DEVELOPMENT OF THE NEW GENERATION POWER UNIT WITH THE BN-1200 REACTOR

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Abstract. One of the most important stage of works for the BN-1200 power unit project, which are implemented since 2007 according to Rosenergoatom Concern JSC program and Target Federal program “Nuclear energy technologies of the new generation for 2010-2015 and for perspective to 2020”, became the development of technical designs of the reactor plant (RP), turbine plant and materials of the power unit project in 2014.

Main requirements at the technical design of the RP project defined development of the technical solutions in comparison with the solutions implemented in the previous projects, and ensured not only complete integration of the primary circuit in the reactor pressure vessel, but also significantly reduced number of systems, equipment, valves and pipelines, and optimized architectural solutions of the main and auxiliary buildings and constructions of the power unit, and optimized general layout of the site. These improved the main technical and economical indicators of the BN-1200 power unit and ensured their comparability with VVER RP not only in the field of safety, but also in the field of specific capital costs and levelized cost of electricity (LCOE).

Further development of the project was defined with the design research of systems and equipment in the second half of 2015 and 2016, which indicated the following main directions of design work:

- increase of the power of the unit without change of the equipment design;
- change of design and layout solutions of the primary circulating pumps, emergency heat removal system, cold absorption trap filter of the secondary circuit, refueling box, and the secondary circuit.

Implementation of the proposed technical solutions defines further optimization of the architectural solutions for the power unit and improvement of the technical and economical indicators without reduction of the safety level.

1. Introduction

BN-1200 power unit is being developed under the Federal Target Program of *Next-Generation Nuclear Power Technologies for 2010-2015 and up to 2020*, as well as from the funds allocated for first-priority R&D of JSC Rosenergoatom Concern. By 2015, final designs of the reactor plant, turbine plant and of the materials of power unit design had been developed.

Basic design requirements at the stage of reactor plant final design development include improvement of the main technical and economic features of the power unit and its safety enhancement. The adopted new engineering solutions with respect to the implemented ones in the previous designs had ensured complete integration of the primary circuit in the reactor pressure vessel (RPV), substantial reduction of systems, equipment, valves and pipelines. Along with that, architectural and civil engineering solutions of main and auxiliary buildings and structures had been optimized as well as NPP site plot plan.

Further design development activities were defined based on additional design engineering research work on systems and equipment, which spotted the opportunity of improving power unit characteristics by means of:

- enhancing the unit power without changing the equipment design,
- changing engineering and layout solutions of the main circulation pumps, of emergency heat removal system (EHRS) and secondary circuit cold trap filter, of refueling compartment and the secondary circuit.

Application of proposed engineering solutions does not reduce the achieved level of power unit safety and reliability [1].

2. BN-1200 Design Status and Development of Requirements

The BN-1200 activities started in 2007.

The main design requirements are as follows [1]:

- safety requirements: exclude the need for population evacuation or resettlement under any kind of accidents, provide cumulative probability of core severe damage of not more 10^{-6} per reactor per year, confine the core damaged elements within the RPV during a postulated severe accident,
- reliability requirements: provide referential engineering solutions in the design of equipment and systems, ensure assigned service life of the main equipment which of not less than 60 years, assure not more than three replacements during the entire service life of the main replaceable equipment,
- economic requirements: power factor of not less than 0.9, specific metal content of the reactor plant of not more than 6.0 t/MW(e), specific structural volume of the reactor building of not more than 550 m^3/MW(e), construction period of the first-of-a-kind power unit of not more than 60 months,
- additional requirements: effectively apply inherent safety properties and passive safety systems, reliably eliminate radioactive sodium leakage and ensure compliance with requirements for Generation IV reactor plants.

By 2014, the power unit design documentation had been prepared, including reactor plant final design and turbine plant final design. It was exactly in 2014, when all the main crossroads of process options were passed (Table 1).

Table 1. Crossroads of process options of BN-1200 design.

