Power unit with RP BREST-OD-300

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Abstract. Pilot demonstration energy complex (PDEC) is designed for elaboration of technology for closure of the nuclear fuel cycle (CNFC) for further implementation of high-power energy complexes in the industrial scale. The project “Construction of the pilot and demonstration power unit with the lead-cooled fast neutron reactor on the site of abandoned territory “Seversk” (BREST-OD-300) is developed in accordance with requirements specification for development and implementation of nuclear power technologies and natural safety based on the fast neutron reactors and closed nuclear fuel cycle. The article describes the power unit with a reactor plant, its design characteristics, the layout of the primary circuit equipment, as well as special attention is paid to safety systems, nuclear and radiation safety and regulatory compliance in support of the safe operation of the reactor plant.

1. Introduction
Pilot demonstration energy complex (PDEC), erected at present in Seversk city, Tomsk region, is designed for elaboration of technology for closure of the nuclear fuel cycle (CNFC) for further implementation of high-power energy complexes in the industrial scale [1]. At PDEC (figure 1) the following will be implemented:

• elaboration of technologies for CNFC operation and modes on the lead-cooled fast neutron reactor plant BREST-OD-300;
• elaboration of technological processes for fabrication, refabrication and recycling of fuel for fast neutron reactors, demonstration of the integrated solution for RAW handling problem;
• improvement of efficiency for using the natural uranium and the spent nuclear fuel with step-by-step implementation of radiation equivalent principle for handling nuclear materials (NM) in CNFC.

The project “Construction of the pilot and demonstration power unit with the lead-cooled fast neutron reactor on the site of abandoned territory “Seversk” (hereinafter - Project “BREST-OD-300”) is developed in accordance with requirements specification for development and implementation of nuclear power technologies and natural safety based on the fast neutron reactors and closed nuclear fuel cycle (“Proryv” Project Stream).

Construction of PDEC facilities on JSC SICP site is carried out in four stages:

• Stage 1: construction of the module for fabrication and start-up facility for refabrication of the solid mixed uranium-plutonium fuel for fast neutron reactors; the facilities for handling radioactive waste in the volume required for recycling medium radioactive waste, low radioactive waste and very low radioactive waste and temporary storage of medium radioactive waste, low radioactive waste and very low radioactive waste; PDEC infrastructure facilities in the volume required for erection and operation of the fabrication / refabrication (FRM) module;
• Stage 2: construction of the power unit with RP BREST-OD-300 and the infrastructure facilities necessary for erection and operation of RP BREST-OD-300;
• Stage 3: construction of the module for recycling of the spent nuclear fuel of RP BREST-OD-300, the facilities handling RAW and PDEC infrastructure facilities;
• Stage 4: transition (modernization) of FRM for refabrication of NF from the projects after RP BREST-OD-300 SNF recycling.

2. Power unit of BREST-OD-300
Purpose of power unit with RP BREST-OD-300:
• practical confirmation of basic engineering solutions used at the lead-cooled RP operating with CNFC and main provisions of the natural safety concept;
• step-by-step justification of life characteristics for RP elements for creation of commercial NPP with the lead-cooled RP;
• electric power generation.

BREST-OD-300 PU (figure 2) includes 104 buildings and structures, for power unit needs, as well as the buildings and structures (FRM) other stages facilities are used ensuring operation of PDEC as a single object.

Basic project characteristics of the power unit with RP BREST-OD-300:
• thermal power 700 MW;
• electrical power 300 MW;
• capacity factor 0.8;
• reactor life cycle 30 years;
• industrial-production manpower 316 persons.

PU project considers the following possible external impacts of natural and technogenic character:
• aircraft crash m=5.7 t, v=100 m/s (Learjet);
• shock wave 10 kPa;
• whirlwind Level F2.4;
• earthquake: DLE (ductility-level event) – 0.17g, DE (design earthquake) – 0.085g.
Two-loop cycle is used: the first loop – the lead-cooled RP loop, the second loop – the water/steam loop of the fluid supplied to the turbine. Condensing full-speed turbine K-300-15,7/50 type. The closed-feed cycle and the feed-water mixing heater for provision of feed water temperature at SG (steam generator) input at least 340°C is used in the second loop. The water chemistry condition is neutral, correction-free, the oxygen requirements are provided in the special heater having deaeration function, the structure material of the condensate-feed pipeline - corrosion-resistant steel. The reversible service water supply with the cooling tower is adopted in the project.

