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Joint Stock Company
St. Petersburg Research
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ATOMENERGOPROEKT
(JSC SPbAEP)

BN-800 NPP

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JSC SPbAEP today:

- more than 80 years of successful work;
- more than 1700 world-class specialists;
- Quality Management System ISO 9001;
- unique projects implemented in 19 countries;
- participation in designing 118 power stations,
including 18 nuclear power plants.

Introduction

Role of BN-800 concept in the development of fast reactor technologies

The current state of fast reactor technologies (including projections for the next 10 to 15 years) makes the erection of Power Unit 4 of Beloyarskaya NPP (BNPP) particularly important for:

- further enhancement of safety aspects;
- demonstration of competitiveness of the technology;
- optimization of the closed-loop fuel cycle as a basis of nuclear energy production in future and development of non-proliferation strategies;
- efficient implementation of weapon-grade plutonium recycling program based on the inherently local technologies which reduce the risks involved in the use of new MOX-fuel at existing nuclear power plants;
- satisfying local demand for energy.

Below are described the main ways of implementing the aforesaid fast-reactor technologies.

BN-800 as a basis of further development of the technology of BN-800 concept in the enhancement of NPP safety and competitiveness

BN-800 design retains all principal BN-600 legacy solutions and wide experience which has been gained for many years of operation of BN-600 reactors. At the same time, it employs new concepts targeted at higher safety level, viz.:

- additional «passive» safety system consisting basically of three absorber rods hydraulically suspended in sodium flux, which would drop into the core if sodium flow decreases to 50% of rated level;
- system (also passive) of residual heat removal through air heat exchangers connected to every loop of the secondary coolant circuit;
- corium catcher that prevents fuel from dropping onto the bottom of the reactor pressure vessel and its escape outside primary coolant circuit in case of a beyond design basis accident. This feature also prevents core recriticality;
- sodium plenum in the upper part of the core designed to keep sodium bubble volume reactivity effect below β eff when the reactor operates on MOX or nitridic fuel;
- passive devices ensuring rupture of «siphons» in case of a sodium leakage from any section of a primary circuit pipeline partly laid outside the reactor pressure vessel.



Introduction

The above provisions resulted in the high resistance of the reactor to beyond-design-basis accidents. This is why practical experience in operating BN-800 safety systems is considered as an important contribution to the development of BN technologies. New solutions such as an increase in rated heat power (from 1470 MW in BN-600 to 2100 MW in BN-800) without any substantial changes in the RPV design, and the use of steam/steam reheating, reduction in number of auxiliary systems and their improvement, etc., lead to a considerable decrease in the metal intensity of the project (from 4.3 t/MW (therm.) in BN-600 to 2.7 t/MW (therm.) in BN-800), which, in turn, enhances its competitiveness.



Role of BN-800 concept in the implementation of fast reactor fuel cycle and recycling of weapon-grade plutonium

Presented in Table 1 are possible scenarios of NPP fuel cycle instantiations with regard to the maturity of a particular fuel technology. By now, vast experience has been gained in Russia in developing and testing MOX fuel assemblies. Hence, it would be expedient to provide first core loadings with MOX in the open-loop fuel cycle enabling effective recycling of weapon-grade plutonium.

Thus, BN-800 reactor in conjunction with BN-600 reactor firing 100% MOX fuel is capable of implementing a program of weapon-grade plutonium transformation into standard spent fuel at an annual rate of up to 3 t. In this case, the risk of electric power underproduction at one BN-800 Power Unit due to the recycling of weapon-grade plutonium is invariably less than that in case when numerous VVER-1000 Power Units are involved in the recycling process.

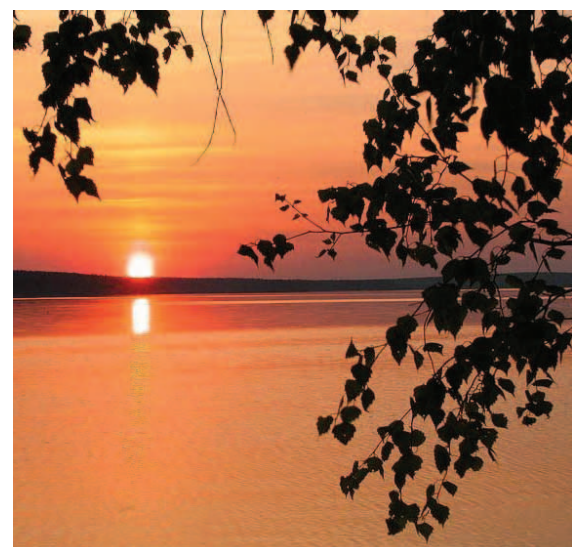
Another important factor is that BN-800 is located at Beloyarskaya NPP site in the vicinity of Mayak Recycling Works. This considerably shortens the transportation routes of weapon-grade plutonium, excludes transportation of plutonium-based fuel through densely populated areas of the European Russia, and contributes to effective supervision thereof, and, ultimately, to the high safety and non-proliferation level. Since weapon-grade plutonium recycling program will expectedly be supported by international investments, reasonable agreements with USA and other would-be partners about their share in the construction of BN-800, and, primarily, of related fuel cycle facilities, could contribute to the solution of the scope of the related problems Minatom currently faces.

Introduction

BN-800 and demonstration of the potential of reactor technology associated with environmentally safe and non-proliferable fuel cycle

Practical experience gained in Russia in recycling of BN-350 and BN-600 experimental fuel assemblies at PT-1 Works may contribute to the gradual transition of BN-800 operation to closed-loop cycle with MOX (if necessary) and/or nitridic fuel (see Table 1).

The most important feature of BN-800 closed-loop fuel cycle is that actinides (including plutonium and lower actinides LA) yielded in the reactor are consumed in the same reactor. The reactor fuel cycle in equilibrium accommodates ca. 5 t plutonium (including ca. 3 t in the core and ca. 2 t in the external fuel cycle), and ca. 200 kg LA. Conservatively assuming ca. 1% of actinides to be wasted in the process, we have ca. 25 kg LA in the radwaste of BN-800 closed-loop cycle. The above evaluation is derived from the assumption that reactor core would be recycled 20 times in 40 years of reactor service life based on 730 equivalent days of a fuel campaign.



