture.

Key Words: transport equation, Monte Carlo method, evaluated nuclear data, precision calculations, nuclear reactors, neutron kinetics

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Critical Experiments for Investigation of VVER Type Uranium-Water Lattices with Relatively High-Enriched Fuel and Erbium Oxide Absorbers

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The series of experiments were performed on the "P" critical facility of NRC "Kurchatov Institute" to study neutron characteristics of VVER type water-uranium compositions that contains fuel pins with uranium enriched up to 6.5% of ^{235}U and erbium oxide (Er_2O_3) absorbers. Geometry and composition of fuel assemblies were chosen to obtain the experimental data which are useful for validation of codes used for research and design of VVER extended cycles with uranium-erbium fuel. The paper describes experimental facility and implemented fuel assemblies and presents the main experimental results.

Key Words: nuclear reactor, critical facility, critical experiments, uranium-erbium fuel.

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Computational Analysis of Critical Experiments for Uranium-Water Lattices of VVER Type with a Relatively High Enriched Fuel and Erbium Oxide Absorbers

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The series of experiments were performed on the "P" critical facility of NRC "Kurchatov Institute" to study neutron characteristics of VVER type water-uranium compositions that contains fuel pins with uranium enriched up to 6,5% of 235U and erbium oxide (Er2O3) absorbers. Computational analysis of experiments was carried out by means of the precise MCU-PD code and the best-estimate code TVS-M, that are used for a VVER fuel cycle design. The paper describes computational models of these codes and presents main results of critical parameter calculations, compared to the experimental data.

Key Words: nuclear reactor, experiments, precision calculations, Monte-Carlo method, MCU-PD code, MDBPD50 data bank, best-estimate code, TVS-M code.

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Neutrino Control of Reactors for the Application of the IAEA Safeguards to Floating Nuclear Power Units.

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The operation of floating nuclear power units in non-nuclear-weapon States does not involve the management of fresh and used nuclear fuel, and the nuclear reactor of the power unit must be hermetically sealed in the manufacturing State. In this regard, the problematic aspect of the application of the IAEA safeguards is the independent verification and confirmation of State information about the declared operating modes of the nuclear power unit, the quality and quantity of nuclear fuel in it. The article shows that the currently available technologies for detecting reactor antineutrinos may well provide the IAEA with independent control of a floating power unit reactor using an autonomous mobile or stationary neutrino detector to confirm the declared operating modes of the reactor, and indirectly confirming the quantity and quality of nuclear material contained in it.

Key Words: nuclear power units, IAEA safeguards, antineutrino, reactor power, quantity and quality of nuclear fuel.

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Evaluation of the Flow Rate of the Pure Condensate in the Starting Range for Reaching MCL of Power after the Operation of the Emergency Protection

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After the emergency protection is triggered, the boric acid solution is immediately introduced into the VVER-1200 reactor core to the concentration stop value. Then the control rods are raised and after that the permission to start the reactor is obtained. When reaching the MCL, first, make-up with pure condensate is performed at a high speed up to the starting interval, the first circuit is mixed, and then the input of the pure condensate begins at a low speed. At the same time, technological regulations for safe operation indicate that the flow rate of the pure condensate in the starting range should not exceed by more than 10 t/h the flow rate of the pure condensate for compensation of xenon poisoning and the rate of injection of positive reactivity should not exceed 0.02 βeff/min. It is not entirely clear how to estimate the flow rate of the pure condensate, since the power unit does not have equipment that measures the magnitude of xenon poisoning and the rate of reactivity injection. In this article, we will answer the question of which flow rate of the pure condensate an operator can use in the starting range in the presence of xenon processes.

Key Words: VVER-1200, MCL, pure condensate, reactor emergency protection, control rods, Novovoronezh NPP, technical regulations for safe operation.

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Method for Calculating the Potential of Hydrogen in the VVER-1000 NPP Sump Solution

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Method for calculating the potential of hydrogen (pH) in the VVER NPP sump solution is developed and verified. It is based on solving the chemical kinetics equations with taking into account operations of the safety systems when an accident with loss of the primary coolant (LOCA) takes place. Hydrazine dissociation constant is measured between 25 and 100 oC and its temperature dependence is integrated into the calculation method. pH estimating tests are performed for VVER-100 NPP sump. It is shown that according to the LOCA scenario the pH value in the sump becomes higher than 7.0 starting from approximately third minute. This provides the conditions when formation of radioactive iodine volatile forms that readily come to the environment is suppressed.

Key Words: NPP, VVER, sump, LOCA accident, hydrazine hydrate, boric acid, potassium hydroxide, dissociation constant, potential of hydrogen.