3. Reactor Building
Project PU with RP BREST-OD-300, as opposed to projects NPP with RP and with pressurized water, has no allocated “nuclear island” and the special-purpose vessel and provides for location of RP main and auxiliary equipment in one common building. The building design specifies “free” location of equipment in the reactor central hall, which during increase of total specific characteristics of the reactor building, simplifies servicing, provides space reserve required for processing of transportation and repair works at the first pilot-demonstration power unit. In the central hall, the operations on handling the equipment and the fuel are performed (figure 3).
4. Reactor Plant BREST-OD-300
The reactor plant with the integrated layout of I loop equipment (figure 4) was used at the power unit BREST-OD-300 [2]. In the casing there is the reactor core and four circulation loops with two steam generators for each and one main circulation pump unit. The casing is metal-concrete with the metal boundary of the first loop. The casing also performs the function of the leak-tight enclosure. At RP, the axial electrical pumps fixed on the casing flanges are used, thus, the pump has no housing operating under pressure. The steam generator is with twisted monometallic heat-exchange tubes. In the top central part of the casing there are two rotating plugs, on which the refuelling machines and other equipment are installed. The casing and the ceiling have passive air cooling. In the central cavity of the casing, the reactor core basket is installed, in which FA, the reflector replacement units and the in-vessel storage channels are located.
The basic principle of the natural safety technology for lead-cooled fast neutron RP consists in preferred use of neutronic and physical-chemical properties of the fuel, coolant and structure materials, as well as design solutions allowing for implementation of these properties to full extent, and, thus, elimination of entire classes of accidents (with uncontrolled growth of power capacity and loss of heat removal) and, with that, reducing build-up of engineering measures and safety systems.

RP power level is selected based on possibility for using BREST-OD-300 technical solutions as the reference ones for high-power RP. Due to the fact that the present-day safety evidence is based not only on referentiality of technical solutions, but on design codes also, in this case, the areas of certification for pilot-demonstration RP will be substantial ground for industrial RP. Removal of conservatism for design codes at industrial RP downloaded at the stage of pilot-demonstration prototype development is possible both during its operation period and during benchmark tests.

The reactor features (the first loop low pressure, the metal-concrete casing, the integrated layout, the coolant large volume, the properties of inherent safety, etc.) allowed for refusing from the containment large volumes, the melt trap, the large volumes of support systems, as well as for degrading the out-of-pile equipment safety class for projects of NPP with WWER.

High level of RP reliability and safety in the project is ensured by using passive safety systems free from operator's intervention, influence of errors and erroneous solutions during their operation, as well as from the support and control systems influencing their functioning.

RP BREST-OD-300 Safety Systems:

- Emergency Core Cooling System (figure 5). The system represents four independent open loops for removal of heat from RP by means of atmospheric air. Due to natural convection, the atmospheric air from the air intake chamber is supplied to the air heat exchangers via the air ducts of the control channel, it is heated up and removed into atmosphere via the exhaust stacks. The system is put into action under liquid metal coolant temperature above 460 °C. Upon failure of any two loops of the system, the function for removal of residual power density from the reactor core and the in-vessel storage is fulfilled by two loops remaining in operation. Probability for ECCS failure on demand according to function of residual heat removal from the core $Q=1.07*10^{-8}$. 

Figure 4. Reactor block.
Steam generator protection system. The elements (fittings) of steam generator protection system are located on the feed water and main steam pipelines and are installed on each feed (supply) and steam (outlet) pipeline. The steam generator protection system is designed for fast shutdown of working fluid (water and steam) pipelines and provision of sufficient leak-tightness, SG protection from exceeding the allowable pressure by means of steam excessive pressure release, limitation of steam-water mixture leakage into the lead coolant during depressurization of SG tubes. Its feature consists in series installation of active and passive fittings with active initiation both according to the steam and feed water. Probability for SG protection system failure on demand for SG isolation functions for each initiating event considered in the project $Q=1.41\times10^{-5}$.

