KLT-40S

Overview

Full name	KLT-40S
Acronym	KLT-40S
Reactor type	Pressurized Water Reactor (PWR)
Coolant	Light water
Moderator	Light water
Neutron spectrum	Thermal neutrons
Thermal capacity	300 MWth
Electrical capacity	70 MWe
Design Status	Under construction
Designer	JSC "Afrikantov OKB Mechnical Engineering" (OKBM)
Last update	23-04-2013

KLT-40S Design Description

1. Introduction

Construction of a small-size floating nuclear cogeneration plant PATES based on a floating power unit (FPU) of 20870 design with KLT-40S reactor plants (RPs) is currently under way in Russia.

Russia has accumulated considerable experience in using nuclear power for propulsion of surface vessels and submarines. High performance characteristics of RPs developed by OKBM have been validated during long-term operation of nuclear icebreakers and one nuclear ice-reinforced vessel on northern sea routes.

A total of 10 nuclear vessels have been constructed. Seven nuclear icebreakers and one nuclear lighter-carrier, with 13 RPs installed on them, are currently in operation. The longest operation time, more than 175 thousand hours, has been demonstrated by the RP on the "Arktika" icebreaker, and the total operating time of RPs on all nuclear icebreakers amounts to nearly 300 reactor-years.

Over the entire period of nuclear vessel operation, there have been no cases of navigation termination due to RP failures, and no incidents associated with fission reaction control failures, core cooldown failures, uncontrolled nuclides transport, or excessive personnel exposure [1].

The experience of development and long-term failure-free operation of nuclear vessels served the basis for developing the small-size floating nuclear power plant (FNPP) design.

Currently, there are two possible applications for FNPPs [4]:

- provision of district heating and electricity to national consumers;

- power supply to the developing countries, including entry to the seawater desalination market.

The PATES is a complex of buildings and structures including:

- FPU of 20870 design, which is the basic element of the PATES;

- hydraulic engineering facilities (special berth and piers for FPU docking, underwater pit, enclosed sea area);

- coastal facilities that transfer the electricity and heat from the FPU to the coastal communities, and also perform certain auxiliary, servicing and protective functions.

The FPU (see Fig. 1) houses two KLT-40S RPs and two turbine-generator sets with cogeneration turbines; these two sets of equipment are installed alongside the two boards of the FPU.

The KLT-40S RP is a pressurized-water reactor. It is based on the commercial KLT-40 marine propulsion plant and is an advanced variant of RPs that power nuclear icebreakers [2, 8].

In order to increase reliability, lifetime, service life, and to improve maintenance conditions, RP components and safety systems underwent modernization with account of the up-to-date requirements of Russian Rostekhnadzor's regulatory documentation applied for nuclear power plants.

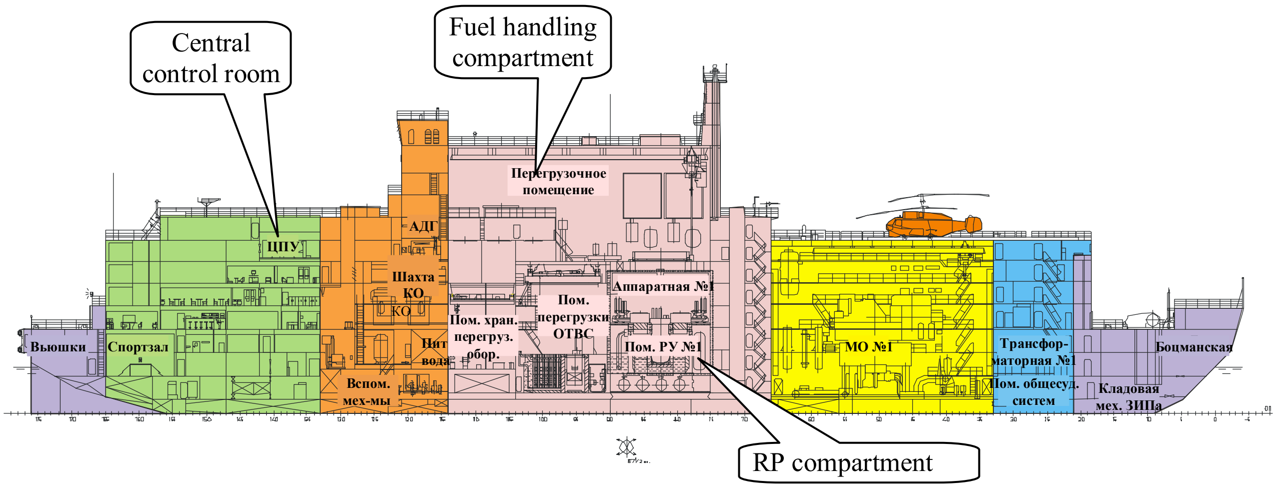


Fig. 1. FPU with KLT-40S RP

The main RP design decisions are as follows [2, 8]:

- modular design: reactor, steam generators (SGs) and main circulation pumps (MCPs) are connected with short nozzles (without long pipelines);

- four-loop system with forced and natural circulation of primary coolant;

- pressurized primary circuit with canned motor pumps and leak-tight bellow-type valves;

- once-through coiled SG;

- external gas pressurizer system;

- passive safety systems;

- proven equipment installation, repair and replacement technologies, as well as proven equipment diagnostic and monitoring systems and tools.

The KLT-40S reactor unit is shown in Fig. 2. The main reactor plant parameters are given in Table “Summary table technical data” in Appendix 1.

2. RP description

The reactor unit consists of the reactor (including the core, three actuators of emergency protection, and eight actuators of compensating groups) connected by short ducts to four SGs of PG-28S type and four hydraulic chambers with four electric pumps installed in them.

The steam generating unit is a system of interconnected high-pressure vessels containing removable parts of the main (replaceable) equipment.

Inner thin-walled nozzles are placed in all main nozzles, thus forming a co-axial structure. Inner thin-walled connecting nozzles, which serve to direct the coolant flow, are fitted together to provide minimum leakage between cavities with different pressures and temperatures.

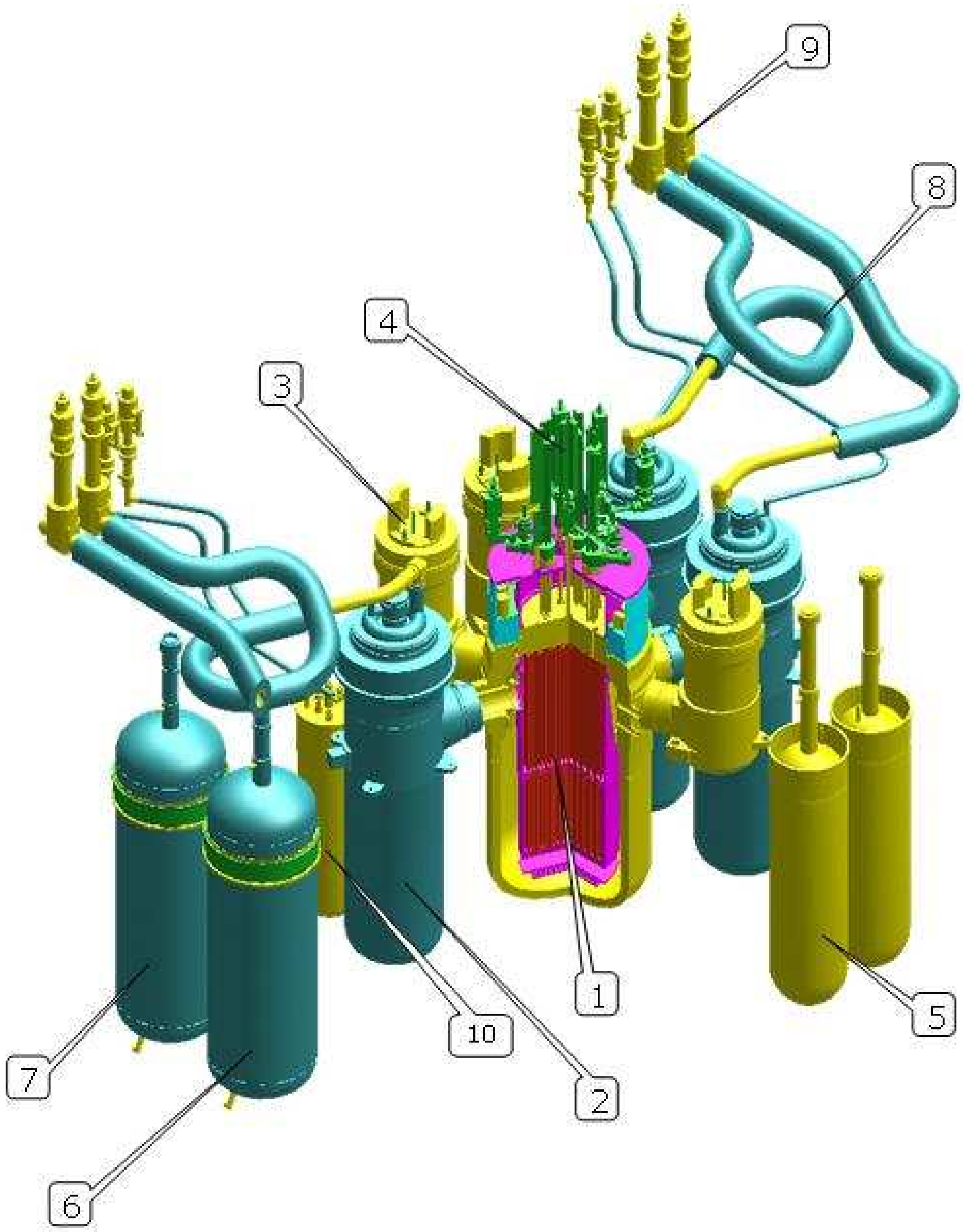
The steam generating unit comprises the main circulation path for heat transfer from the reactor to the SGs.