Crossroad	Adopted decision	Year
Reactor power selection	Reactor power of 1200 MW	2007
Reactor design selection	With complete integration of the primary circuit sodium systems and equipment	2007

Crossroad	Adopted decision	Year
Selection of spent FA handling schematic layout	Reject spent FA drums option, select decay storage of spent FAs in the in-vessel storage	2007
Reactor layout selection	Reactor plant four-looped schematic diagram, emergency heat removal system (EHRS) is connected immediately to the reactor	2008
Selection of temperature-induced displacement compensation method for secondary circuit pipelines	Apply bellows expansion joints	2008
Selection of a steam generator	Shell-type two-module steam generator	2009
Selection of the second circuit layout	Integrate the buffer tank with the main circulation pump (MCP) tank of the secondary circuit, reject the buffer tank, identical loops	2012
Fuel selection	Main fuel is nitride mixed uranium-plutonium fuel Backup fuel is MOX fuel	2012
Selection of the actuation principle of passive overtemperature trip assembly	Manufacture the overtemperature self-actuated device based on fusible element	2013

The BN-1200 design development results were largely presented at the FR-13 Conference [2].

In 2015, an industry expert review of BN-1200 design documentation was conducted. The expert review results generally confirmed the designers’ conclusions that BN-1200 reactor plant design is viable, it technical and economic performance and safety characteristics comply with technical assignment requirements.

In addition to that, it was admitted expedient to continue activities aimed at improving power unit technical and economic characteristics. The activities performed in the latter half of 2015 and in 2016, were aimed at developing new engineering solutions of reactor plant equipment design, layout of the systems and equipment, optimizing architectural and civil engineering solutions.

3. Efficiency of Engineering Solutions Applied in BN-1200 Design

Main technical specifications of BN power units are given in Table 2 [1-8].

Application of a package of advanced engineering solutions, along with reference engineering solutions implemented in the BN-600 and BN-800 designs, ensured sufficient improvement of the main performance characteristics of the BN-1200 power unit.

Complete integration of the primary circuit main sodium systems and equipment inside the reactor pressure vessel (FIG. 1) has been provided through substantial changes in the equipment design and layout solutions, thus all the primary circuit pipelines with radioactive sodium have been excluded from the area outside the RPV. The following results have been achieved through application of new engineering solutions on the primary circuit:

- the service life of the main equipment have been extended up to 60 years through using a new structural material applied for RPV and pipeline component parts, as well as through optimizing the in-vessel protection and reduction of radiation-induced impact on reactor non-replaceable component parts,

- replaceable equipment life time has been extended by approximately three times (number of replacements has been reduced from 10 to 3) particularly due to optimized flow path of MCP-1 aimed at enhancing the cavitation resistance,
- in-vessel shielding has been reduced by approximately 30 times due to application of boron shielding assemblies as part of the reactor core,
- spent fuel sodium casks and supporting systems have been excluded upon enlarging the in-vessel spent fuel assemblies (FA) storage,
- fuel cycle has been extended, at least by 2–2.5 times (from 465 to 920 and 1,320 EFPD for mixed nitride uranium-plutonium fuel (MNUP-fuel) and MOX-fuel, respectively) due to core power density reduction (from 450 to 230 MW/m^3) with fuel rod diameter increase (from 6.9 to 9.3 mm),
- autonomous heat exchangers of emergency heat removal system (EHRS) are arranged immediately in the reactor vessel along with natural circulation provided in the circuits, whereas in the BN-800 design EHRS heat exchangers are connected to the secondary circuit.

The results of optimized design engineering solutions adopted for BN-1200 reactor plant secondary circuit by contrast to BN-800 reactor plant are expressed in the following parameters:

- the length of pipelines has been reduced by 1.9 times through application of bellows expansion joints as well,
- the number of sodium valves has been cut down by approximately 80%; valves provided for the secondary circuit main pipelines were excluded from the BN-1200 reactor plant design,
- specific volume of the reactor building has been reduced by approximately 30%,
- SG specific metal content has been reduced from 1.48 to 0.33 t/MW (by 78%) and specific building volumes of SG compartments from 32 to 16 m^3/MW(e) (by 50%) achieved through using of vertical once-through shell-type SG (8 modules) instead of sectional-modular SG in BN-600 (72 modules) and BN-800 (60 modules),
- SG life time has been extended from 23 to 30 years (by 30%) owing to application of a new structural material, namely steel 07Cr12NiMoVNb,
- life time of MCP-2 replaceable parts has been extended by approximately 3 times (number of replacements has been reduced from 10 to 3),
- number of site welds has been reduced by approximately 4 times.

