PROSPECTS FOR THE UTILIZATION OF SMALL NUCLEAR PLANTS FOR CIVIL SHIPS, FLOATING HEAT & POWER STATIONS AND POWER SEAWATER DESALINATION COMPLEXES

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Abstract

Small power nuclear reactor plants developed by OKB Mechanical Engineering are widely used as propulsion plants in various civil ships. Russia is the sole country in the world that possesses a powerful ice-breaker and transport fleet which offers effective solution for vital socio-economic tasks of Russia's northern regions by maintaining a year-round navigation along the Arctic sea route. In the future, intensification of freighting volumes is expected in Arctic seas and at estuaries of northern rivers. Therefore, further replenishment of nuclear-powered fleet is needed by new generation ice-breakers equipped with advanced reactor plants. Adopted progressive design and technology solutions, reliable equipment and safety systems being continuously perfected on the basis of multiyear operation experience feedback, addressing updated safety codes and achievement of science and technology, allow the advanced propulsion reactor plants of this type to be recommended as energy sources for floating heat and power co-generation stations and power-sea water desalination complexes.

1. EXPERIENCE AND PROSPECTS OF SMALL REACTOR PLANTS UTILIZATION FOR CIVIL SHIPS IN RUSSIA

In the history of the Russian Arctic regions exploration and development this year (1999) is notable by three remarkable anniversaries, viz.: a century of the Russia's ice-breaker fleet, 60th anniversary of Murmansk shipping company — ice-breakers operator and 40th anniversary of civil nuclear-powered fleet, which history originated with the first nuclear ice-breaker "Lenin".

Prospects of economic activity development in regions adjoining the Russia's Arctic seas coast seem to be problematic without the intensive use of nuclear-powered ice-breaker/cargo fleet, that proved for a short time its indisputable advantages compared to other type (conventional) ice-breakers. Due to the use of nuclear-powered ice-breakers a cargo traffic volume was increased along the Arctic sea route, so that it in a factor of about 10 exceeds a traffic volume in the remainder (foreign) part of Arctic. In future, as projects of abundant Arctic oil and natural gas fields development would be realized and cargo flows increase between Europe and Asia, a freight traffic will build-up (see Fig. 1) and consequently a role of nuclear-powered fleet will respectively become more vital. Due to this reason a challenge exists for the coming years to preserve the existing potential of nuclear-powered ice-breaker fleet and then to develop it further.

The nearest task in this field is to extend lifetime of the propulsion reactor plants, that would permit to continue the nuclear ice-breakers operations in the Arctic seas and to obtain a time reserve needed for design and construction of new generation nuclear ice-breakers. These are, first of all, ice-breakers for shallow areas of Arctic coast and Siberian river estuaries, and capital ice-breakers for year-round running of cargo ships along traditional ways of the Arctic route.

The Russia's civil nuclear-powered fleet currently consists of seven nuclear ice-breakers and one cargo (lighter carrier) ship. The ice-breaker "Lenin" is already removed from operation. The nuclear-powered ships and their reactor plants main performance indicators over the period from 1970 till 1998 are summarized in Table 1.