The KLT-40S RP uses a thermal neutron spectrum, pressurized water reactor.

Structurally, the reactor (see Fig 2, Pos.1) is a high-pressure vessel with a cover. The vessel houses the core, compensating rods and emergency protection rods. On the cover, there are actuators of compensating groups and emergency protection groups, resistance temperature transducers, and thermoelectric temperature transducers intended to measure reactor temperature.

The PG-28S SG consists of:

- strong and leak-tight case with the main coaxial nozzle supplying/removing the primary coolant and attachments for SG fixing on the metal-water shielding tank;



1- Reactor
2- SG
3- MCP
4- Control rod drive mechanisms
5- ECCS accumulator
6- Pressurizer (1st vessel)
7- Pressurizer (2nd vessel)
8- Steam lines
9- Localizing valves
10- HX of purification and cooldown system

ECCS – emergency core cooldown system; HX – heat exchanger

Fig. 2. General view of the KLT-40S RP.

- internals, including the SG cover with secondary coolant supply/removal nozzles and the coiled tubing system with flow restrictors.

The tubing system is assembled of 15 cylindrical multiple-wound coils of 22×2.5 mm tubes. The total number of 22×2.5 tubes in the tubing system is 100.

The MCP is intended to transfer primary coolant inside the steam generating unit. The MCP is canned, centrifugal, single-stage, vertical, with shielded double-speed (double-winding) asynchronous electric motor.

The KLT-40S RP core is based on ship technologies and uses uranium fuel with U^{235} enrichment below 20%, which is termed "Low Enriched Uranium (LEU)" by the IAEA. The limitation of uranium fuel enrichment to below 20% U^{235} is considered by the IAEA to be a factor that enhances proliferation resistance of nuclear systems, as LEU is not a direct use nuclear material [10]. In order to increase uranium content, the core has a close-packed cassette structure and therefore can contain the maximum possible number of fuel elements (FEs) and, correspondingly, the maximum possible volume of fuel in the limited volume of the core.

The core uses FEs with smooth cylindrical cladding of corrosion-resistant zirconium alloy (∅6.8 mm). The FEs are structurally the same as those of icebreaker reactors, but use fuel with higher uranium content based on uranium dioxide pellets in inert matrix.

The core consists of 121 hexahedral shrouded fuel assemblies (FAs) (Fig. 3) placed in the angles of a regular triangular lattice with a pitch of 100 mm. FA heated part height is 1200 mm, across flats size is 98.5 mm, overall length is 1670 mm.

FEs are placed in FAs at a regular triangular lattice pitch of 9.95 mm.

Gadolinium-based burnable poison rods (BPRs) used in FAs fully compensate the reactivity margin for fuel burnup and are similar in design to BPRs of icebreaker reactors.

Table 1. Main characteristics of the KLT-40S reactor core

Parameter	Value
1 Thermal power, MW	150
2 Number of FAs	121
3 FA across flats size, mm	98.5
4 Triangular lattice pitch, mm	100
5 Core diameter, mm	1220
6 Core height, mm	1200
7 FE dimensions across cladding, ∅×δ, mm	6.8×0.5
8 FE cladding material	Zirconium alloy
9 Absorber element layout in FA	Central absorber element
10 Number of control rods in the core	8 compensating rods + 3 emergency protection rods

The selected method of burnup reactivity margin compensation by means of heterogeneous poison in the BPR and control rod absorber element, the type of fuel and the main structural material of core elements, as well as fuel lattice parameters, provide negative reactivity coefficients for power, fuel and coolant temperature, coolant specific volume in the entire envelope of parameters and at any moment of core life. The mentioned factors define the high level of KLT-40S RP inherent self-protection.

The core map is given in Fig. 4.

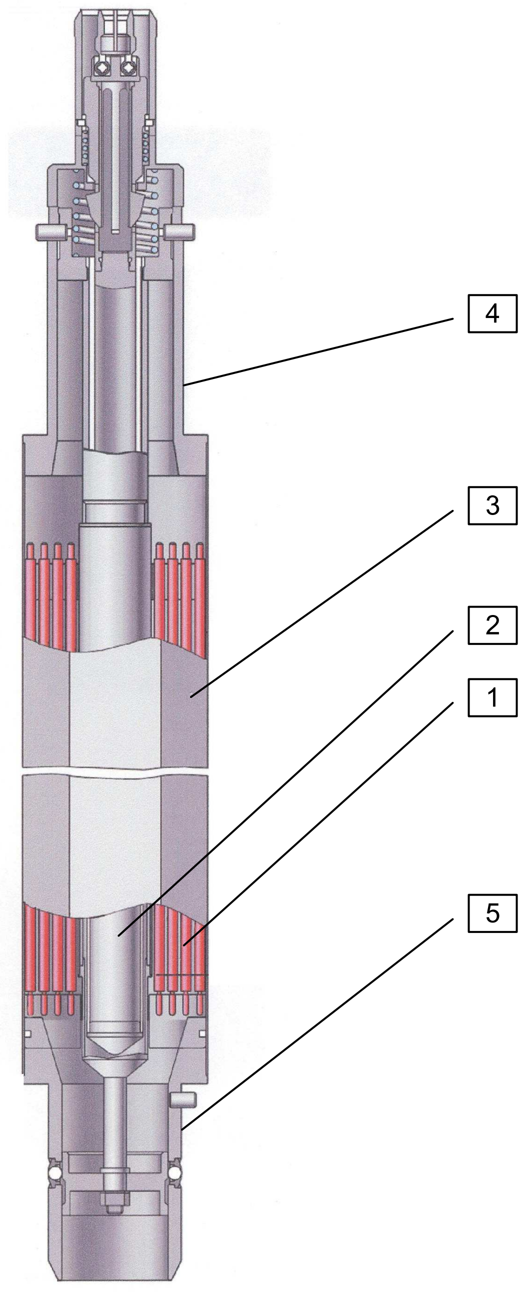


Fig. 3. KLT-40S RP fuel assembly

1 – FEs; 2- absorber element; 3 - nozzle; 4 – upper end; 5 – lower end.