Introduction

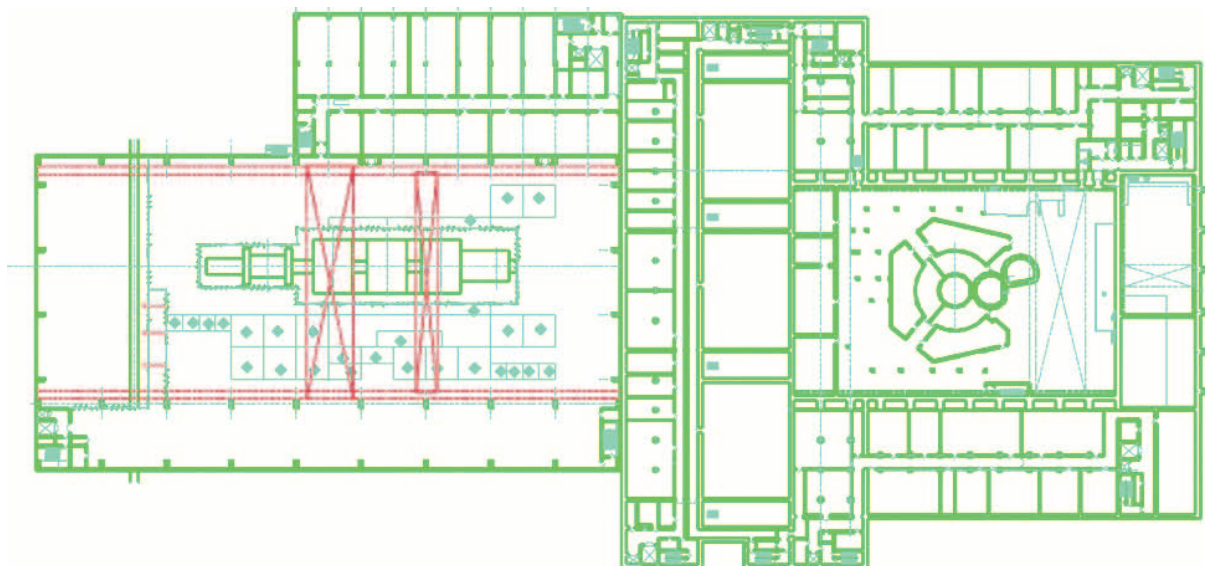
Table 1. BN-800 fuel cycle scenarios

Scenario			Main tasks	
Open-loop fuel cycle	}	>	MOX	<ul style="list-style-type: none"> • Elaboration and implementation of recycling program ex-w-Pu • Tweaking burn-up technologies for lower actinides yielded by heat reactors (BN-800 > 2 VVER-1000)
Closed-loop fuel cycle		>	MOX	<ul style="list-style-type: none"> • Elaboration on closed-loop cycle technologies yielding no LA or Pu (ecology, non-proliferation)
Closed-loop fuel cycle	}	>	Nitride	<ul style="list-style-type: none"> • Comprehensive elaboration on solutions targeted at higher safety, environment protection, and non-proliferation

For comparison sake consider the following data concerning radwaste of WWER-1000 reactor firing uranium fuel in the open-loop fuel cycle. Some 20 t of waste fuel are unloaded from such a reactor annually. This amount contains ca. 20 kg LA. Hence, the total of LA accumulated for 40 years of reactor service life amounts to ~ 800 kg. Taking into account the ratio of WWER-1000 and BN-800 rated power values, we find that the previous ultimately yields ca. 30 times as much LA as the latter.

The above data concerning LA recycling capacity are true to both BN-800 versions under design (firing biased nitridic fuel and mixed oxidic fuel, respectively). BN-800 enables the simplest techniques of LA burn-up: mixing of some LA with fresh fuel under production. Naturally, more efficient recycling may only be achieved in a dedicated core (to be designed), using, e.g., fuel free from uranium-238 based on active matrix.

Additionally, BN-800 firing energy-grade plutonium accumulated at Mayak Works could assist to settle economical and, primarily, environmental issues associated with the storage of plutonium.



New generation nuclear power plant featuring BN-800 reactor

BN-800 power unit (under design) for Beloyarskaya NPP accommodates all principal concepts and solutions used in its predecessor BN-600, substantiated by over 20 years of its successful operation at high performance (capacity factor 80% at efficiency 42%).

BN-800 Power Unit is designed primarily for the production of heat and energy. The Power Unit as a part of the grid operates with constant rated load (basic mode).

However, BN-800 characteristics and physical features dictate its multi-purpose usage. Viz., the reactor is used for:

- electric and heat power generation;
- plutonium consumption and, if necessary, production;
- processing of long-lived supertransuranics accumulated in the radwastes of reactor of any type;
- production of isotopes.

No other reactor type combines so wide a range of functions.

Equipment of the reactor and its systems involved in the handling of fuel assemblies containing isotopes and supertransuranics is designed to perform the above-mentioned functions.

General view of an NPP with BN-800 reactor



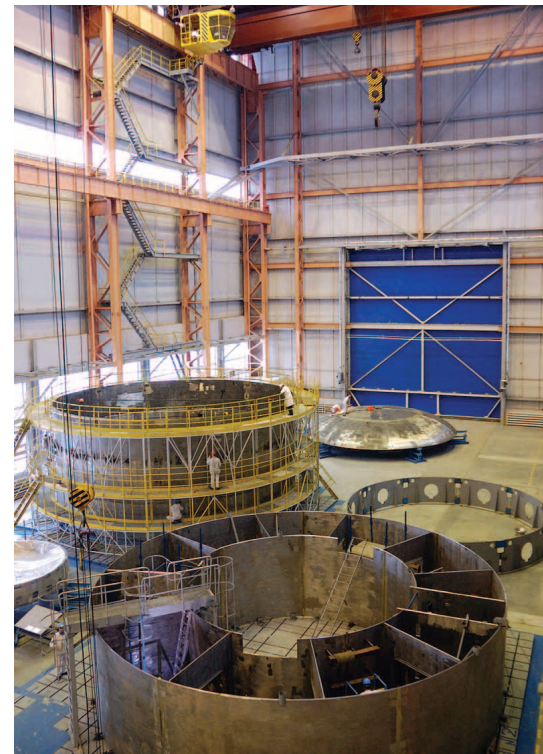
New generation nuclear power plant featuring BN-800 reactor

Design of NPP with BN-800 provides solutions to the problems which nuclear power industry is currently facing. These are:

- safety performance that meets the specifications established by the applicable Russian codes and standards;
- accommodating international trends in the sphere of enhancing the safety of fast reactors;
- use of age-proven technologies and equipment to a maximum possible extent;
- higher Power Unit efficiency and reduction of initial investments into its construction.

