OPERATIONAL EXPERIENCE WITH PROPULSION NUCLEAR PLANTS

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Abstract

Russia possesses a powerful icebreaker transport fleet which offers a solution for important socio-economic tasks of the country's northern regions by maintaining a year-round navigation along the Arctic Sea route. The total operating record of the propulsion nuclear reactors till now exceeds 150 reactor-years, their main equipment items operating life amounted to 120,000h. Progressive design-constructional solutions being perfected continuously during 40 years of nuclear-powered ships creation in Russia and well proven technology of all components used in the marine nuclear reactors give grounds to recommend marine NSSSs of KLT-40 type as energy sources for heat and power co-generation plants and sea water desalination complexes, particularly as floating installations. Co-generation stations are considered for deployment in the extreme north of Russia. Nuclear floating desalination complexes can be used for drinkable water production in coastal regions of Northern Africa, the Near East, India etc.

1. STEPS IN DEVELOPMENT OF TECHNOLOGY

Russia is a single country in the world which now operates a nuclear-powered icebreaker-transport fleet which offers a solution for vital social-economic tasks of the country's northern regions by maintaining a year-round navigation along the Arctic Sea route.

The first nuclear icebreaker "Lenin" - was laid in 1956 and commissioned in 1959 as a pilot commercial vessel registered to the Murmansk shipping company. Experience of its first sailing seasons (1959-1964) had shown significant advantages of icebreakers with nuclear propulsion plant in the Arctic, particularly their practically unrestricted sea endurance and ice breaking capability. [1].

Up to the date, three degeneration of nuclear propulsion plants have been created and gone through comprehensive verification by long-term exploitation under severe operating conditions (Table 1).

The first triple-reactor propulsion plant with a loop-type configuration had been operated during six years in the icebreaker "Lenin". By the end of that period an operating record of its main components did not exceed 25,000 h. The experience gained with that vessel had shown the expediency to construct a whole series of nuclear-powered icebreakers for extensive operations in the Arctic seas. With that aim a new twin-reactor propulsion plant of a modular type had been developed. Its pilot specimen was installed in the icebreaker "Lenin" instead of the first nuclear plant. Successful operation and high performance indicators of the plant allowed it to be recommended as a basis one for subsequent icebreakers "Aretica" (Fig. 1), "Sibir", "Russia", "Sovetsky Sojus" and "Yamal". In 1994 the next capital icebreaker "50th Anniversary of Victory" was launched, which is currently being completed the construction.

TABLE I MAIN CHARACTERISTICS OF PROPLUSION REACTOR

Data	Reactor Index				
	OK-150	OK-900	OK-900A	KLT-40	KLT-40M
1. Ship incorporating NSSS	ice-break "Lenin"	ice breaker "Lenin"	icebreakers "Lenin", Arctica" "Sibir", Rossiya", "Sovetsky Soyuz" "Yamal", "50 let Pobedy"	lighter carrier "Sevmorput"	icebreakers "Taimyr" Vaigach"
2. Displacement, tons	16000	15940	23500	62000	18620
3. Total shaft power, h.p.	44000	44000	75000	40000	48000
4. Number of reactors	3	2	2	1	1
5. Reactor power, nominal MWth	90	159	171	135	171
6. Operation life with one fuel load, days	500	1050	1050	1460	1120
7. Primary coolant parameters at nominal power:					
1) core inlet temperature, °C	261	278	273	279	273
2) core outlet temperature, °C	284	318	316	311	316
3) primary system nominal pressure, MPa	18	13	13	13	13
8. Secondary circuit parameters at nominal power:					
1) steam flow, t/hr;	3x90	2x220	2x240	215	240
2) steam flow, °C	290	305	290	290	300
3) steam pressure, MPa	3.1	3.19	3.34	4	3.4