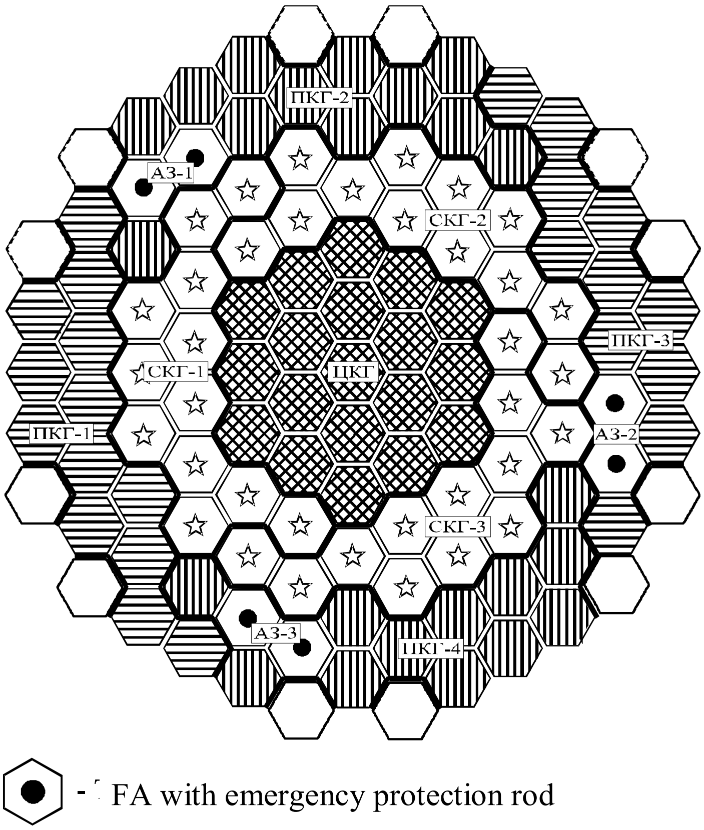


Fig. 4. Reactor core map

Fuel handling complex

One of the advantages offered by the FPU-based PATES under construction is long-term autonomous operation in remote regions with decentralized power supply.

The design stipulates that every 3-4 years of operation the reactor is refuelled, the spent nuclear fuel is then stored onboard the FPU and no special maintenance and refuelling ships are necessary. For that purpose, the FPU incorporates fresh and spent FA storages, storages of liquid and solid wastes generated during operation and refuelling, and the fuel handling complex.

The spent FA and solid radioactive waste storage includes two stages: the wet storage, which ensures reliable heat removal from spent FAs immediately after they have been unloaded from the reactor, and subsequent dry storage with air cooling, which makes possible safe storage of spent FAs at a minimum cost.

The wet storage uses leak-tight wet decay storage tanks. The spent FA and solid radioactive waste storage includes three independent wet storage tanks, each capable of holding the inventory of spent FAs from one reactor core. During normal operation, decay heat is removed by one of the two active heat removal channels through three loops: from the cooling circuit through the intermediate circuit to the seawater. There is also a passive heat removal channel that operates by evaporating the water from the wet storage tank cofferdam into the ventilation system.

The dry storage uses leak-tight canisters of ChT-14 type installed into dry storage containers. The spent FA and solid radioactive waste storage includes four independent dry storage containers, each capable of holding the inventory of spent FAs from one reactor core. The heat from the canisters in the storage containers is removed by open-loop ventilation.

The fuel handling complex is used for reactor refuelling. It performs the entire range of operations from cutting the welds, which attach the sleeves of emergency protection, resistance thermometers and thermoelectric transducers to the reactor cover, to reactor bringing to first criticality, including unloading of spent FAs from the reactor, their transportation and placement into wet storage tanks and dry storage containers, unloading of neutron sources, lower ends of emergency protection, resistance thermometer and thermoelectric transducer sleeves, and loading of fresh FAs into the reactor.

In order to maintain a high capacity factor, refuelling is performed 13 days after reactor shutdown when the levels of residual heat releases from spent FAs are still high.

The fuel handling complex for the KLT-40S RP was developed based on the experience of designing, manufacturing and operating fuel handling equipment for propulsion reactor plants, with account of the modern requirements for safety assurance during potentially nuclear and radiation hazardous activities. Many of the proven solutions validated by years of operation have been used in the developed equipment.

The fuel handling complex includes:

– refuelling container for spent FAs;

– alignment mechanisms installed on the reactor vessel, wet storage tanks and dry storage containers;

– machine for cutting the welds attaching the sleeves;

– hydraulic jacks, pump station, observation device, etc.

Auxiliary systems

Pressurizer system

The pressurizer system is intended to develop and keep the primary circuit pressure within the prescribed limits in all operation modes. The KLT-40S primary circuit uses external gas pressurizer system.

The system includes:

- four pressurizers;
- two main gas cylinder groups (6 cylinders in each group);
- stand-by cylinder group (6 cylinders);
- gas compressor;
- piping, valves, instrumentation.

System technical characteristics are given in Table “Summary table technical data” in Appendix 1.

In the nozzle connecting the system to the reactor vessel, there is a DN25 restriction device intended to prevent primary circuit outflow in case of pipeline rupture.

Purification and cooldown system

The purification and cooldown system is intended to maintain the required quality of primary circuit water and to remove residual heat from the core to the third circuit water.

The system includes:

- primary-third circuit HX;
- primary circuit filter;
- two electrical cooldown pumps;
- piping, valves, instrumentation.

The system maintains the primary circuit water quality at power operation in accordance with the established requirements.

Fuel cycle

Ensuring maximum operation period between refuellings was an objective during development of the fuel cycle for the KLT-40S RP. Taking into account this factor, single loading has been accepted. The use of LEU fuel (initial uranium enrichment does not exceed 20%) has been employed to enhance proliferation resistance.

To provide maximum fuel burnup taking into account the accepted limitation on uranium enrichment (decrease of natural uranium inventory), the fuel lattice (water-uranium ratio) has been optimized.

Parameters of cermet fuel accepted for the KLT-40S RP allow core operation in the manoeuvre mode without limitation in customer requirements.

The main parameters of the KLT-40S RP are given in Table 2.

Table 2.

Parameter	Value
Reactor thermal power, MW	150
Fuel type	Cermet
Refuelling mode	Single loading with replacement of all FAs
Uranium inventory, kg	1273
Uranium-235 inventory, kg	179
Average uranium enrichment in the core, %	14.1
Fuel life at N_{rated}, eff.days	14 000
Operation period without refuelling, yr.	~ 2.3
Specific consumption of uranium-235, g ^{235}U/(MW·day)	2.05
Average fuel burnup fraction on oxide fuel basis, MW·day/kg U	45.4

3. Safety concept

The principal safety solutions for the FPU with the KLT-40S RP are discussed in References [3, 6, 7]. The objectives are:

- to apply a systematic approach integrating the experience and achievements in the safety of nuclear power plants and marine propulsion plants;

- to comply with the modern safety requirements and principles developed by the world nuclear community and established in IAEA Safety Standards and in Russian codes and standards applicable to nuclear engineering and shipbuilding.

The engineering solutions incorporated in the design correspond to worldwide trends followed by all state-of-the-art advanced nuclear power plants:

- priority to accident prevention measures and design simplification;

- inherent safety features;

- defence-in-depth principle;

- passive safety features;

- limitation of the consequences of severe accidents;

- better protection against external impacts, including terrorist attacks.

The KLT-40S RP was designed on the basis of proven engineering solutions:

- compact structure of the steam generating unit with short nozzles connecting the main equipment, without large-diameter primary circuit pipelines;

- proven reactor emergency shutdown actuators based on different operation principles:

  • fast-response emergency protection rods;

  • compensating groups.

- emergency heat removal systems connected to the primary and secondary circuits;

- elimination of weak design points based on the experience of prototype operation (improvement of the primary circuit pressurizer system and several SG units, etc.);

- use of available experimental data, certified computer codes and calculation procedures.

The passive safety solutions of KTL-40S RP include inherent safety features and 'external' passive safety systems.

RP inherent safety is expressed in its capability to prevent occurrence, restrain development, and mitigate consequences of the initiating events, which could lead to accidents, using, among all, natural feedbacks and processes with no operator intervention, power consumption or external help for a certain period of time which can be used by the personnel to evaluate the situation and to make necessary corrective actions.

RP inherent safety is provided by the following:

a) negative reactivity coefficient for fuel and coolant temperatures, specific volume of coolant, and negative steam and integral power coefficients of reactivity;

b) high thermal conductivity of the fuel composition determining its relatively low temperature and correspondingly low stored energy;

c) appropriate natural circulation flow in the primary system;

d) high RP heat storage capacity which is provided by the high heat capacity of primary coolant and metalworks, by the use of 'soft' pressurizer system, and design safety margin the for pressure in case of emergency pressure increase;

e) compact design of the steam generating unit with short nozzles between the main equipment, without large-diameter primary pipelines;

f) installation of flow restrictors in the nozzles connecting the primary circuit systems with the reactor in order to limit the coolant outflow rate, and selection of optimal positions of these nozzles such as to provide fast transition to the steam outflow of the primary coolant in case of break of the corresponding pipelines;

g) favourable conditions for realization of the "leak before break" concept for the structural elements of the primary circuit;

h) use of once-through SGs limiting the secondary circuit heat removal power the in case of steam pipeline break accident.