Contributors to BN-800 designing:

- SPbAEP — General Designer;
- OKBM — General Designer of the reactor plant;
- RNC FEI — Chief consultant on nuclear and radiation safety issues;
- Beloyarskaya NPP — BN-600 & BN-800 operator;
- other Russian sub-contractors who have gained vast experience in nuclear power;
- production sector.



BN-800 NPP: heat flow chart

The Power Unit consists of a fast reactor with sodium coolant and a turbine unit.

Characteristic of BN reactor unit is the integrated design of primary coolant circuit, which means that principal equipment of active primary coolant circuit and reactor coolant are contained in the reactor tank. BN-800 Power Unit features 3-circuit heat flow diagram.

Primary coolant circuit includes 3 loops, each containing reactor coolant pump (RCP-1), controllable check valve, and two intermediate heat exchangers (IHE).

Secondary (intermediate) coolant circuit has also three loops, each containing two IHE, modular steam generator (SG), buffer vessel, RCP-2, and piping. Sodium is used as secondary (intermediate) coolant.

Tertiary (steam/water) coolant circuit consists of a modular steam generator (three sections) and a turbine unit.

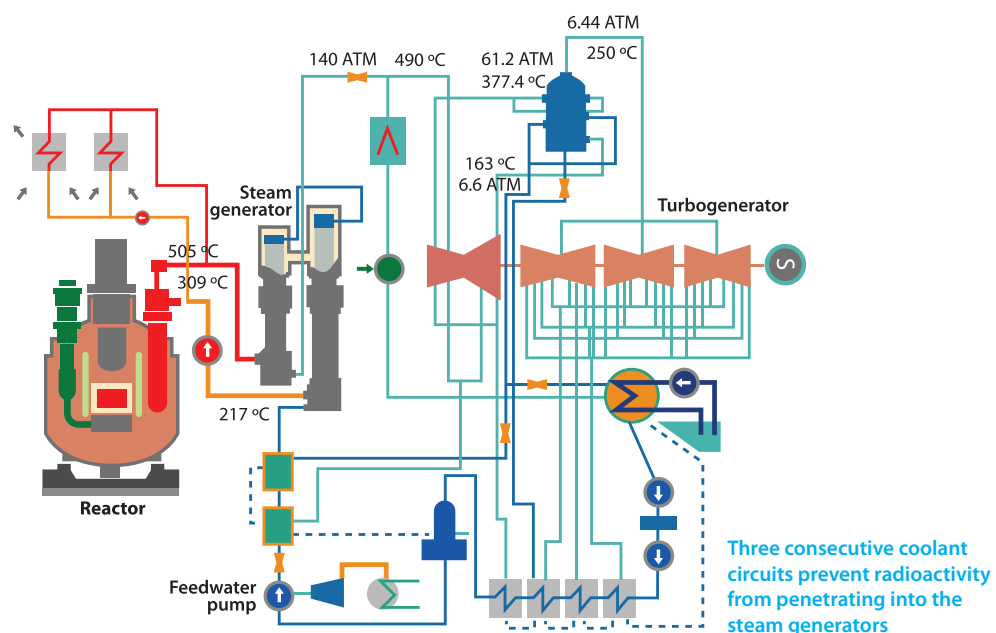
RCP-1 of each loop feeds sodium to the reactor pressure chamber, and further, to fuel assemblies located in the reactor core and blanket, and for the cooling of the reactor pressure vessel, neutronic shield, and in-vessel biological shield. Sodium heated in the reactor core up to 547 °C is fed to each loop's IHE, where it heats secondary sodium and returns to RCP-1 inlet. Secondary sodium heated in IHE of this loop up to 505 °C is fed to modular SG to generate and superheat water steam.

Steam exhausted from turbine HP cylinder is separated and reheated in MSR.

Positive pressure differential is maintained between secondary (intermediate) coolant and primary (reactor) coolant, which prevents radioactive primary sodium from penetration into the secondary coolant circuit.

Pressure differential between primary and secondary coolant circuits is provided by maintaining needed pressure levels in respective gas plenums, as well as by proper equipment layout.

BN-800 NPP: heat flow chart



Prior to filling, sodium loops are evacuated, filled with inert gas (argon), and heated. The reactor is heated with hot gas by gas heating systems, whereas other equipment and piping are heated with electric heaters up to 250 °C. The turbine condenser is cooled with water taken from the storage pool.

BN-800 reactor

Characteristic of BN-800 reactor is the integrated (tank-based) arrangement of primary circuit equipment. Basically, the reactor pressure vessel is a cylindrical tank with toroidal-tapered-spherical bottom and tapered top. Tapered and spherical parts of the reactor vessel bottom are connected (in the middle part thereof) to a ring, which transfers the weight of the reactor vessel through the support structure (guard tank ring and thrust blocks) to the barrel welded to the reactor shaft foundation. Installed onto the guard tank ring is box-shaped supporting belt that constitutes principal in-vessel load-bearing structure.

The supporting belt is designed to carry load from the following components:

- pressure chamber with its headers, primary reflector, and core fuel assemblies;
- side and bottom primary shielding;
- reactor vessel heat shields;
- six intermediate heat exchangers, and
- three reactor coolant pumps.

Reactor coolant pumps and intermediate heat exchangers are placed in cylindrical barrels installed on the supporting belt of the reactor vessel. The latter, in its upper part, has six ducts to be connected to respective heat exchangers, and three ducts to be connected to respective pumps.

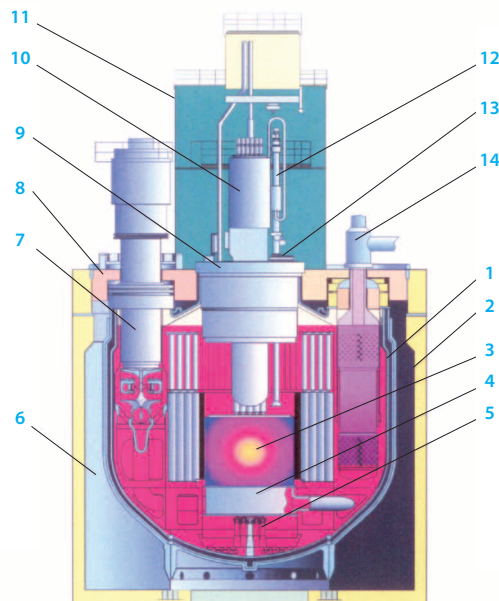
Expansion bellows compensate for difference in thermal expansions of pump/heat exchanger support barrel flanges and reactor vessel ducts.

Reactor vessel walls are forcedly cooled with “cold” sodium from the pressure chamber.

Biological shielding consists of steel cylindrical shields, steel billets, and graphite-filled tubes.