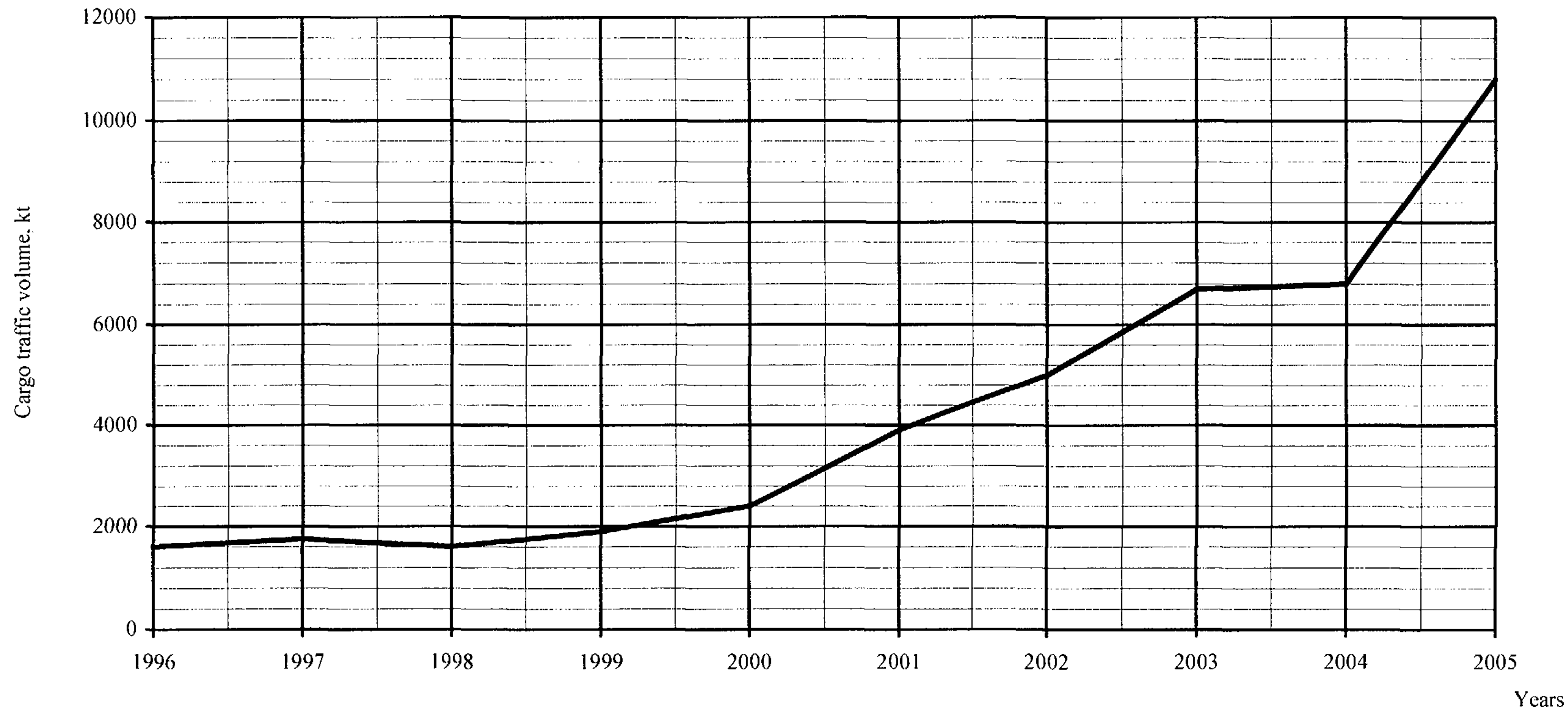


Fig. 1. Cargo traffic volume variation with time at Arctic sea route.

TABLE 1. NUCLEAR-POWERED SHIPS PERFORMANCE INDICATORS OVER THE PERIOD FROM 1970 TO 1999

Characteristics	Name of ship								
	i.-br. "Lenin"	i.-br. "Arctica"	i.-br. "Sibir"	i.-br. "Russia"	i.-br. "Sov. Souz"	i.-br. "Taymir"	i.-br. "Vaygach"	i.-br. "Yamal"	l.-cr. "Sev-morput"	i.-br. "50th celebration of Victory"
1. Year of commissioning	1970	1975	1977	1985	1989	1989	1990	1992	1988	under construction
2. Averaged duration of operation per year, days	230	235	232	208	273	300	288	298	275	
3. Total reactor operating record from power startup, h	106736 / 106384	131669 / 132321	94785 / 94043	66779 / 66118	58958 / 58522	62164	56311	35704 / 35081	68210	
4. Total energy produced from power start-up, $\times 10^3$ MWt·h	6523 / 6398	8680 / 7978	6095 / 6934	4630 / 4894	3899 / 3875	4918	4811	2062 / 2601	3744	
5. Distance sailed, miles 1) total;	654400	878599	740786	424311	351743	335919	258053	229819	258107	
2) incl. through ice	560600	773203	472787	391182	301159	330817	232363	204648	88234	
6. Number of ships conducted	3700	2913	1711	1212	501	984	680	572	–	

i.-br. — ice-breaker
l.-cr. — lighter-carrier

The total operating record of the reactors exceeds 160 reactor-years, while that for individual equipment items in some operating reactors exceeds 130 thou h and continues to increase further. During that period no incidents involving chain reaction control violation or inadmissible release of radioactivity were identified [1].