Both active and passive safety systems (Fig. 5) are provided as a part of RP to perform the following safety functions:

- reactor emergency shutdown;
- emergency heat removal from the primary circuit;
- emergency core cooling;
- radioactive products confinement.

Active safety systems

- system of reactor shutdown with insertion of compensating control rods by the electric drive;
- system of emergency cooldown through the SG with steam dump to the process condenser;
- system of emergency cooldown through the purification and cooldown system HX;
- system of emergency water supply from ECCS pumps and recirculation pumps;
- filtration system for releases from the protective enclosure.

Passive safety systems

- system of reactor shutdown with insertion of compensating control into the rods core by gravity and insertion of emergency protection rods by for force of accelerating springs when the locking electromagnets are de-energized;
- passive system of emergency cooldown through the SG;
- system of emergency water supply from hydraulic accumulators;
- containment and normally closed localizing valves in the primary circuit auxiliary systems and interfacing systems;
- passive reactor vessel cooldown system;
- passive self-actuating devices for actuation of safety systems;
- passive containment cooling system;
- containment.

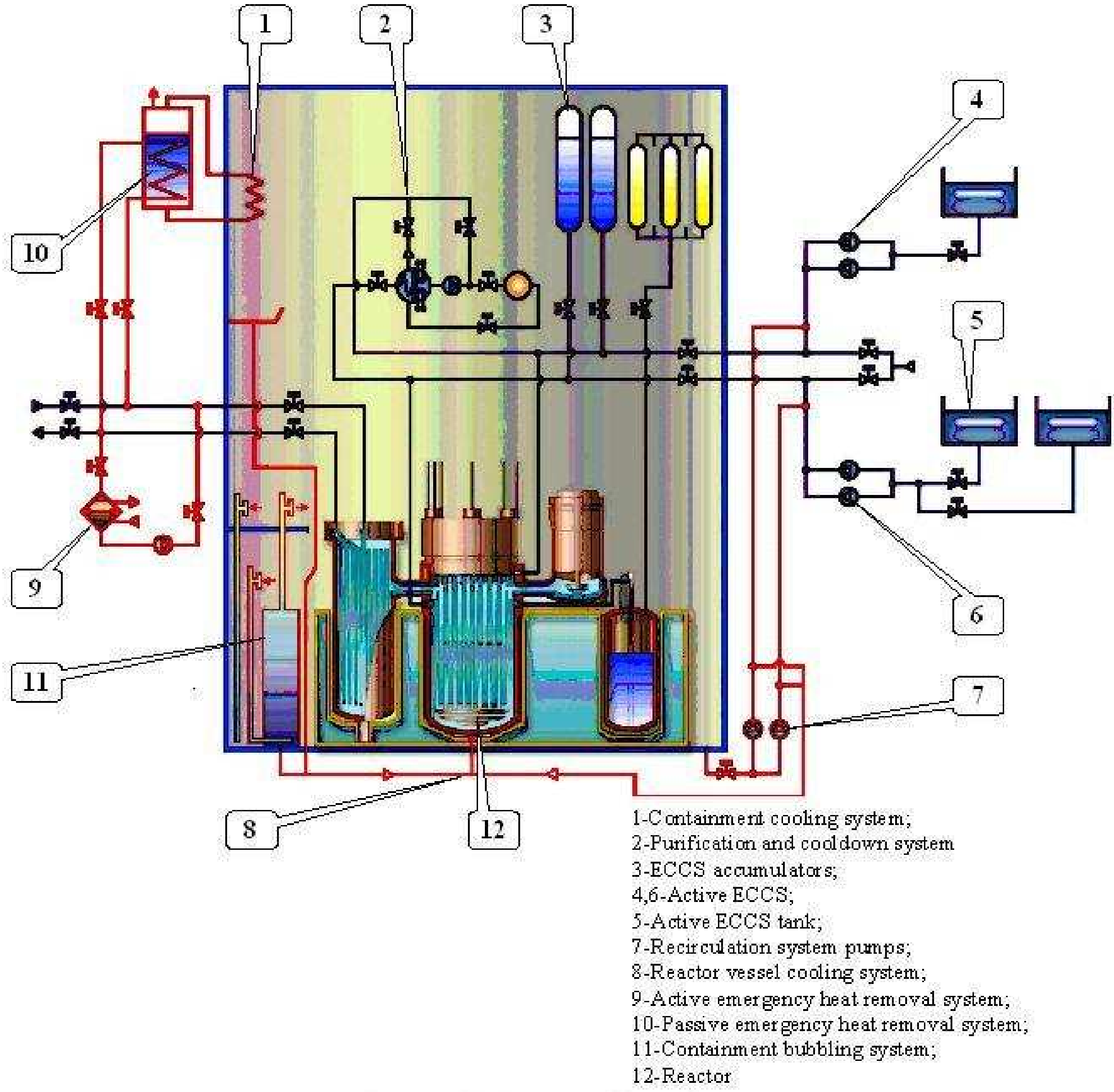


Fig.5. KLT-40S RP safety systems

Passive safety systems use natural coolant circulation and compressed gas energy.

The required functions of safety systems are provided taking into account external natural and man-caused impacts and internal impacts caused by the accident conditions. Functioning of safety systems is provided in case of potential failures such as single failure, common cause failure resulting from a single failure or impact, or personnel error.

Reliability of safety systems is provided through the systematic approach stipulating use of redundancy, independence (separation), and diversity principles, as well as the following measures:

- use of systems combining passive and active operation principles and elements corresponding to the safe failure principle in the maximum extent possible (i.e. elements which are put in the safety functioning mode in case of failures);

- automation of control, and actuation of safety functions by actuating safety systems from self-actuated devices (by the direct action of the medium);

- conservative approach in design of protection barriers, safety systems, selection of the range of initial events, accident development scenarios, selection of determining emergency parameters and characteristics, and design margins.

The majority of KLT-40S RP safety systems use a two-channel configuration with internal reservation of active elements such as valves and pumps. Use of the two-channel configuration of safety systems in particular conditions of a floating vessel (such as a necessity to minimize equipment size and weight, as opposed to ground-based nuclear power plants) permits to reduce the amount of bulky equipment such as tanks and HXs.

Structures, systems and equipment of FNPPs are developed taking into account natural and man-caused impacts typical of nuclear power plant location site and FPU towage routes and meet the requirements of OPB-88/97, the Sea Shipping Register of Russia and other regulations. FNPP safety is ensured under specified design-basis parameters of natural impacts on the FPU and RP occurring at a frequency of 10^{-2} 1/year, and impacts from operational-base and safe shutdown earthquakes occurring at a frequency of 10^{-2} 1/year and 10^{-4} 1/year respectively.

For the operation site of the PATES with KLT-40S RPs, the magnitude of the operational-base earthquake is estimated at 7 points, and that of the safe shutdown earthquake equals 8 points.

Equipment, machinery, safety-related systems and their attachment units withstand shock loads with acceleration not lower than 3 g in any direction, and maintain operability during heaving which is typical during FPU operation

Safety of the PATES with KLT-40S reactors is based on the defence-in-depth principle. This principle stipulates accident prevention and mitigation strategy, a system of physical barriers preventing propagation of ionizing radiation and radioactive materials into the environment, and a system of technical and organizational measures on protection of the barriers and retaining their effectiveness, as well as measures on protection of the personnel, population and environment.

There are several levels of technical and organizational measures under the defence-in-depth principle [6]:

Level 1 – Prevention of abnormal operation and failure.

Level 2 – Control of abnormal operation and detection of failure.

Level 3 – Control of accidents within the design basis.

Level 4 – Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe accidents.

Level 5 – Mitigation of radiological consequences of significant release of radioactive materials.

Inherent passive safety features and passive safety systems of the KLT-40S reactor that ensure the effectiveness of physical barriers for each defence-in-depth level are described below.