Reactor pressure vessel is confined within the guard tank. Expansion bellows on respective necks and torus rings on tapered roof of the reactor vessel compensate for difference in thermal expansions of the reactor vessel and the guard tank.

The upper section of the reactor pressure vessel also supports three (large, medium, and small) rotating covers.



1. Reactor pressure vessel 2. Guard tank 3. Reactor core 4. Pressure chamber 5. Corium catcher
 6. Reactor cavity 7. Reactor coolant pump 8. Fixed upper shield 9. Large rotating cover
 10. Central rotating cover 11. Protective hood 12. Reloading device
 13. Small rotating cover 14. Intermediate heat exchanger

BN-800 reactor

BN-800 NPP: principal specification & performance

Nº	Parameter	Value
1	Power Unit	
1.1	Design service life	40 years
1.2	Rated heat power	2100 MW
1.3	Rated electric power	864 MW
1.4	Power unit net efficiency	39.35%
1.5	Electric energy produced annually	5522 Mln. kW-h
1.6	Effective hours of running at rated load	7000 h/year
1.7	Electric power percentage consumed by auxiliaries	7.4%
1.8	Annual heat energy production (except for auxiliaries)	83 MW
2	Reactor Core	
2.1	Full load operation between refueling periods	140 days
2.2	Refueling duration	14...17 days
2.3	Fuel: (core/breeding blanket)	PuO ₂ -UO ₂ / depleted UO ₂
2.4	Maximum amount of fuel assemblies and control rods unloaded during refueling	229 pcs
2.5	Average fuel burnup	66 MW-day/kg
2.6	Average core power density	430 kW/l
3	Primary coolant (liquid sodium) circuit	
3.1	Number of primary coolant circuit loops	3 pcs
3.2	Reactor coolant temperature (core inlet/outlet)	354/547 °C
3.3	Reactor coolant flow (in three loops)	31920 t/h
3.4	Reactor coolant inventory	910 t
3.5	Pressure in the reactor gas plenum (operation)	0.054 MPa
3.6	Primary sodium radioactivity	18*10 ¹¹ Bq/h
4	Secondary coolant (liquid sodium) circuit	
4.1	Number of secondary coolant circuit loops	3 pcs
4.2	Secondary coolant temperature (inlet/outlet of the intermediate heat exchanger)	309/505 °C
4.3	Coolant flow per secondary circuit loop	11500 t/h
4.4	Pressure in buffer vessel gas plenum	0,35 MPa
4.5	Secondary sodium radioactivity	3.7*10 ⁴ Bq/h
5	Tertiary coolant (steam, water) circuit	
5.1	Number of secondary loops	3 pcs
5.2	Steam generator type	modular sectional
5.3	Number of sections in steam generator	10
5.4	Evaporative capacity per steam generator	792.0 t/h
5.5	Superheated steam pressure	14.0 MPa
5.6	Superheated steam temperature	490 °C
5.7	Feedwater temperature	211 °C
5.8	Turbounit type K-800-130/3000	1
5.9	Turbine arrangement	HPC+3LPC
5.10	Superheated steam flow	3170 t/t
5.11	Superheated steam temperature	485.0 °C
5.12	Steam temperature after superheating	250.0 °C
5.13	Output in condensing operation mode	880.0 MPa
5.14	Alternator voltage	24 kV
5.15	Stator & rotor winding coolant	water

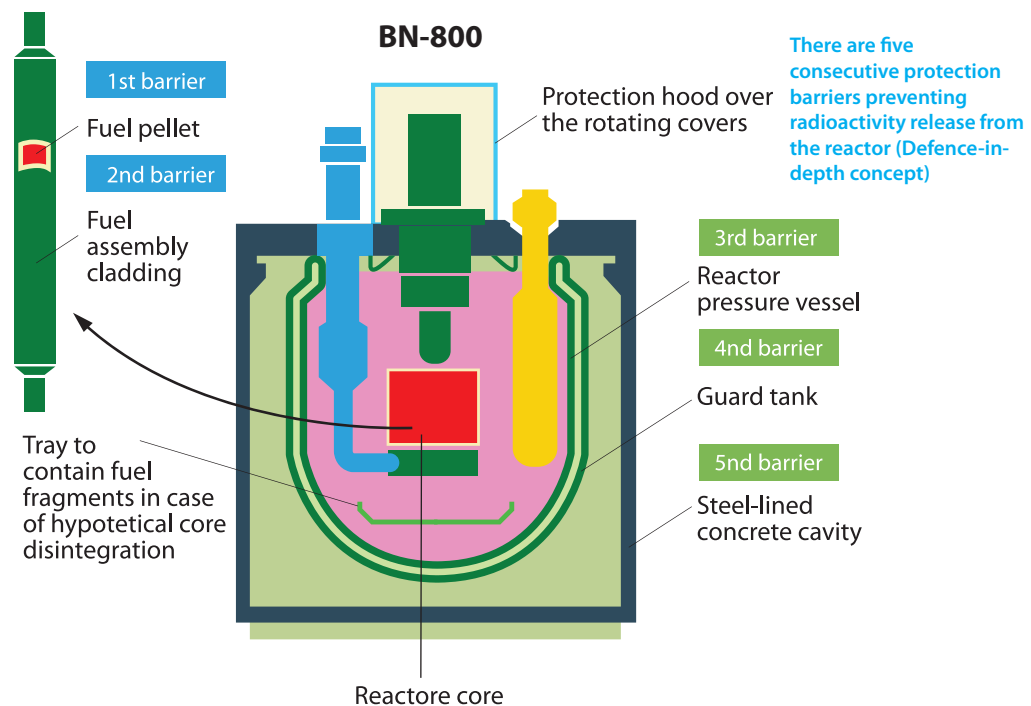
Design approaches to safety systems of NPP with BN-800 reactor

BN-800 NPP design is based on the safety criteria established by the applicable Russian standards and regulations.

Apart from applicable Russian standards IAEA recommendations are also heeded.

BN-800 safety approach is based on the defense-in-depth concept, which implies using a system of barriers for preventing ionizing radiation and radioactive substances from spreading to the environment. The concept also provides for a number of engineering and institutional measures aimed at protecting these barriers and ensuring their efficacy for the protection of local population.