FIG. 2 visually shows the changes in layout solutions related to the secondary circuit.

Reactor	BN-600	BN-800	BN-1200
Nominal thermal power, MW	1,470	2,100	2,800
Electric power, gross load, MW	600	880	1,220
Number of heat generating loops	3	3	4
Primary coolant temperature, °C (at the IHX inlet/outlet)	535/368	547/354	550/ 410
Secondary coolant temperature, °C (at steam generator inlet/outlet)	505/318	505/309	527/355
Third circuit parameters: - main steam temperature, °C - main steam pressure, MPa - feed water temperature, °C	 505 14 240	 490 14 210	 510 17 275
Efficiency factor, gross/net, %	42.5 / 40	41.9 / 38.8	43.5 / 40.7

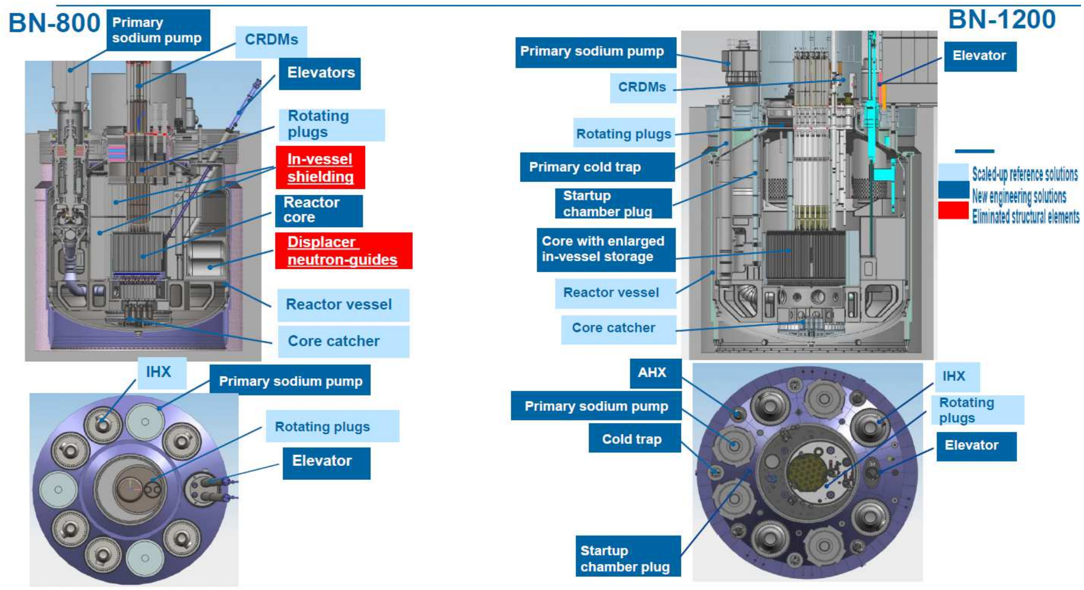


FIG. 1. Reactor.

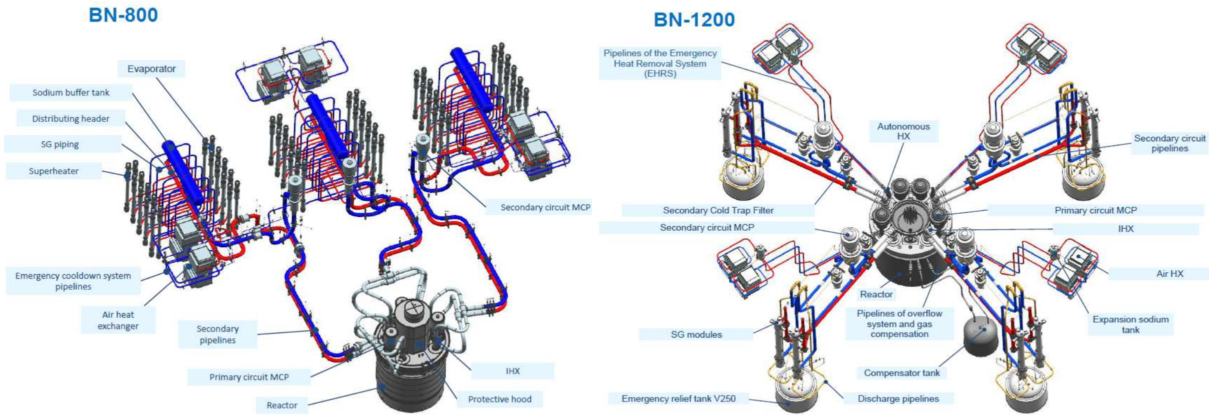


FIG. 2. Secondary circuit.