During the entire reactor plants lifetime designers of systems and equipment carried out supervision for their operation. Every event of failure or deviation from normal operating conditions was thoroughly analyzed. Simultaneously, new technical solutions are tested and plants operation modes are optimized. Resulting from the consistent conduction of planned activity on perfection of equipment and systems, and optimization of operating modes a specified useful lifetime of the plant's key equipment has been increased from 25-30 thou h up to 100–150 thou h.

A great complex of work is currently being performed that is associated with examination of equipment and piping of nuclear ice-breaker "Lenin", that have already exhausted its specified life. Results of the comprehensive study will allow a justified decision to be made about further extension of the reactor plants lifetime, eventually up to the ship service life value. Considerable organizational efforts are currently applied by design and operating enterprises to attain this goal.

Multiyear data of laboratory monitoring of snow, soil and vegetation samples around areas where the nuclear ships are stationed at does not reveal their environmental effect. Mean-annular exposure dose to personnel does not exceed 0.5 rem.

Level of safety and environmental cleanliness of last modification propulsion reactor plants meets all the requirements imposed by effective domestic and international safety guides, eliminates any restrictions on their deployment areas. Commercial cruises of the nuclear ice-breakers with foreign tourists on board to the North Pole corroborate a sufficiently wide recognition of the ships safety and reliability.

Furthermore, Russian design organizations basing on the solid accumulated experience, proceed to develop prospective reactor plants for future nuclear ice-breakers, that will meet the actual requirements of the Customer in terms of their safety, service life, useful lifetime, mass and other technical characteristics.

As the nuclear ice-breakers service life exhaust their decommissioning will become more and more urgent problem. Russia's Ministry for nuclear power (MinAtom) and Ministry for transport (MinTrans) currently carry out preparatory activities to solve this problem. Positive multiyear experience of the propulsion reactor plants fault-free operation gives grounds to recommend KLT-40 - type NSSS as a source of energy for heat and power supply and for seawater desalination purposes.

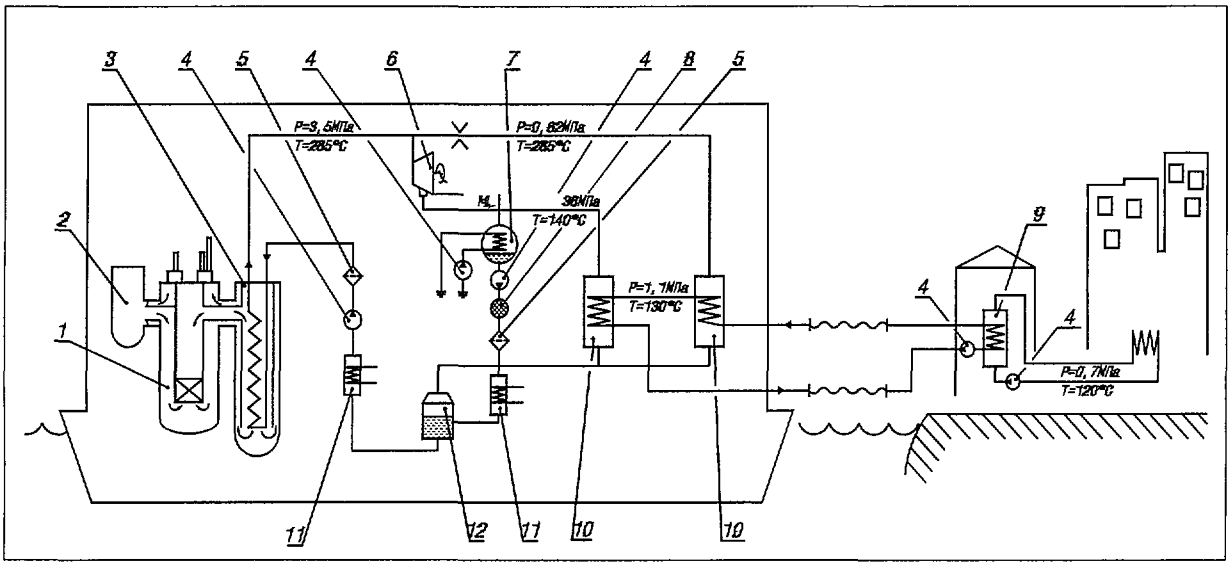
2. PROSPECTS OF SMALL NUCLEAR REACTOR PLANTS USE FOR FLOATING HEAT AND POWER CO-GENERATION STATIONS