Protection barriers



Vast experience gained in researching, developing and operating sodium-cooled fast reactors testifies to their undeniable intrinsic safety features, viz.:

- stable power and temperature degenerative feed back ensured by negative power and temperature reactivity effects; no reactor poisoning after reactor shutdown;
- negligible variation in neutron flux spatial distribution during normal operation and transients induced by input disturbances (in coolant temperature, coolant flowrate, and reactivity); excellent controllability of the reactor;
- corrosive impact of sodium on reactor structures is negligible;
- pressure in the reactor vessel is approximately the same as the atmospheric pressure. Moreover, sodium boiling point exceeds maximum coolant temperature in the most stressed fuel assembly by ca. 300 °C;
- as the design of the reactor vessel is fully integrated, primary coolant leakage, however large, will not result in a nuclear accident;
- great thermal capacity of the primary circuit. According to calculations supported by direct experiments on BN-350 and BN-600, the rate growth of the mean primary sodium temperature caused

Design approaches to safety systems of NPP with BN-800 reactor

by reactor trip (with no heat removal from the primary circuit) does not exceed 30 °C/h. Given sufficient critical heat flux, this leaves enough time for measures to be taken to mitigate a beyond design basis accident;

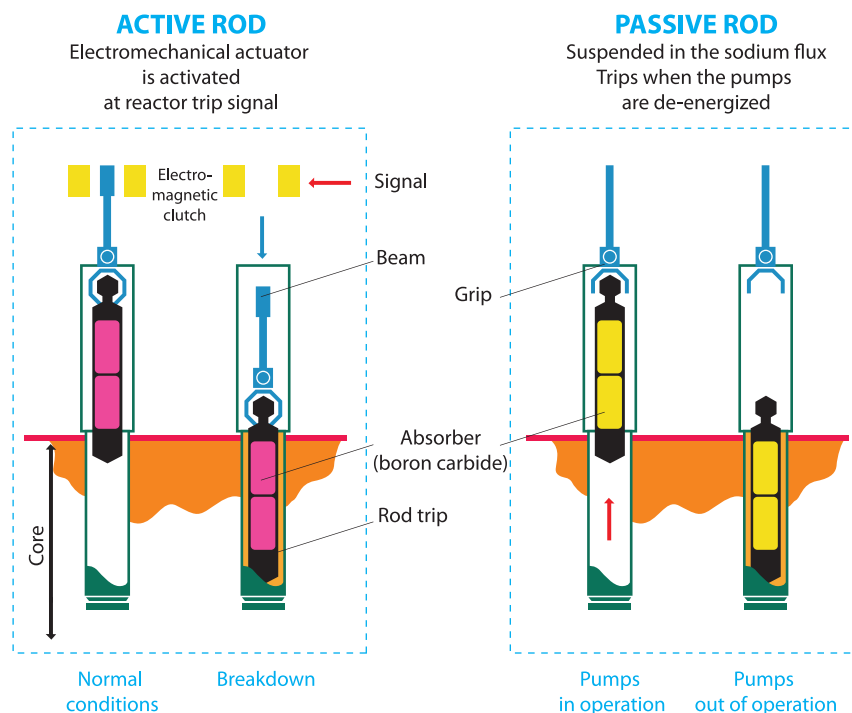
- decrease in sodium heat-transfer coefficient caused by transition to natural coolant circulation is negligible.
- Effective natural coolant circulation that ensures the removal of residual heat from the reactor core when forced circulation is lost.

Apart from the above intrinsic safety features, the following design safety provisions have been adopted in BN-800:

- reactor core with zero sodium bubble volume coefficient, whose parameters are substantiated by many years of analyses and experiments, including those carried out on full-scale physical simulation test stand;
- special devices which limit (without any automatic action) maximum total leakage of primary sodium in case of a guillotine break in external pipelines of auxiliary systems having no protective guard;
- emergency safety rods that would passively drop in case of an accident involving RCP failure. Full-scale physical model of such a device has been tested on a water test stand;
- tray for containing and cooling molten fuel fragments in hypothetical situations;
- highly efficient steam generator protection system.

Reactor trip

The reactor is tripped by twelve safety absorber rods (9 active and 3 passive rods)



Design approaches to safety systems of NPP with BN-800 reactor

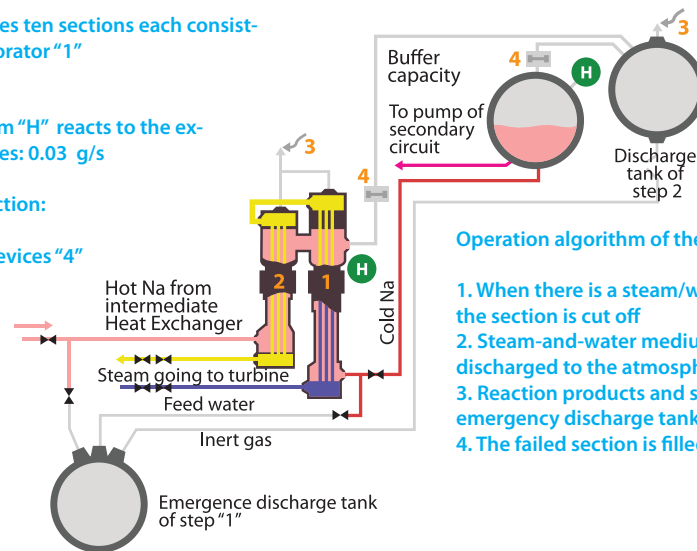
Steam generator protection system

Steam generator includes ten sections each consisting of modules of evaporator "1" and overheater "2"

Hydrogen control system "H" reacts to the extremely low leakage rates: 0.03 g/s

Passive means of protection:

- safety valves "3"
- bursting membrane devices "4"



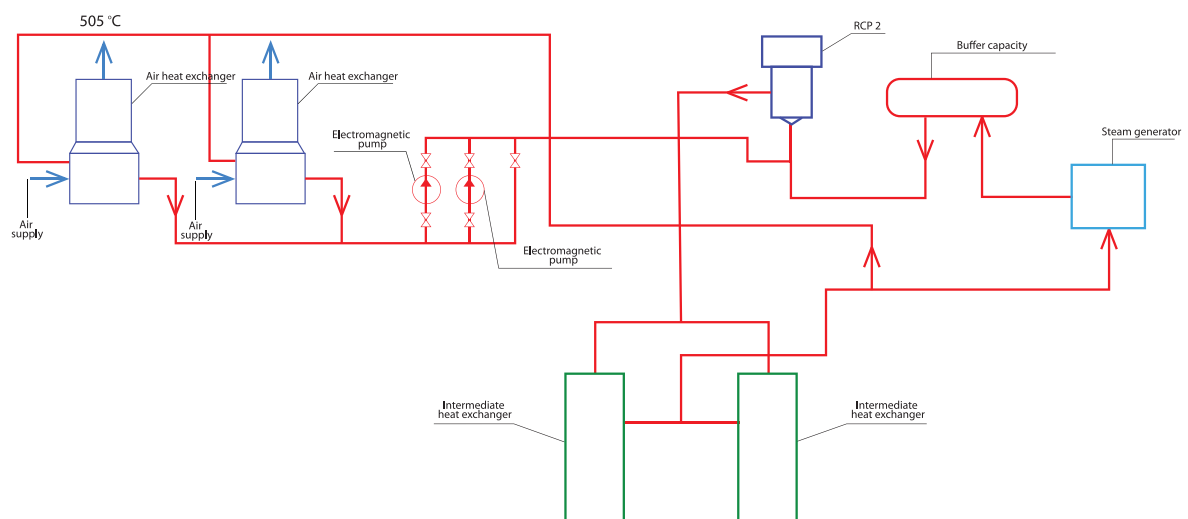
Operation algorithm of the protection system:

1. When there is a steam/water leakage into sodium the section is cut off
2. Steam-and-water medium from the failed section is discharged to the atmosphere (safety valve "3")
3. Reaction products and sodium are discharged into emergency discharge tanks
4. The failed section is filled with inert gas

System of reactor emergency cooling through air heat exchangers connected to the secondary sodium pipelines. The system includes three independent safety trains, each providing 100% capacity.

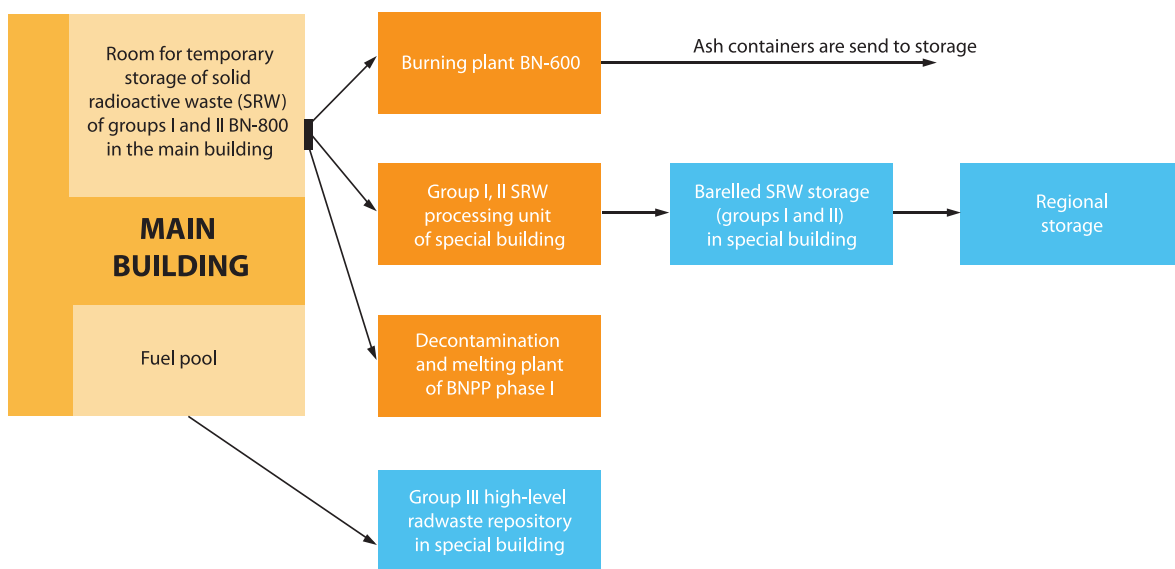
Safety and reliability parameters of the power unit have been substantiated by probabilistic safety analysis included in the technical design. The analysis considers, in particular, over 30 emergency scenarios (including over 1000 probable sequences). The resultant probability of core disintegration is shown to be below 7×10^{-6} 1/year.

Emergency reactor cooling system

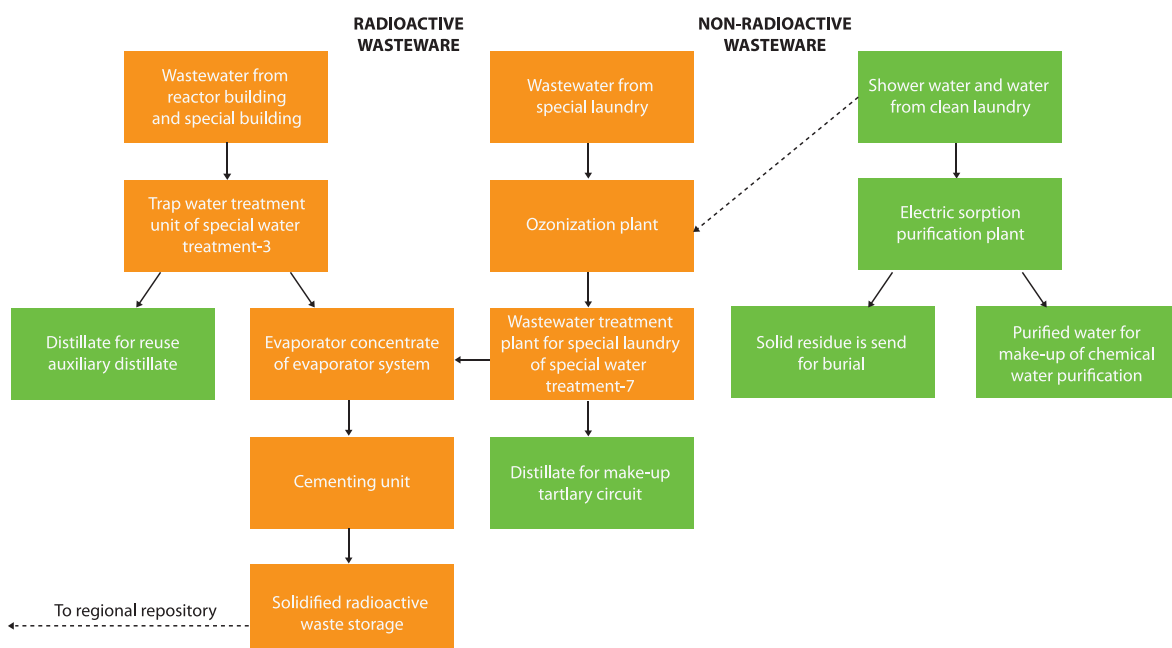


Diagrams of radioactive waste handling at NPP with BN-800

Solid waste handling



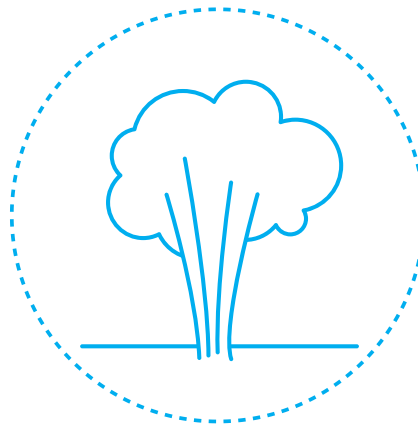
Wastewater treatment at Unit 4 of the Beloyarskaya NPP