The new engineering solutions related to refueling system (FIG. 3) also lead to significant reduction of auxiliary systems, length of pipelines and number of valves:

- reduction of equipment (spent FA cask, transfer machine of washing compartment, washing compartment, gas gate valves, overflow tank, etc.),
- reduction of the total mass of refueling equipment by 780 t,
- reduction by approximately a half of the total time assigned for refueling activities per year.

Engineering solutions related to the reactor plant building have been substantially changed, including:

- application of radial layout of reactor plant secondary circuit loops in the cylindrical nuclear island,
- strengthening of external building structures along the building perimeter without changing the internal volumes along with strengthening of requirements for accountability of man-caused accidents,
- introduction of a control joint along the external diameter of nuclear island walls, eliminating impact of man-caused and extreme conditions transmitted onto the nuclear island equipment,

- application of a light-weight spherical dome over the central hall in combination with up-to-date high-strength types of concrete and valves integrated into reinforced concrete blocks, which shortens the starting dates of nuclear island main equipment installation,
- setting of the new fuel storage building and spent fuel pool building into a separate module allowing without substantial engineering and layout changes to use it both as an option of centralized fuel production and as an option of on-site storage,
- provision of spent nuclear fuel cooling in the spent fuel pool in the blackout mode owing to passive systems with a single-phase thermosyphon filled with water,
- substantial reduction of the equipment amount in the emergency power supply system by contrast with BN-800 owing to passive safety systems as well as a result of EHRS direct connection to the reactor.

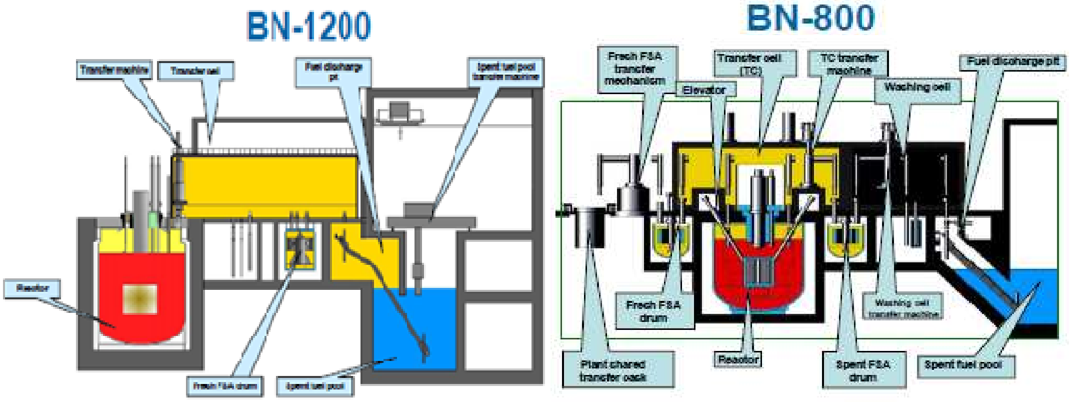


FIG. 3. Refueling system.

The totality of the applied design engineering solutions ensured substantial reduction of construction volumes (up to 30 %), primarily of the nuclear island (FIG. 4).

Considerable improvement of the safety level has been achieved in BN-1200 design due to upgrading of the safety systems (EHRS reliability improvement, as previously stated, and introduction of additional safety rods of temperature-actuated passive safety system) [9, 10]. Probability of the reactor core severe damage for internal events during reactor power operation for BN-1200 is approximately 5×10^{-7}, which is considerably lower than the respective values for BN-600 which is about 10^{-5} and BN-800 which is about 2×10^{-6}.

As a result of severe BDBA analysis (such as ULOF and UTOP) using not only the design codes but also the next generation codes, it has been proven that the exposure doses of the population beyond the boundaries of the NPP site under the most adverse accident conditions do not exceed 30 mSv during the first year after the accident. Thus, the compliance with the requirement to eliminate the necessity for the population evacuation in case of accidents has been proven.