Level 1: Prevention of abnormal operation and failure

- negative reactivity coefficients for fuel and coolant temperature, coolant specific volume, and total power in the whole range of reactor parameters that make reactor self-control possible;

- high thermal conductivity of the fuel composition determining its relatively low temperature and correspondingly low stored energy;

- compact modular design of the steam generating unit with short co-axial nozzles between the main equipment, without long large-diameter primary pipelines, and with flow restrictors, which excludes the possibility of large and medium LOCAs;

- pressurized primary system with welded joints, glandless canned pumps and leak-tight bellow-type valves;

- possibility of realizing the “leak before break” concept for primary circuit elements;

- gas pressurizer system that excludes failures of the electric heaters;

- SG with lower tube-side pressure during normal operation that reduces the probability of inter-circuit leaks.

Level 2: Control of abnormal operation and detection of failure

- active systems of control, restriction, protection and diagnostics.

Level 3: Control of accidents within the design basis

- insertion of emergency protection rods into the core by the force of accelerating springs;

- insertion of compensating rods into the core by gravity;

- passive emergency heat removal system with natural coolant circulation in all circuits and evaporation of the water stored in the tanks;

- sufficient level of natural circulation flow in the primary circuit to cool the reactor core in case of MCP switch off;

- restriction of unauthorized control rods movement by the overrunning clutch under the influence of impact loads and control rod drive mechanism casing rupture; motion restraints used in case of control and protection system standpipe rupture;

- self-actuating devices in emergency reactor shutdown system and ECCS;

- once-through SGs limiting secondary circuit heat removal power the in case of steam pipeline rupture;

- high RP heat storage capacity which is provided by the high heat capacity of primary coolant and metalworks, by the use of “soft” pressurizer system, and design pressure margins;

- flow restrictors in the pipelines of primary circuit systems and connection of these systems to the hot leg of the reactor.

Level 4: Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe accidents

- ECCS accumulators that provide a time margin for accident control in case of active ECCS systems failure;

- passive reactor vessel bottom cooling system that ensures retention of the molten corium inside the reactor vessel;

- passive containment cooling system to decrease containment pressure and to limit release of the radioactivity;

- protective enclosure.

Level 5: Mitigation of radiological consequences of significant release of radioactive materials

- Mitigation of radiological consequences of significant release of radioactive materials is ensured mainly through organizational measures.

The design utilizes the systematic approach to safety analysis and validation. This approach combines the deterministic and the probability methods.

Besides design basis accidents, the design analyses a wide range of severe accidents where initiating events are coupled with additional safety system failures and/or personnel errors.

Severe accidents include:

- complete power plant de-energization with safety actuation system failures;

- primary pipeline rupture coupled with complete de-energization or core cooldown failures;

- transient processes with safety actuation system failures.

In severe LOCAs with failure of all ECCS pumps, the core remains flooded during at least 1.5 hours.

A first-level probabilistic safety analysis (PSA) has been performed for the PATES based on the FPU with the KLT-40S RPs.

Probabilistic safety targets adopted in the PSA for the PATES based on the FPU with the KLT-40S RPs were according to the top level Russian regulatory document NP-022-2000 and included the probability of core damage and probability of large emergency radioactive release.

According to NP-022-2000, the target is to ensure that PSA-estimated cumulative probability of core damage does not exceed 10^{-5} per reactor-year and probability of large emergency radioactive release does not exceed 10^{-7} per reactor-year.

According to the PSA, the point estimate of the resulting core damage probability for the KLT-40S RP in case of internal initiating events does not exceed 1.0E-7 per reactor-year for the internal initiating events for full power operating conditions. Analysis of the uncertainty of RP probabilistic safety parameters was performed by the method of statistical testing (Monte-Carlo method) and showed that the upper confidence bound (95% quantile) of the core damage rate is not higher than 10^{-6} per reactor-year.

Low probability of severe accidents with core damage is conditioned by the internal safety and design features of the modular reactor design, and also by the redundancy and diversity of safety systems, application of both active and passive safety systems, and use of reliable safety-related equipment that has been proven by long operation of prototypes.

However, the design does analyse accidents with severe damage (meltdown) of the core.

Analysis of the most probable scenarios of severe accidents, as well as the PSA, shows that the most critical scenario from the viewpoint of core damage is the one which is accompanied by the failure of standard ECCS channels resulting from the failure of active elements (ECCS pumps or connecting valves of the same type).

For this situation, the design stipulates water supply into the reactor via primary circuit purification system pipelines using steam turbine plant pumps.

Measures on **mitigation of severe accident consequences** include measures on limitation of core damage scale, measures on molten corium retention inside the reactor vessel, and measures on mitigation of radiological consequences.

Measures on limitation of core damage scale

The KLT-40S core damage process is relatively slow due to supply of water from the ECCS accumulator that cools overheated and partially degraded core elements. Successful implementation of measures assuring water supply into reactor at this stage of accident will ensure flooding and cooldown of core materials, prevent formation of molten pool at the reactor bottom and attack of molten corium on the reactor vessel.

Measures on molten corium retention inside the vessel

In order to ensure retention of the molten corium inside the reactor vessel, the design provides for a special external reactor vessel cooling system for accidents with core melting and relocation of the melt to the vessel bottom.

Retention of the molten corium inside the vessel allows ruling out all negative phenomena connected with molten corium egress into the containment.

Measures on mitigation of radiological consequences

In order to exclude personnel and population overexposure in severe accidents, the following complex of protective measures should be performed:

1. To ensure personnel safety, it is necessary to avoid personnel presence in compartments adjoining to the containment and in other compartments with high radiation levels.

2. To limit the exposure for population living within a radius of 1 km from the PATES, it is possible (depending on actual radiation situation) that some protective measures will have to be taken: shelter, iodine prophylaxis. One of protective measures is temporary limitation on consumption of contaminated agricultural products grown within a radius of 5 km from the PATES.

Evacuation is not needed at any distance from the PATES.

4. Proliferation resistance

Proliferation resistance of floating nuclear cogeneration plant designs is achieved, first of all, owing to the inherent properties of RPs and FPUs, which underlie the design concepts and are implemented through the corresponding technical solutions and organizational measures.

Such solutions include:

- lower than 20% enrichment of the fuel, as well as its chemical form (ceramics dispersed in the inert matrix), makes it unattractive for production of mass destruction weapons;
- neither fresh, nor spent fuel is stored on the coastal facilities outside the FPU.

Operation of floating nuclear cogeneration plants in other countries is planned on conditions “build–own-operate”, which means that the FPU will be under jurisdiction of the Russian Federation all the time and will be serviced by Russian personnel only.

In this case, external non-proliferation measures, apart from existing political obligations of IAEA member countries, will include negotiation of an appropriate agreement between the

Russian Federation and the importing country, which will deal with inviolability of the FPU and its external physical protection and guarantees of services not related to ownership rights for the FPUs and reactor plants, and also performance of IAEA checks within the framework of the system of guarantees.

Refuelling is performed on site, inside the FPU; spent fuel is unloaded into the temporary storage and then the FPU is transported to the supplier country where the spent fuel is unloaded from the temporary storage and the reactor is refuelled and repaired.

Enhancement of proliferation resistance when handling spent fuel from the PATES with the KLT-40S RP in Russia is achieved through:

- reactor refuelling only in special maintenance centres;

- use of the standard fuel cycle of nuclear icebreaker reactors with available infrastructure and mechanisms of protection against proliferation.

5. Physical protection

Plant physical protection system includes the following technical measures:

- security alarms, TV observation system, and operational communications;
- access control system;
- engineered security features;
- organizational measures.

The physical protection system is zoned. For FNPP there are two zones: the zone of water area (bound by breakwaters and dams) and coastal service area, and the zone of FPU which is highly controlled.

6. Turbine-generator set

The steam turbine plant converts the heat power of the steam generated in the RP into the electric power and heat power for heating water in the intermediate circuit of the cogeneration system.

The FPU has two independent steam turbine plants, one for each RP. Main rated characteristics of steam turbine plants are given in the Table of Appendix 1.