NPP protection from external impacts

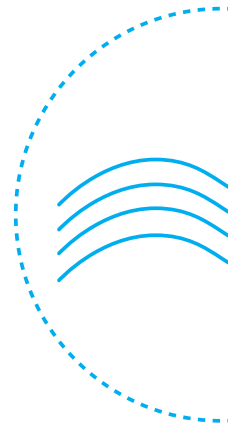
EXTERNAL EXPLOSIONS

Safety-related NPP components are designed to withstand shock wave caused by external explosion. Shock front pressure is estimated at 10 kPa, the duration of compression phase being 1 s

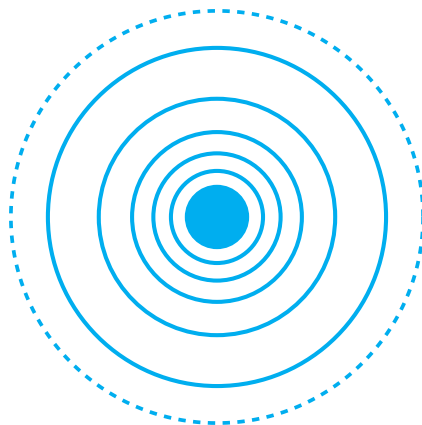


WIND

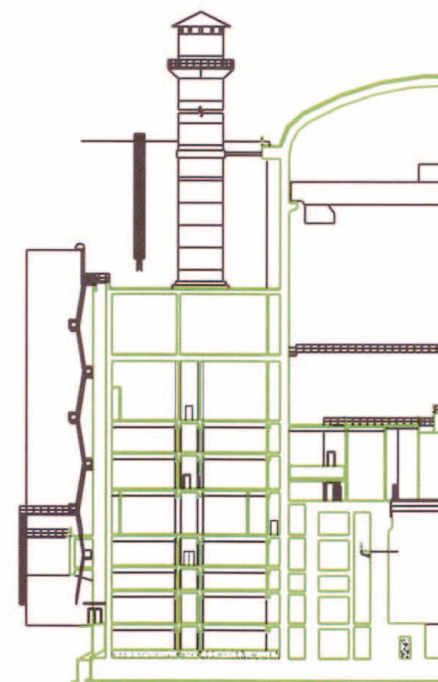
Safety components are designed to withstand loads from wind with a velocity of 44 m/s at height of 10 m.



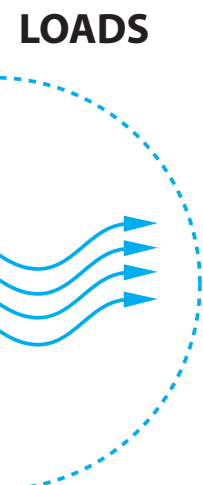
SEISMIC LOADS



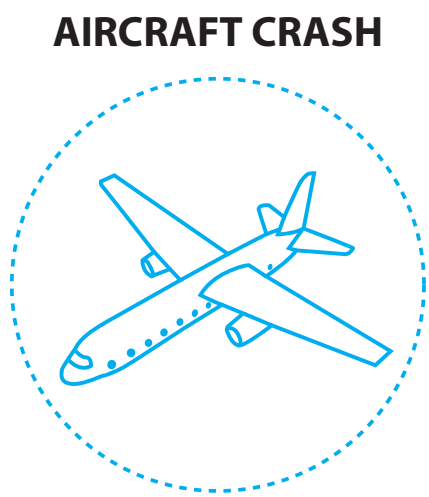
The NPP is designed to withstand earthquake-induced maximum horizontal acceleration of 0.1 g at the earth level



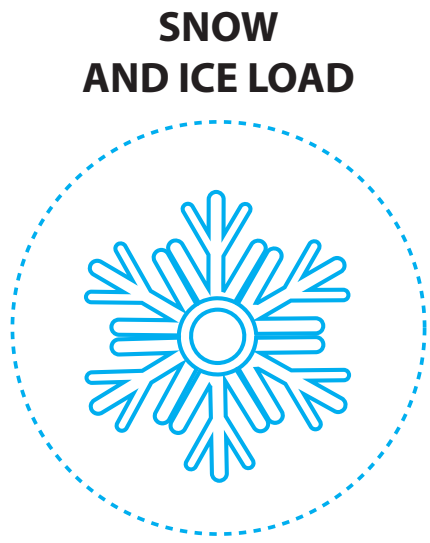
NPP protection from external impacts



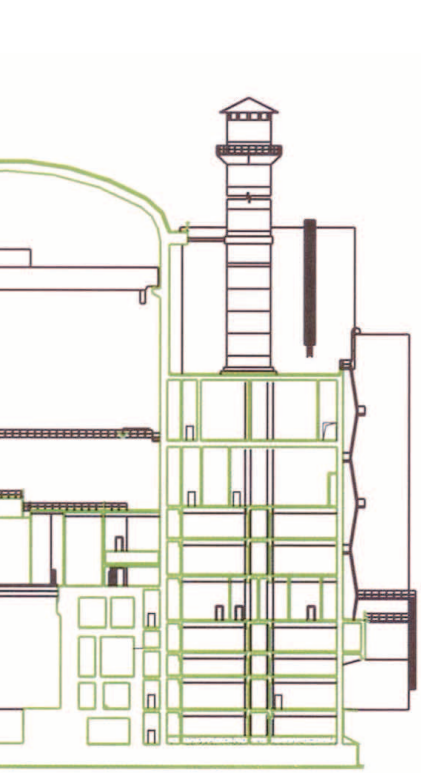
Extreme wind pressure adopted in the design is $W_0 = 0.56$ kPa. Fujita Class 2 whirlwind with probability 0.00000018 is assumed



The NPP is designed to withstand the impact of 5.7 t aircraft falling at a speed of 360 km/h



Peak (extreme) design-basis snow load is estimated at 0.2 kPa



Radiation impact of NPP with BN-800 reactor

Normal NPP operation

According to the experience gained in operating BN Power Units currently in service, radiation impact of nuclides contained in gas-aerosol emissions and wastewater does not exceed 1% of maximum acceptable annual (average) dose established by supervision authorities. The design proves that the amount of nuclides released to the environment with aerosols and wastewater during normal BN-800 operation will be less than that produced by BN-350 and BN-600 NPPs.