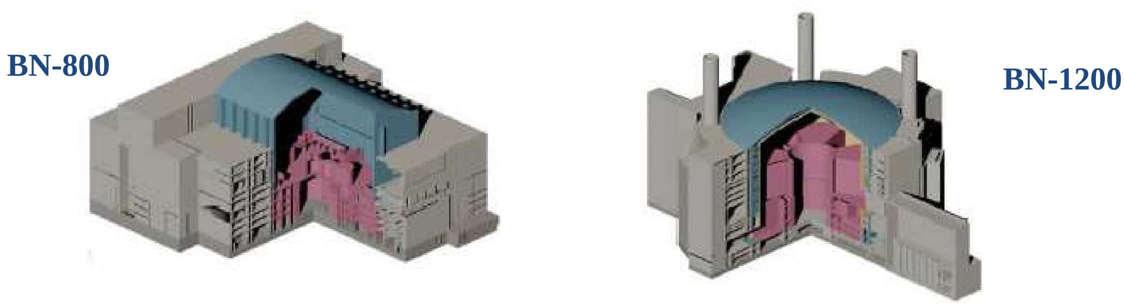


FIG. 4. Changes in construction volumes.

Extensive efforts in the area of calculated and experimental research have been made for the design validation; some of them are illustrated in FIG. 5-10.

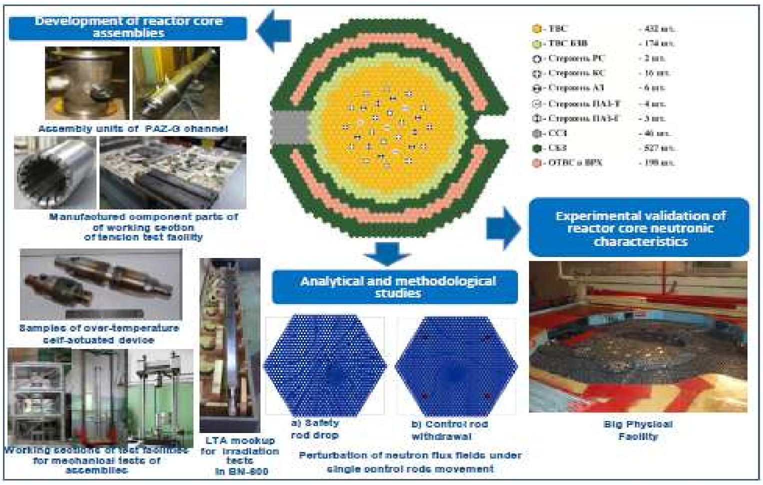
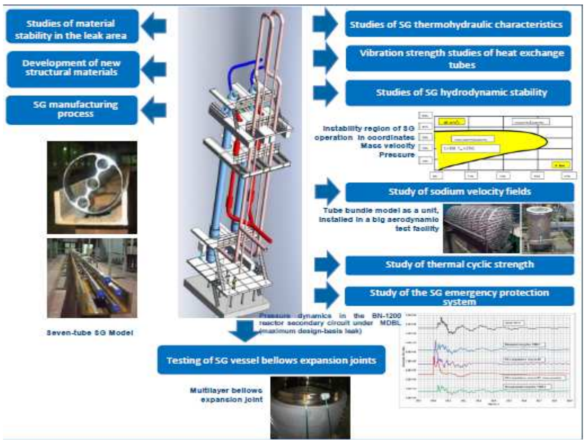


FIG. 5. Reactor Core R&D Work.



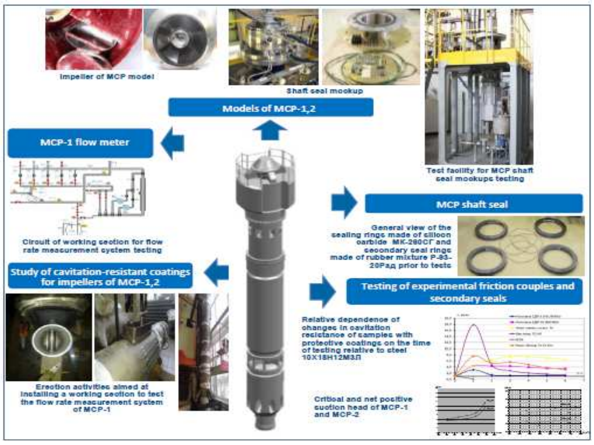


FIG. 6. SG R&D work.