Each steam turbine plant consists of the following main equipment:

- turbine set;
- main ejector and seal exhaust system ejector;
- two double-speed circulation pumps (each of 60% capacity);
- three electric feed pumps with variable-speed electric drives (each of 60% capacity);
- one distribution feed pump;
- two fresh water circulation electric pumps for the generator cooldown system;
- deaerator and equalizing tank;
- four ion-exchange and two duplex mechanical filters;
- one condensation removal pump;
- regenerative feed water heaters (PND No.1 and double-case PVD No.2 and PVD No.3);
- two main heaters (each of 50% capacity) and one peaking intermediate water heater;
- air cooler for the vented steam from main ejectors, seal ejectors, and deaerators;
- steam and condensate-feed systems;
- turbine set oil supply system;
- seawater cooling system;
- intermediate circuit system.

For RP hot water and cooling tubes, there are technological condensation plants located in reactor compartment rooms.

District heating is provided by heating the intermediate circuit water, which circulates between the FPU and the coastal facilities, by the steam extracted from the turbines. The intermediate circuit water is heated from 70 to 130ºC in the heaters located in turbine halls.

The following systems are shared by both steam turbine plants:

- turbine oil intake, transfer, distribution and separation system;

- feed water intake and transfer system.

The turbine set works inside the steam turbine plant which converts the heat power of the steam generated in the RP into the electric power and heat power for heating water in the intermediate circuit of the cogeneration system.

The turbine set consists of the following main equipment:

- steam turbine with release system, turning gear, steam distribution, stop valves, control and protection system;
- electric generator;
- surface double-circuit condenser with expansion tank, hot well, and safety diaphragm;
- three main electrical condensate pumps (each of 60% capacity);
- two coolers of fresh water of generator cooling system;
- piping and valves;
- level controller for the condenser;
- level controller for seals;
- maintenance platforms and turbine set framework.

Steam condensing system

The steam condensing cycle was designed with the main emphasis on increasing cycle efficiency as compared with the cycles of marine propulsion RPs:

- use of an advanced system of regenerative feed water heating (in low-pressure heaters, deaerator and high-pressure heaters) which provides a 170°C temperature at the inlet to RP SGs;
- power for FPU house loads is taken directly from main generators;
- use of electric drives for all main steam turbine plant pumps (condensate, circulation and feed pumps);
- removal of high-temperature condensate directly into the deaerator.

7. Power output system and house loads power supply

The FPU electrical power system consists of the system generating and supplying power to the coastal power grid, house loads power supply system, and reserve power supply system.

The system generating and supplying power to the coastal power grid includes:

- three-phase alternating current generator with switchboards of the feed and control systems;
- main switchgear;
- transformers (including standby ones);
- power output switchboard.

The house loads power supply system includes:

- standby diesel generators;
- main switchboards;
- transformers.

All power consumers installed on the FPU, depending on their functions and importance for safety, are referred to one of four power supply reliability groups.

To supply power to consumers of groups I and II, there is and independent two-channel emergency power supply system consisting of:

- emergency diesel generators;
- emergency diesel generator switchboards;
- RP switchboards and feeder switchboards for automated systems;
- uninterrupted power supply units;
- transformers.

8. Spent fuel and radwaste management

Fuel utilization efficiency is provided by the following engineering solutions:

- use of all improvements of nuclear fuel and fuel cycles of nuclear icebreaker reactors; spent fuel reprocessing;
- increase of fuel burnup through the use of dispersion FEs.

Wide application of FNPPs with KLT-type reactors presupposes use of the closed fuel cycle providing for radiochemical processing of spent fuel.

At present, the spent fuel from nuclear icebreaker RPs, which are prototypes of RPs for small-size FNPPs, is currently reprocessed at an existing factory. It is planned to update the existing dispersion fuel processing line to add the cermet fuel processing capability.

The minimum amount of radwaste generated by the KLT-40S reactor is provided by:

- pressurized primary circuit which is standard for marine propulsion RPs;
- closed primary coolant purification system;
- waste-free coolant handling technologies;
- modern low-waste radwaste reprocessing technologies;
- refuelling is performed in special maintenance centres.

9. Plant layout

The RPs and turbine-generator sets are located on the FPU. The FPU is a towed flush-decked berth-connected vessel with a developed multi-tiered superstructure (Fig. 6). In the midship of the FPU there is the reactor compartment. The turbine-generator and electric equipment compartments are located to the bow from the reactor compartment, and the auxiliary equipment compartment and living block are located to the stern.

This layout ensures the required safety conditions and allows optimal layout of pipelines and electric cables.

The FPU hull is all-welded, fitted with ice reinforcements and special fixtures for towing and fixing. The hull is divided into watertight compartments by watertight bulkheads reaching the upper deck.

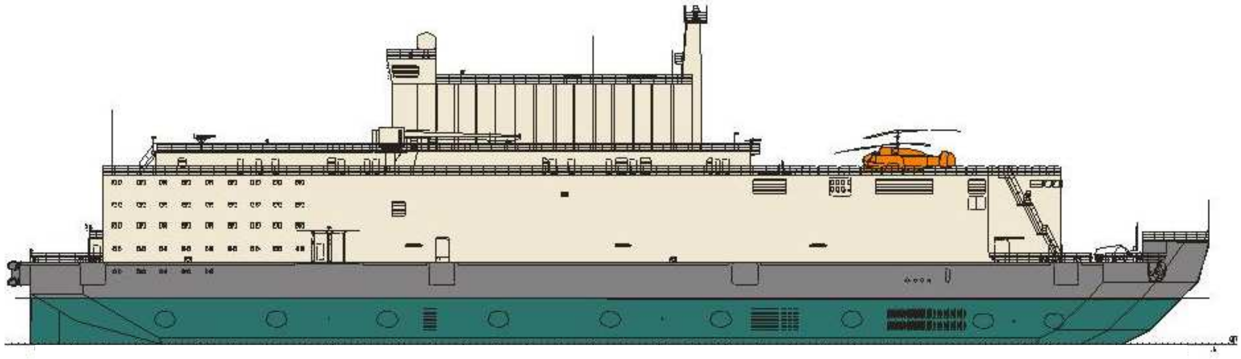


Fig. 6. The FPU

FPU floodability is ensured when any two adjoining compartments are flooded an all specified load modes and in compliance with the Sea Shipping Register of Russia.

Reactor compartment

The RP is installed in the reactor compartment located in the midship of the FPU.

Each RP has its own steel leak-tight protective shell. The reactor compartment is guarded on the outside by the protective enclosure consisting of multi-layer ceilings of the superstructure roof, machine room bulkheads, and superstructure side rooms.

All these structures constitute the external protective barrier of the reactor compartment, which is capable of withstanding external physical impacts, including aircraft crash on the FPU.

Turbine compartment

The FNPP has an autonomous machine room housing the turbine-generator set with auxiliary servicing systems, and the power unit. The machine room is located to the bow from the reactor compartment and is separated by the transverse bulkheads of the reactor compartment protective enclosure.

General layout

Normal operation of the FNPP requires a certain arrangement of water space and coastal infrastructure. The coastal infrastructure includes:

- hydraulic engineering structures (jetties, beacons, boom barriers, etc.);

- waterfront structure (sea-walls, piers, etc.);

- transmission pylons intended for transport of generated electricity to the consumers;

- coastal structures.

Hydraulic engineering structures are intended for FPU safe offshore location and fixing. Technical communication with the coast is carried out using the berthing facilities. Support and maintenance vessels can approach and moor alongside the FPU. The coastal infrastructure and special devices are intended for transfer of electricity and heat from the FPU to the consumers.