The extreme northern and similar remote regions of Russia occupy more than half of the country's territory, where the major portion of mineral and energy resources are located, including oil, natural gas, nickel, gold, diamonds and rare metals. However, majority of these regions are not provided with a centralized power supply systems, have no fuel-energy resources expedient for effective utilization, while fossil fuel delivery there entails great difficulties and expenses. Therefore, application of NPP, especially floating ones, becomes justifiable and prospective for these regions.

Investigations performed have shown that in the indicated regions of Russia there are tenths of places where a need of nuclear heat and power plants exists just now or will appear in the nearest future. Several sites for potential deployment of floating nuclear heat and power plants are currently studied, viz.: at Peveck (Chuckot autonomous district), Norilsk industrial region (RAO "Norilsky nickel"), coastal areas of Kamchatka peninsula and Far East, where small decentralized power sources are basically used now.

In Russia the design of floating power unit (FPU) with KLT-40 - type reactor plants is currently nearing completion for a leading nuclear heat and power co-generation plant (NHPP) to be deployed at Peveck [2].

Manufacturing of the most labor-consumption equipment for the reactor plants is already underway. The floating power unit is intended to generate electricity and heat, being a constituent of the nuclear co-generation station. The FPU includes two KLT-40S reactor plants and two steam turbines with electric generators, combined in two individual units of 35 MW(e) capacity each. The turbines have steam extraction bleed-off for heating a feed water and intermediate circuit water supplied into a related heating grid. Principal flow diagram of the FPU together with a coastal heating circuit is shown in Fig. 2.