FIG. 7. MCP-1 and MCP-2R&D work.

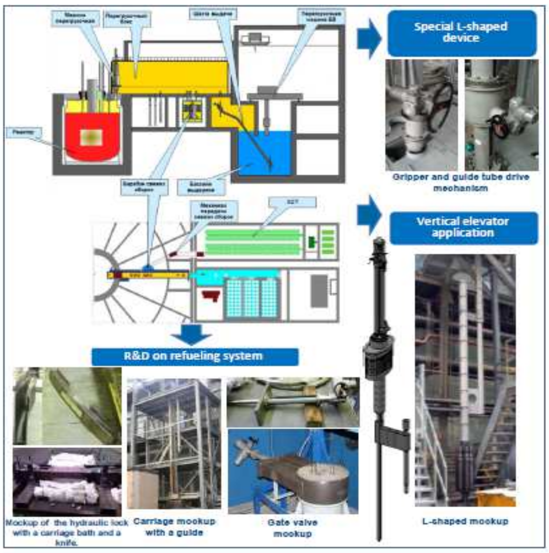


FIG. 8. EHRS R&D work.

FIG. 9. Refueling system R&D work.

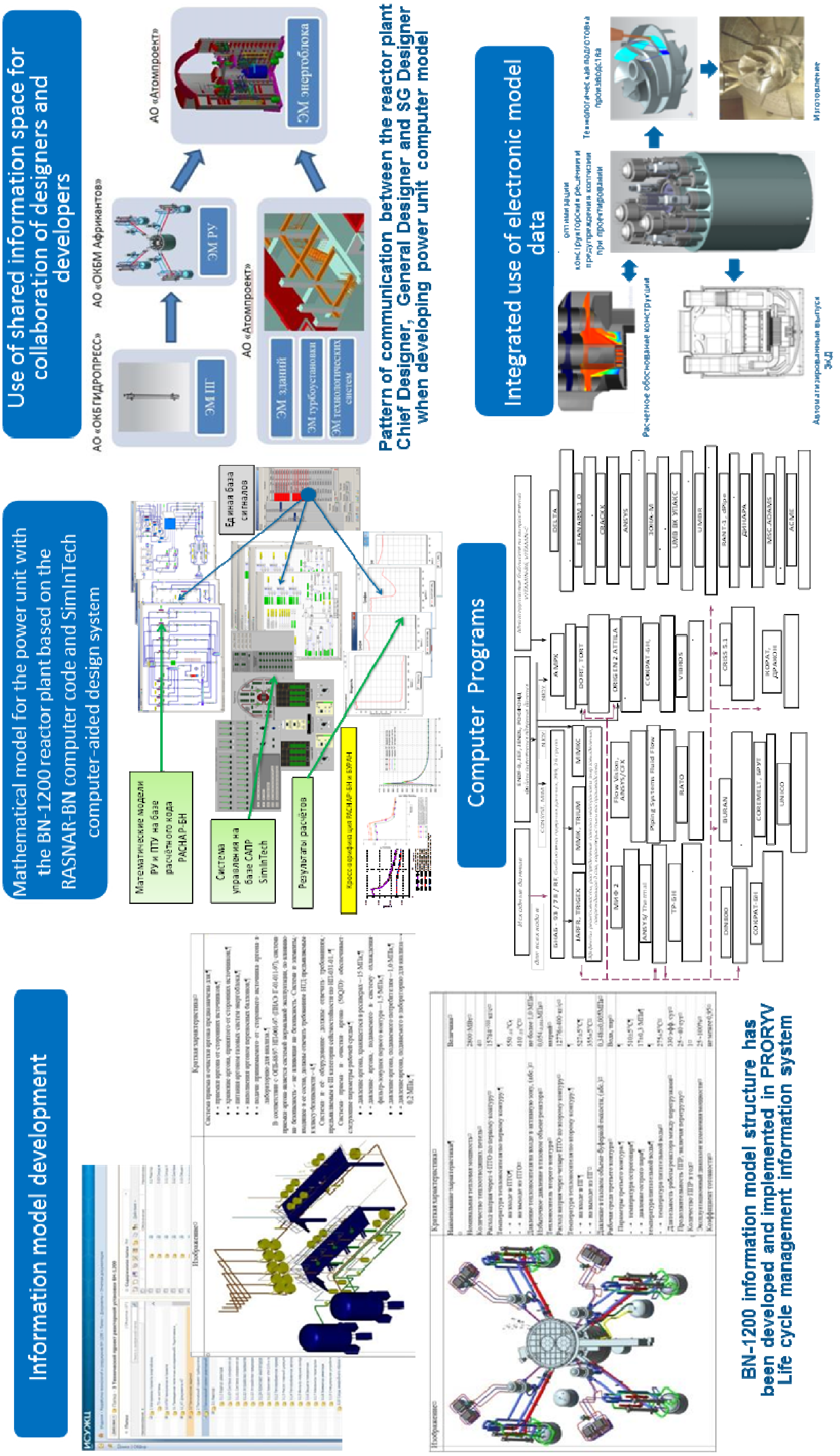


FIG. 10. Research work on computer codes and IT technologies.

The engineering solutions applied in the power unit design up to 2017, ensured substantial improvement of technical and economic indices and competitiveness of BN-1200 at the market of energy sources (FIG. 11).

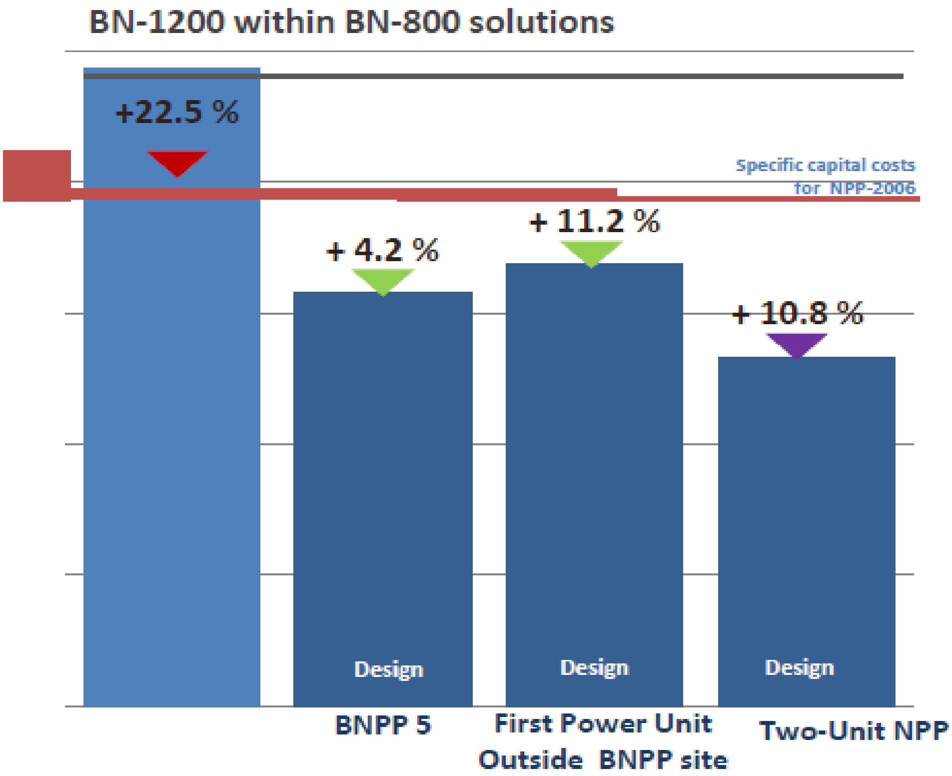


FIG. 11. Improvement of technical and economic indices.

4. Conclusion

The best configuration of the reference and new engineering solutions makes it possible to obtain the required level of safety and competitiveness of BN-1200 power units and consider it as Next Generation Power Unit.

The achieved level of BN-1200 development and validation with account of the production facilities available in Russia ensures construction of the first-of-a-kind BN-1200 reactor before 2027 and the possibility of proceeding to further commercial construction of such reactors.

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