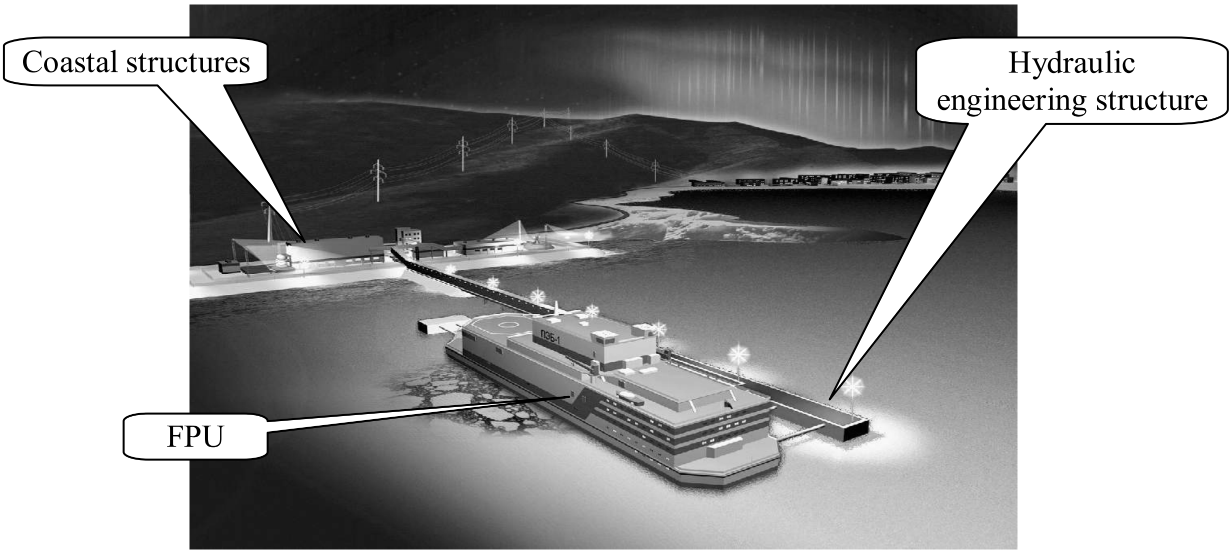


Fig. 7. General view of PATES based on the FPU of 20870 design

10. Efficiency and performance

The efficiency of the FNPP with KLT-40S RPs is determined by the following factors [2, 5]:

- the RP is based on the commercially produced marine propulsion RP of KLT-40 type and offers high reliability and guaranteed safety, which was demonstrated by failure-free operation of similar RP designs during about 300 reactor-years

- FNPPs can be serially manufactured in shipyards and then delivered to the customer fully assembled, tested and ready for operation;

- compact modular layout of the RP and, accordingly, minimum size of the containment;

- minimum scope and cost of capital construction work needed to prepare the FNPP operation site and the water area;

- no need to create transportation links, power transmission lines, or preparatory infrastructure required for ground-based nuclear power plants;

- high degree of freedom in selecting the location for a FNPP as it can be moored in any coastal region;

- considerable reduction of construction period (4 years);

- availability of the entire nuclear vessels servicing and maintenance infrastructure in Russia will permit to minimize costs for FNPP maintenance and refuelling;

- FPU disposal at a specialized factory;

- FNPPs with expired service life can be replaced with new ones;

- possibility of RP operation in manoeuvre modes without limiting consumer requirements;

- FPUs can be used as part of desalination complexes.

Fuel utilization efficiency and reduction of natural uranium consumption is provided by the following engineering solutions:

- use of all improvements of nuclear fuel and fuel cycles of nuclear icebreaker reactors; spent fuel reprocessing;

- increase of fuel burnup through the use of dispersion FEs.

Main technical and economic parameters of the PATES based on the FPU of 20870 design with KLT-40S RPs are given in Table 3.

Table 3. Main technical and economic parameters, as predicted by the developers, of the PATES

Index	Value
FPU displacement, t	21 500
Rated electric output, MW	2×30
FOAK plant delivery term, years	4
Plant service life, years	40
Plant availability target	0.85
Number of Operation Personnel	58
Specific capital investments for construction, $/kWe	3500 …4000
cost of generated electric power (condensation mode), ¢/kW·hr	~5.0
Net cost of heat power, $/Gcal	~20

11. Development status of technologies used for the plant Technologies used for KLT-40S RP development and their current status are given in the Table below.

Reactor technology	Status
Modular PWRs for Russian nuclear vessels	Widely used reactor technology, operation experience of marine multi-purpose reactors exceeds 6500 reactor-years
Icebreaker type KLT-40S reactor for the FOAK FNPP	The RP and FPU designed were developed; FPU construction license was obtained from the regulatory authority (RF GAN); fabrication of RP and steam-turbine plant equipment is under way
Nuclear shipbuilding technology	The total of 11 nuclear vessels was constructed (icebreakers, one lighter carrier), FPU construction is in progress
Reactor of the nuclear cogeneration plant (AST-500) regarding safety ensuring approaches and solutions	Under construction; IAEA review was performed [11]

Main engineering solutions of the KLT-40S RP are as follows:

- modular layout of the main equipment (reactor, steam generator, MCPs); coaxial cross-nozzles of the main primary coolant circulation path;

- pressurized primary circuit;

- once-through coiled modular SGs;

- cassette core with cermet fuel (uranium oxide in the silumin matrix); enrichment does not exceed 20%;

- passive safety systems;

- use of existing metallurgical, press forging and machine-assembly technologies available at the manufacturers of nuclear icebreaker power plants;

- use of existing equipment mounting, repair and replacement technologies and systems and means of equipment diagnosis and monitoring;

- minimum impact on personnel, population and the environment; consequences of any accidents are minor, which is confirmed by the long operation experience of nuclear icebreakers.

The **basic** KLT-40S RP production **technologies** mastered on the commercial scale are as follows:

- technology of main equipment fabrication and vessel system welding;

- technology of SG tubing manufacture of titanium alloys;

- technology of manufacturing and assembling the in-vessel coaxial elements that provide coolant circulation;

- canned MCPs fabrication technology;

- dispersed FE and FA fabrication technology;

- technology of structural materials providing FE corrosion and radiation resistance during operation;

- technology of fabrication of normal operation system and safety system elements (self-actuated devices, pressurizer, tanks, HXs, pumps, filters);

- nuclear ship building technologies.

Potential application of the above technologies:

- manufacture of RPs for ground-based nuclear power plants of small-size (with KLT-40S RP) and medium size (such as VBER-300);

- establishment of nuclear power-generation and desalination complexes;

- application of KLT-40S RP as a source of process steam;

- development of FNPPs that do not require refuelling on the operation site [9].

12. Design status and planned schedule

The design of the PATES based on the FPU of 20870 design with KLT-40S RP is being developed by Russian organizations and enterprises having a unique experience in designing, building and operating nuclear reactors for the Navy and civil fleet.

Main participants of the ATES-MM project

Company	Responsibility area
JSC "Afrikantov OKB Mechanical Engineering" (OKBM), Nizhny Novgorod	Chief designer of the RP, packaged supplier of the RP
RRC "Kurchatov Institute", Moscow	Scientific supervisor of the RP design
JSC "TsKB "Iceberg", Saint Petersburg	General designer of the FPU
Krylov Shipbuilding Research Institute	Scientific supervisor of the FPU design
JSC "Atomenergo"	Designer of coastal and hydraulic engineering facilities
United Shipbuilding Corporation, "Baltiysky Zavod", Saint Petersburg	FPU builder
Rosatom, JSC "Energoatom Concern", Directorate of FNPPs under Construction	Project customer and investor
JSC "Kalouzhsky Turbine Plant"	General designer and supplier of the turbine set

The design of a PATES based on the FPU with KLT-40S RPs was developed in accordance with State Atomic Energy Corporation ROSATOM long-term activity program (2009 -2015).

Construction of the FPU and equipment fabrication has been under way since 2007. Initially, FPU construction started in the shipyard of "Sevmash" plant in Severodvinsk. However, since "Sevmash" was overloaded with other projects, FPU construction was handed over to "Baltiysky Zavod". "Baltiysky Zavod" (Saint Petersburg) is a member of the United Shipbuilding Corporation and specializes in building Navy vessels, large-capacity civil cargo vessels, and icebreakers (powered by nuclear or diesel plants).

The contract between "Baltiysky Zavod" and JSC "Energoatom Concern" was signed on 27 February 2009 and renewed on 7 December 2012. The contract includes construction, launching, fitting-out, testing and commissioning of a FPU of 20870 design for the PATES with KLT-40S RPs.

In accordance with the contract, the FPU is to be ready for transportation in 2016. After integrated testing inside the PATES, the FPU will be commissioned to the "Energoatom" Concern at the operation site.

At present, fabrication of main equipment for the PATES reactor and turbine-generator sets is completed.