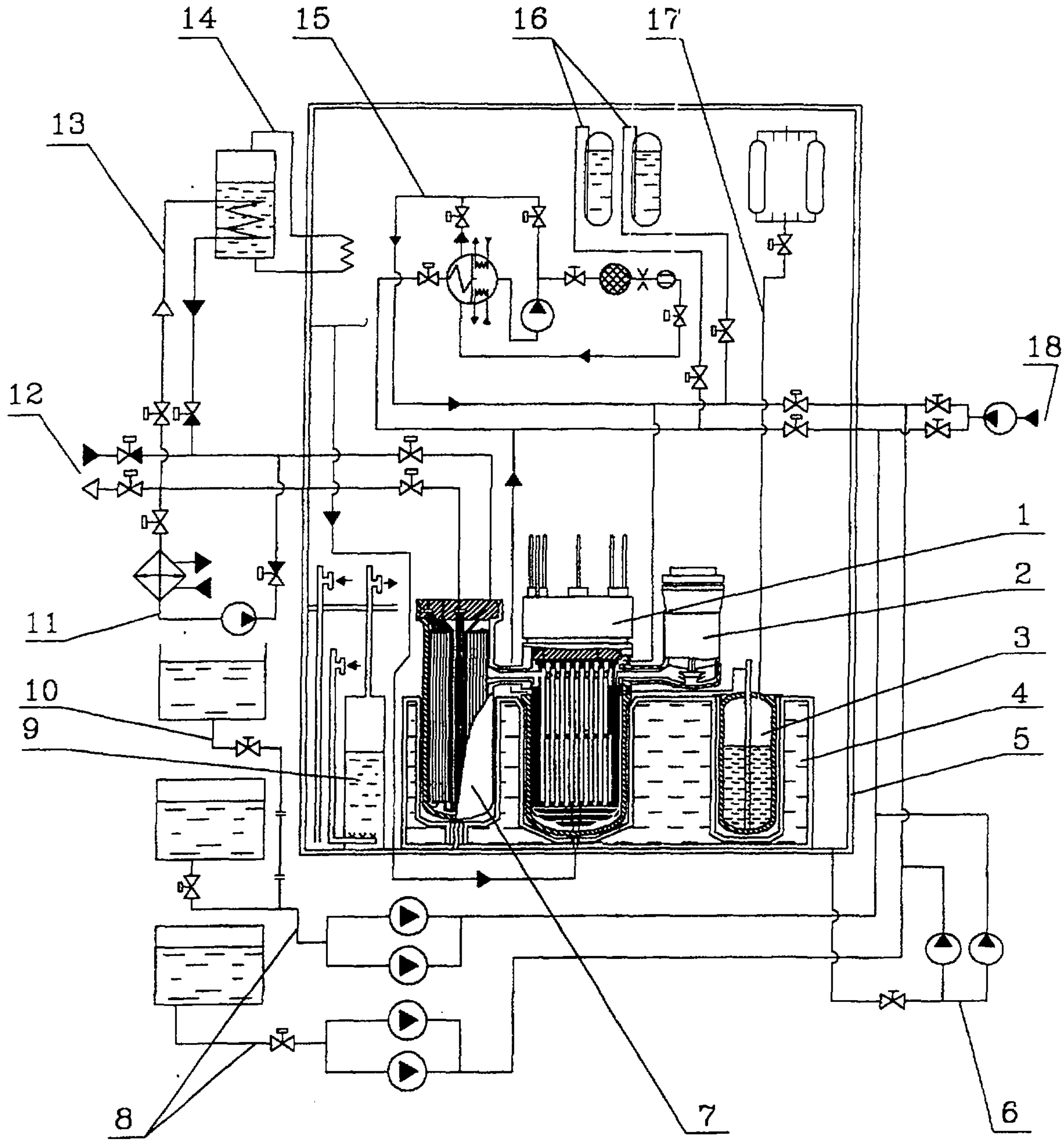


1 – Reactor	7 – Condenser
2 – Primary pump	8 – Ion exchange filter
3 – Steam generator	9 – Feed water heater
4 – Feed water pump	10 – Intermediate circuit heat exchanger
5 – Mechanical filter	11 – Feed water heater
6 – Turbine generator	12 – Deaerator

FIG. 2. Schematic plow diagram of NCGP with the shore heat supply system.

The KLT-40S nuclear reactor plant has been developed based on equipment used in the ice-breakers, with reliance on shipbuilding technologies and engineering solutions proven by many-year operating experience under the most severe navigation conditions in Arctic.

PWR as the most widely used and proven reactor type is used in KLT-40S reactor plant. Its steam generator is of once-through coiled type, reactor coolant pump is canned centrifugal two-speed circulator. The reactor plant components, viz.: reactor, 4 steam generators and 4 reactor coolant pumps are joined in a steam-generating unit by nozzles with the same robustness as the reactor pressure vessel, thus forming four circulation loops. The reactor plant is enclosed into a protective shell (containment), which in turn is located within a protective enclosure. The reactor plant is equipped with engineered (active) and passive safety systems. Fig. 3 shows principal system configuration of the KLT-40S reactor plant.



1 – Reactor
2 – Reactor coolant electric pump
3 – Pressurizer
4 – Metal-water shielding tank
5 – Protective shell
6 – Recirculation system
7 – Steam generator
8 – ECCS
9 – Bubbler system for pressure Suppression in protective shell
10 – Liquid absorber removal system
11 – Emergency shutdown cooling system
12 – To STP
13 – Passive emergency shutdown cooling system
14 – Protective shell pressure suppression emergency condensation system
15 – Primary circuit purification and cooldown system
16 – Passive ECCS
17 – Pressurization system
18 – From STP

Fig. 3. Nuclear steam supply system with KLT-40C reactor.

The design of KLT-40S reactor plant is developed in conformity with the latest general regulatory provisions for nuclear safety - OPB-88/97, Rules for nuclear safety of reactor plants for NPP-PBYa RU AS-89, Radiological safety regulations NRB-99, the Russian Federation law "On radiological safety of population", Rules for nuclear ships classification and construction of the Russia's maritime Register, IAEA safety guides etc. Presently a site for the floating nuclear co-generation plant is being licensed in the Russia's regulatory body (Gosatomnadzor).

Inherent self protection properties of the reactor, maximal utilization of passive and self-actuated safety features ensure the reactor resistance against any errors of personnel and failures of equipment. Exposure dose to population under normal operation conditions at a distance of 1 km from the plant is about 0.01 m rem per year. Evacuation of local population during accidents in the plant is not needed.