Anticipated operational occurrences

BN-800 design also demonstrates that the amount of nuclides contained in gas-aerosol exhaust and non-radioactive wastewater during anticipated operational occurrences (caused by equipment faults or human errors) is limited and/or reduced to design target values through functioning of NPP control and waste handling systems.

Therefore, anticipated operational occurrences will not result in the excess of maximum individual doses to which population can be exposed, as specified for normal operation conditions (i.e. the doses will remain below 0.1 mSv/year).

Design basis accidents

Main yearly limit of dose rate to which population can be exposed as a result of a design basis accident is estimated at 5 mSv as required by the standards and regulations currently in force.

According to the design analyses, the dose which population is exposed to in case of the most severe design basis accident with BN-800 does not exceed 0.1 mSv, that is well within the established limit.

Beyond design basis accidents

According to standards and regulations currently in force, evacuation of the population outside the NPP buffer area (3 km in radius) is required if dose rate exceeds 500 mSv.

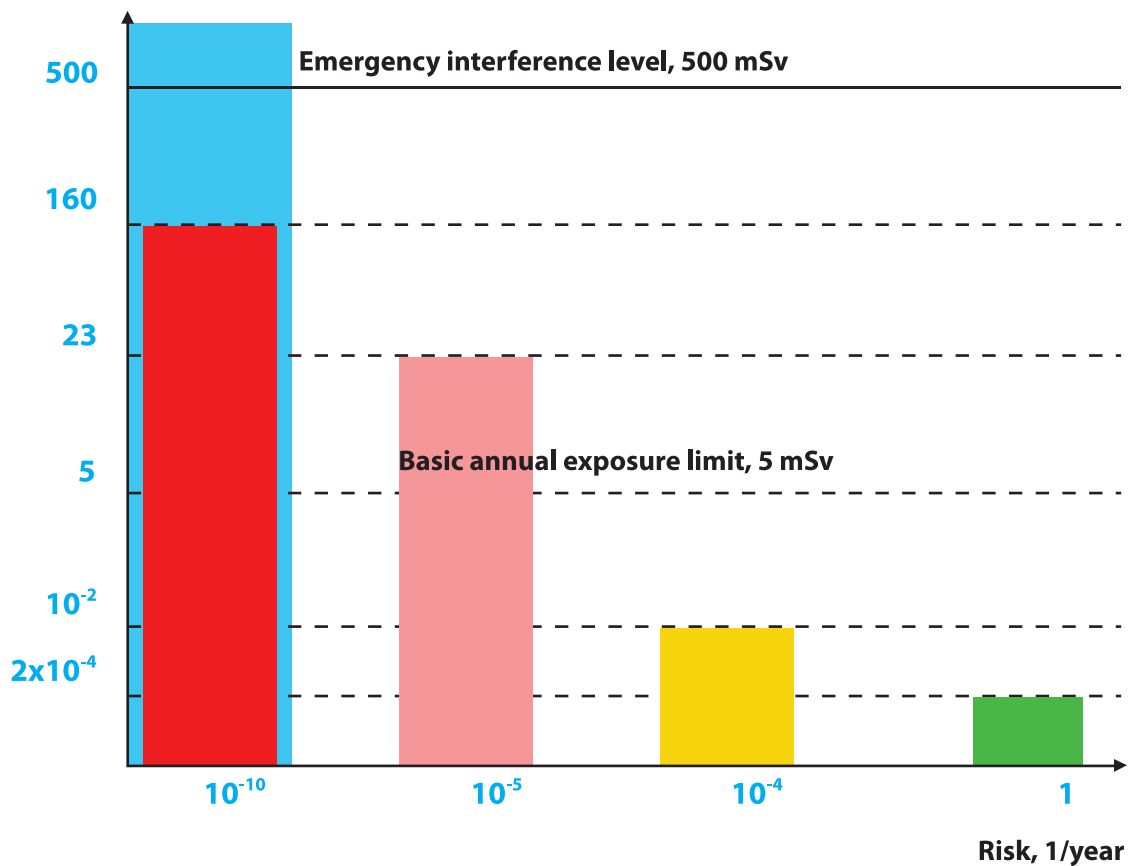
According to the design analyses, in case of the most severe beyond design basis accident with BN-800 (with release expectancy exceeding 10^{-7} 1/year) main yearly limit of dose rate does not exceed 23 mSv, which poses no hazard for the population in the vicinity of a faulty Power Unit.

Maximum design population exposure resulting from hypothetical beyond design basis accidents

Additionally, the NPP design considers the scenarios of hypothetical (impossible) beyond design basis accidents. According to the analysis, in case of the most severe accident (with release expectancy below 10^{-7} 1/year) the dose rate, which population is exposed to at the boundary of the buffer area, does not exceed 160 mSv. This does not call for the implementation of emergency protection plan.

Radiation impact of NPP with BN-800 reactor

Risk dose for population dwelling at the boundary of the buffer area (3 km in radius) during operation of BN-800



- Normal operation
- The most severe design basis accident
- The most severe beyond design basis accident (with release expectancy exceeding 10⁻⁷ 1/year)
- Hypothetical beyond design basis accident (with release expectancy below 10⁻⁷ 1/year)
- Negligible risk area (release expectancy below 10⁻⁷ 1/year)

SPbAEP Today

At present the engineering company SPbAEP is the General Contractor and the General Designer of the Leningrad Nuclear Power Plant, Stage 2, reactor type VVER-1200. Power unit 4 of the Beloyarsk NPP with a BN-800 reactor, designed by the Company, is under construction in the Sverdlovsk Region. The advanced design BN-1200 is currently under development. The Company is also the General Designer of the Baltic NPP, reactor type VVER-1200, which is now under construction in the Kaliningrad Region. The latter project differs from the others in that for the first time in the history of the Russian nuclear power industry private foreign investors are invited to participate in the project. In August 2010 an official launch ceremony was held at the Bushehr NPP in Iran (reactor type VVER-1000), for which SPbAEP designed the turbine hall. For the city of St. Petersburg the Institute has designed the South-West Cogeneration Plant. Stage 1 of this facility, which is very important for the power generation sector of the region, was put into operation in December 2010. SPbAEP also participates in projects for renovation and life extension of the operating power units of the Kola, Beloyarsk, Kursk, Smolensk and Leningrad nuclear power plants as well as of some other power facilities in Russia.

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