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Abbreviations

ATES-MM	- small-size floating nuclear cogeneration plant
BPR	- burnable poison rod
ECCS	- emergency core cooldown system
FA	- fuel assembly
FE	- fuel element
FNPP	- floating nuclear power plant
FOAK	- first of a kind
FPU	- floating power unit
HX	- heat exchanger
LOCA	- loss of coolant accident

LWR	- light water reactor
MCP	- main circulation pump
NOAK	- n-th of a kind
OKBM	- JSC “Afrikantov OKB Mechanical Engineering”
OPB	- “General provisions on nuclear power plants safety”
PSA	- probabilistic safety analysis
PWR	- pressurized water reactor
R&D	- research and development
RP	- reactor plant
SG	- steam generator

Appendix 1

Summary Table Technical Data of KLT-40S RP

Parameter	Value	Dimension
General plant data		
Reactor thermal output	2×150	MW(th)
Power plant output, gross	2×35	MW(e)
Power plant output, net	2×30	MW(e)
Power plant efficiency, net	23.3*	%
Mode of operation	Load follow	
Plant design life	40	Years
Plant availability	85	%
Operating base earthquake (safe shutdown earthquake) PGA, g	OBE-7 (SSE-8); maximum acceleration 3 g	
Primary coolant material	light water	
Intermediate coolant material, if applicable	-	
Moderator material, if applicable	light water	
Type of cycle	Indirect core cooldown	
Thermodynamic cycle	Rankine steam condensing cycle	
Non-electric applications:		
- Potable water	20000-100000**	m^3/hour
- Process steam	-	
- Heat (for district heating or process)	2×73 (max)	Gcal/hr
- Hydrogen (or other advanced energy carrier)	-	
- Other	-	
Safety goals		
Core damage frequency	10^{-6}	/reactor-year
Large early release frequency	10^{-7}	/reactor-year
Occupational radiation exposure	~1,0	Person-mSv/reactor-year
Operator action time (Grace period)	1.5	hr
Economic goals		
Mode of deployment	Distributed	
Levelized unit electricity cost for NOAK plant	4.5-5 (as of 2006)	¢/kW·hr
Levelized unit cost of a non-electrical product for		

NOAK plant		
- Heat	20-22	$/ Gcal
- Potable water	0.8-0.9	$/m^3
Reactor core		
Fuel column height	1.2	m
Equivalent core diameter	1/155	m
Average linear heat rate	14.0	kW/m
Average fuel power density	117.8	kW/kgU
Average core power density	119.3	MW/m^3
Fuel material	UO_2 in inert matrix	
FE type	Smooth-rod, cylindrical	
Cladding material	Zirconium alloy	
FE outer diameter	6.8	mm
Lattice geometry	triangular	
Number of FE in FA	69; 72; 75	
Number of FA	121	
Enrichment of reloaded fuel in equilibrium core	13; 15.7***	Weight %
Fuel cycle length	28	Months
Average discharge burn-up of fuel	45.4****	MW·d/kg
Burnable absorber (mode of use/material)	gadolinium; 46.3	kg
Mode of reactivity control	Control rods	
Mode of reactor shut down	Control rods	
Control rod absorber material	Dysprosium titanate, boron carbide	
Soluble neutron absorber	Cadmium nitrate	
Primary coolant system		
Primary coolant flow rate	761	kg/s
Reactor operating pressure	12.7	MPa
Core coolant inlet temperature	280	°C
Core coolant outlet temperature	316	°C
Intermediate coolant system	-	
Power conversion system		
Working medium	water, water steam	
Working medium flow rate at nominal conditions	67	kg/s
Working medium pressure/temperature (SG outlet)	3.82/290	MPa/°C

Working medium supply flow rate at nominal conditions	67	kg/s
Working medium supply temperature	170	°C
Reactor vessel		
Inner diameter of cylindrical shell	1920	mm
Wall thickness of cylindrical shell	128	mm
Total height, inside	3892	mm
Base material	Steel 15Cr2NiMoVA-A	
Design pressure/temperature	16.2/350	MPa/°C
Transport weight	70.5	t
Guard vessel	-	
SG or HX of the power circuit		
Type	Vertical, coiled, once-through	
Number	4	
Mode of operation	Secondary coolant on the tube side, primary coolant on the shell side	
Total tube surface area	284	m^2
Number of HX tubes	100	
Tube outside diameter	22	mm
Tube material	Titanium alloy	
Transport weight	23	t
Intermediate HX	-	
Primary circulation system		
Circulation type	Forced	
Pump type	Canned, centrifugal, single-stage, vertical, double-speed	
Number of pumps	4	
Pump speed		rpm
- large pump speed	50	s^{-1}
- small pump speed	16.7	s^{-1}
Head at rated conditions	38	m
Flow at rated conditions	870	m^3/h
Intermediate circulation system	-	
Circulation system of the power circuit		
Circulation type	Forced	

Pump type	Condensate and feed electric pumps	
Number of pumps	3 condensate pumps; 3 feed pumps	
Pump speed		rpm
- condensate pump	2970	
- feed pump	1200-3000	
Head at rated conditions		m
- condensate pump	110	
- feed pump	750	
Flow at rated conditions		m^3/h
- condensate pump	150	
- feed pump	150	
Pressurizer		
Type	External, gas-operated, with gas cylinders	
Total volume	8.16	m^3
Working medium volume: full power/zero power	6.03/6.1	m^3
Active devices used	No	
Primary containment		
Type	Steel	
Overall form (spherical/cylindrical)	Rectangular parallelepiped	
Dimensions (diameter/height)	12×7.92×12	m
Design pressure/temperature	0.5/200	MPa/°C
Design leakage rate	1.0	Volume %/ day
Secondary containment		
Type	System of compartments	
Overall shape	Rectangular	
Dimensions	15 000	m^3
Design pressure/temperature	-	
Design leakage rate	Waterproofness and leak-tightness according to the Sea Shipping Register of Russia	
Equipment and systems located in the space between the primary and the secondary containment	-	
Residual heat removal systems		
- Active heat removal through the purification and	1 channel with equipment	

cooldown system	redundancy	
- Active heat removal through the process condenser	1 channel with equipment redundancy	
- Passive heat removal through ECCS HXs	2 channels	
Safety injection systems		
- Active system for water supply from makeup pumps (2 channels)		
- Active system for water supply from recirculation pumps (2 channels)		
- Passive system for water supply from hydraulic accumulators (2 channels)		
Turbines		
Type of turbines	Steam, condensing-extraction	
Number of turbines	2	
Number of turbine sections per unit (e.g. HP/MP/LP)	2	
Turbine speed	3000	rpm
HP turbine inlet pressure/temperature	3.43/285	MPa/°C
Generators		
Type	Three-phase	
Number	2 (on FPU)	
Rated power	43.75	MVA
Active power	35	MW
Voltage	10.5	kV
Frequency	50	Hz
Total generator mass including exciter	80	t
Condensers		
Type	Surface, double-circuit	
Condenser pressure	5	kPa
Compressors	-	
Plant configuration and layout		
Plant configuration options	Floating, two RPs on a barge	
Surface area of the plant site		
- area of water	15 000	m^2
- coast territory	8000	m^2
Elevation or underground embedding of the nuclear	Floating	

island	
Core catcher	None. The molten corium is to be contained inside the reactor vessel owing to external cooling of the vessel bottom
Protection against aircraft crash	Collision protection against helicopter crash (type Ka-32s, mass 11 t, crash speed 15 m/s) owing to thicker plating and floors, and stiffness ribs. Protection against aeroplane crash is ensured by organizational measures
Protection against flooding	Not required
Features for protection against collision with other ships	To mitigate collision consequences, and in accordance with the requirements of RF Rules for Nuclear Vessels, the FPU is fitted with anti-collision protection means. The anti-collision protection was developed based on the nuclear ice-breaker design experience and has the following features which improve its capacity. In the areas of RP anti-collision protection, the existing floors are reinforced by thicker plating sheets and deck plating and longitudinal framing with larger cross-sections. Board plating thickness is increased from 18 to 22-30 mm, longitudinal stiffness ribs of the board are reinforced, thickness of upper deck plating near the board is increased from 8 to 22 mm, thickness of the first-tier superstructure deck plating near the board is increased from 10 to 30 mm, longitudinal stiffness ribs of the first-tier superstructure deck near the board are reinforced. The design takes into account the following navigational accidents: - docking impact; - collision with other vessels during towage; - stranding during towage.
Features for protection against tsunamis	Ensured by siting the FNPP in protected water areas (bays, river mouths) and building appropriate protective structures (breakwaters,

	dams, etc.)
Notes: * in the mode of maximum electric output ** when used in a desalination complex (FPU+desalination unit) *** for FOAK cores (for NOAK cores, enrichment does not exceed 19.75%) **** on oxide fuel basis	