The steam turbine plant (STP) is used to generate electric energy and to heat water in the intermediate circuit of the related heating system. The STP consists of a steam turbine, double-section horizontal condenser and electric generator. The intermediate circuit includes heating grid water heaters, where steam from intermediate bleed-offs of the turbine is used as a heating coolant, and a peak heating grid heater, where steam from the main steam line is used.

3. PROSPECTS OF SMALL REACTOR PLANTS UTILIZATION FOR FLOATING POWER-SEA WATER DESALINATION COMPLEXES.

World demands in fresh water is growing steadily as population increases and industrialization level rises. That is the reason why sea water desalination facilities are being developed, including those used nuclear energy, particularly for utilization in remote coastal regions.

On the basis of floating nuclear power unit a number of conceptual designs of dual-purpose power-desalination complexes for production of electricity and fresh water has been developed.

Facilities with multistage horizontal-tube film evaporators, developed by Sverdlovsk Research Institute for Chemical Machinebuilding (Ecaterinburg, Russia) [3], are used in the designs as distillation desalination plants. Facility proposed by "Candesal" company, based on utilization of highly-permeable membranes manufactured using technology of Dow Film Tec [4], is adopted as reverse-osmosis desalination plant. The power plant design options use condensation and back-pressure turbines.

3.1. Power-seawater desalination complexes based on distillation desalination technology

During analysis of technical and economic characteristics the following configurations of power-sea water desalination complexes were considered:

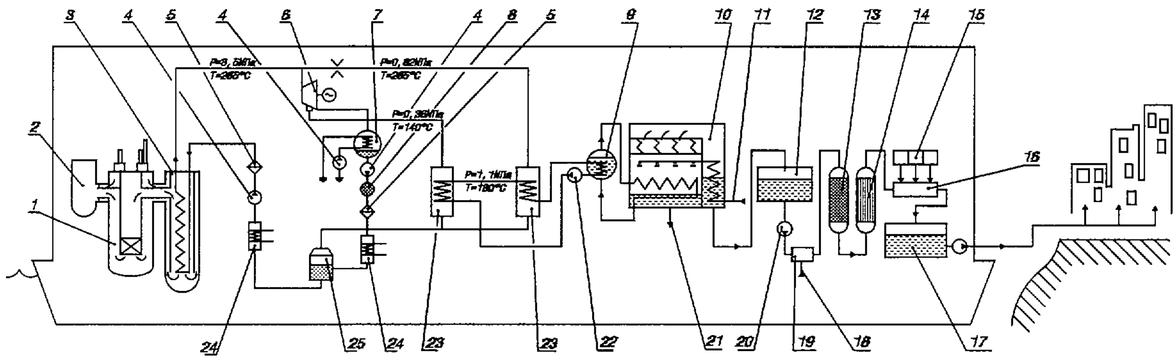
- use of steam extracted from condensation turbine bleed-offs for distillation desalination facilities (Fig. 4);
- use of a back-pressure turbine and heat extracted from a condenser for distillation desalination facilities (Fig. 5).

Heat and flow diagram of the complex to the first design option is similar to that of the floating nuclear heat and power co-generation station. Its distinctive feature is in the use of steam extracted from turbine bleed-off for sea water desalination, rather than for heating purposes.

3.2. Power-seawater desalination complexes based on reverse-osmosis technology

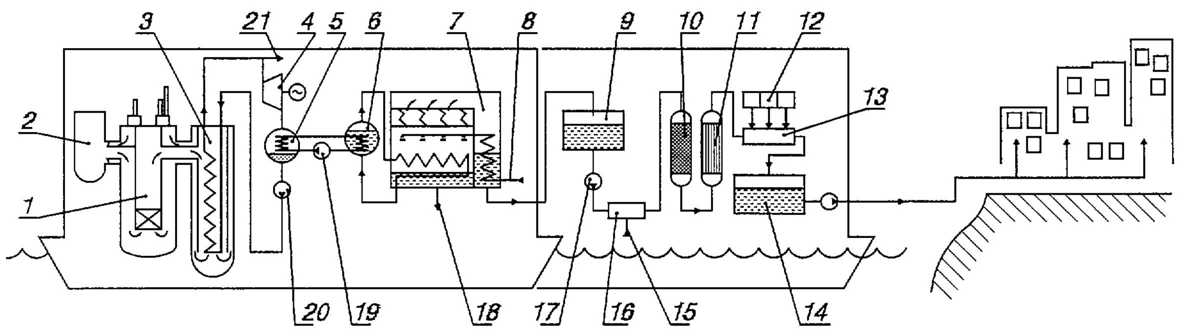
For the given type desalinators a configuration with a condensation turbine are considered for electricity generation and with turbine condenser waste heat utilization for heating of seawater to be desalted.