Steam generator leakage isolation system (figure 6). The system consists of four identical loops connected to the reactor unit gas cavity, which are designed for reactor unit protection against excess of pressure during standard operation violation caused by breakdown of interloop seal, as well as isolation of radioactive gas and the second loop working fluid arriving from the reactor unit gas cavity during interloop leakiness. The passive system (water hydraulic lock) and performs its function upon reaching the pressure value 0.115 MPa in the reactor unit gas cavity and in the system loop. The system performance capacity is sufficient for isolation of leakage of up to eight SG heat exchange tubes.
• Emergency protection. The emergency protection is designed for reactor shutdown due to impact on reactivity under abnormal conditions. The emergency protection function (control of emergency protection operating members) is implemented on the digital three-channel set. CPS (control and protection system) also includes the second shutdown system, which is implemented on the digital three-channel set as well. In accordance with IAEA (International Atomic Energy Agency) recommendations, the diverse protection system based on the analog equipment was designed.

5. Reactor Core
In the reactor core design, the mixed nitride-uranium-plutonium (MNUP) fuel was used, the low-swelling ferrite-martensite steel was used as the fuel element jackets, the fuel elements are in the jacket-free FA.

The selected dense and heat-conducting nitride fuel combined with the lead coolant allows for complete breeding of fissile material in the reactor core, which ensures permanent small reactivity margin and does not permit run-away on instantaneous neutrons during reactor operation. The complete breeding of fuel in the reactor core BR ~1.05 (without blanket) and small reactivity margin within the range of power capacity 30-100% - 0.45 βeff (0.68 βeff without Np effect) was verified by the estimate certified by the software tools. The total error of Keff and reactivity margin is 1.36% Δk/k, including the design error 0.7% Δk/k (certified) and process 1.2% Δk/k (acc. to validated procedures) components.

At present, the technology of dense nitride fuel is implemented on the pilot process lines, improvement of technological processes and creation of industrial production (fabrication-refabrication module) for manufacture of RP BREST-OD-300 fuel are carried out.

To validate operability of fuel and structure material for reactor core articles, testing of fuel elements are performed in the power reactor BN-600 and research reactor BOR-60 [3].

6. Power unit nuclear and radiation safety
The radiation safety in RP conditions is justified based on the data obtained as a result of out-of-reactor and reactor experiments with the use of the lead cooler.

The design justification of nuclear and radiation safety rests on verified design codes [4]. The codes calculating nuclear safety, strength, PSA (probability safety assessment) and individual equipment thermal hydraulics were certified in accordance with the Russian Federation requirements. The rest
design codes are submitted for certification and a number of codes is at the stage of elimination of the experts’ additional remarks.

According to estimation results it was shown that probability of the reactor core damage (without fuel melting) does not exceed $8.65 \times 10^{-9}$ 1/year [5]. The maximal external radiation dose during loss of heat removal by RP systems organized within 1 km radius, and during the first 10 days it will not exceed $5 \times 10^2$ µSv. All of this allows for ensuring acceptable safety level during development of large-scale power generation industry based on the similar type RP.

7. Regulatory compliance
For RP creation, in parallel with technical project development and performance of R&D, the development of a system of standards and regulatory documents considering the lead-cooled RP features. These are regulations for design and safe operation and the calculation standards for strength of equipment and pipelines, as well as the standards detailing their requirements. At present, after extensive discussions with the industry leading enterprises, in accordance procedures, the revision versions of the federal standards and regulations are discussed with Rostekhnadzor for their publication preparation.

8. Conclusion
The technology for the nuclear fuel cycle closure for further implementation in the industrial scale at the high-power energy complexes shall be practised and demonstrated at the pilot-demonstration energy complex erected in Seversk city. The layout solutions for pilot-demonstration unit will enable easy operation at the stage of new technology assimilation.

The reactor features (the first loop low pressure, the metal-concrete casing, the integrated layout, the coolant large volume, the properties of inherent safety, etc.) allowed for refusing from the containment large volumes, the melt trap, the large volumes of support systems, as well as for degrading the out-of-pile equipment safety class for projects of NPP with WWER.

Possibility for reaching small reactivity margin ($< \beta_{eff}$) within the ranger of 30-100% power was validated by R&D results. By results of radiation safety estimation, the target parameters - no need for population evacuation and resettlement beyond the site boundary upon RP abnormal operation with multiple failures (for example, the blackout with emergency protection system non-operation, the input of full reactivity margin) were validated.

By results of the project development, the regulatory legal acts considering the lead-cooled RP and the system of standards detailing their requirements were prepared and they are under approval procedure.

At present, the project of the power unit with RP BREST-OD-300 are under licensing in Rostekhnadzor.

References
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