The complex includes FPU and reverse-osmosis desalination facilities, located on a shore or in a special vessel. Results of analysis made for comparison, of the design options with two KLT-40S reactors are summarized in Table 3.



1 – Reactor
2 – Reactor coolant pump
3 – Steam generator
4 – Secondary circuit electric pump
5 – Mechanical filter
6 – Turbo-generator
7 – Condenser
8 – Ion exchange filter
9 – Steam generator
10 – Distillation desalination plant
11 – Sea water inlet
12 – Distillate intake tank
13 – Water enrichment facility
15 – Plant for water fluorine, chlorine treatment and stabilization
16 – Mixer
17 – Potable water tank
18 – H_2CO_3 solution
19 – Mixer
20 – Potable water preparation plant pump
21 – Evaporated sea water brain
22 – Intermediate circuit electric pump
23 – Intermediate circuit heat exchanger
24 – Feed water heater
25 – Deaerator

Fig.4. Schematic flow diagram of nuclear desalination complex using turbine steam extraction line.



1 – Reactor
2 – Reactor coolant pump
3 – Steam generator
4 – Turbo-generator
5 – Condenser
6 – Steam generator
7 – Distillation desalination plant
8 – Sea water inlet
9 – Distillate intake tank
10 – Water enrichment facility
11 – Running water sorbent containing filter
12 – Plant for water fluorine, chlorine treatment and stabilization
13 – Mixer
14 – Potable water tank
15 – H_2CO_3 solution
16 – Mixer
17 – Potable water preparation plant pump
18 – Evaporated sea water brain
19 – Intermediate circuit electric pump
20 – Secondary circuit electric pump
21 – To condensation turbine

Fig. 5. Schematic flow diagram of nuclear desalination complex with back-pressure turbine.

TABLE 2. SUMMARIZES BASIC TECHNICAL CHARACTERISTICS OF THE FLOATING POWER UNIT.

Characteristic	Value
1 Number of reactor plants	2
2 Type of reactor plant	PWR KLT-40
3 Thermal power, MWt	2 × 148
4 Steam-generating capacity, tons/hour	2 × 240
5 Steam pressure at steam generator outlet, MPa	3,8
6 Steam temperature at steam generator outlet, ^{0}C	290
7 Feed water temperature, ^{0}C	170
8 Installed turbine generator plant electric power, MWe	2 × 35
9 Rated electric power in turbine steam-extraction operation mode, MWe	2 × 30
10 Electric power in turbine condensing operation mode, MWe	2 × 32,5
11 Heat to heat supply system, GCal/h	2 × 25

TABLE 3. POWER-SEAWATER DESALINATION COMPLEXES OUTPUT DATA.

Type of flow diagram	Type of desalination plant	Type of turbine	Maximum output	
			Fresh water, $m^{3/}d$	Electric power, MW
Option 1	Distillation desalination plant	Condensation with steam extraction for DOU desalination facilities	33000 - 0	58 - 5
Option 2	Distillation desalination plant	Back-pressure	147000 - 44000	24.8 - 5
Option 3	Reverse osmosis (input water is heated in condenser)	Condensation	285000 - 0	0 - 65

CONCLUSIONS

(1) Small power nuclear reactor plants are widely used in Russia for nuclear ice-breakers and cargo ships, which operations for a long time provide life sustenance and economic development of Russia's regions at Extreme North and Far East. They have a real prospects of further utilization.

(2) Successful experience of small power propulsion reactor plants operation in nuclear ice-breakers and other civil ships gives grounds to recommend them as energy sources for heat and power co-generation stations and power-seawater desalination complexes.

(3) Based on the advanced propulsion nuclear steam supply system KLT-40S a leading co-generation nuclear station with floating power unit is currently being created in Russia, for deployment at port of Peveck in Chuckot national district.

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