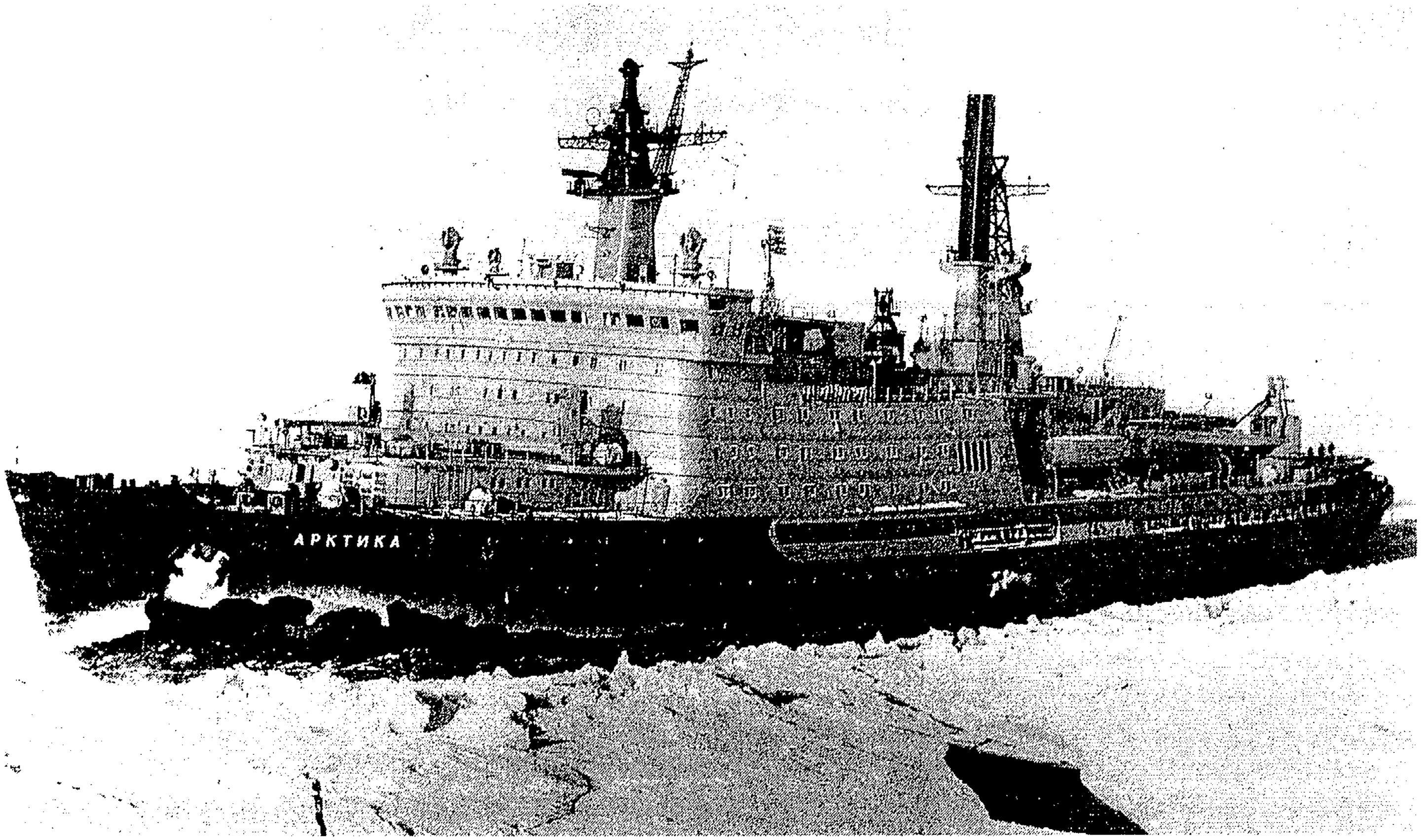

Fig.1. Nuclear icebreaker "Arctica" conducting transport ships on the Arctic sea route.

In spite of similarity of nuclear steam supply systems (NSSS) used for those icebreakers they were gradually step-by-step improved from one vessel to other. Their modifications were primarily directed to elimination of drawbacks revealed during operation of individual components and systems under harsh operating conditions in predecessor NSSSS, to enhancement of operational safety, technical & economic characteristics and operating life.

Safety of the reactor plants is relied upon the reactors inherent self-protection features and application of successive protective barriers, redundant systems and equipment, efficient safety systems.

The next stage in creation of propulsion NSSS was development of a single reactor plant for lighter-carrier "Sevmorput" and limited-drought icebreakers "Taymir" and "Vaygach", constructed jointly by Finnish and Russian enterprises. A decision to build the vessels with single reactor plant was justified by high operational reliability of this type NSSS.

The NSSS for lighter-carrier "Sevmorput" was designed with regard to requirements of the Code for safety of nuclear merchant ships developed by International Maritime Organization (IMO).

A number of unique operations have been performed in the Arctic by the nuclear-powered icebreakers. For instance, in 1977-78 vessel "Lenin" provided for the first time a year-round transport operations in the Arctic Sea route ways. In 1977 vessel "Arctica" carried out a voyage to the North Pole in active sailing, that consequently transformed into regular tourist cruises. In 1978 vessel "Sibir" carried out an experimental high-latitude sailing by a shortest way from Murmansk to Magadan.

In 1989 vessel "Sevmorput" carried out its first commercial voyage over the route: Odessa-Vietnam-Vladivostock, during which the ship's reactor plant way inspected by Administrations of host parts for conformity with requirements of the IMO Code document. For years of the nuclear-powered civil ships operation an appropriate infrastructure has been created in Russia, including specialised repair-technological enterprises, training Centre, auxiliary maintenance ships for the reactor refuelling.

3. RESULTS OF OPERATION

This year (1998) becomes the 39th one in the history of the Russian civil nuclear-powered fleet, which consists of seven nuclear icebreakers and one transport (lighter carrier) ship (Fig. 1). The fleet's forefather, the icebreaker "Lenin", is already removed from operation, while the construction of the newest icebreaker 50th Anniversary of Victory is nearing completion now. The main performance indicators of the nuclear-powered ships over the period from 1970 to 1997 are given in Table 2.

The total operating record of the propulsion nuclear reactors under extreme working conditions (rolling, vibrations, impacts of ice-floes, frequent manoeuvring) exceeds now 150 reactor-years, while that for the main equipment items on some operating reactors attained 120,000 h. During that period, no incidents associated with chain reaction control violation or inadmissible release of radioactivity were indicated.

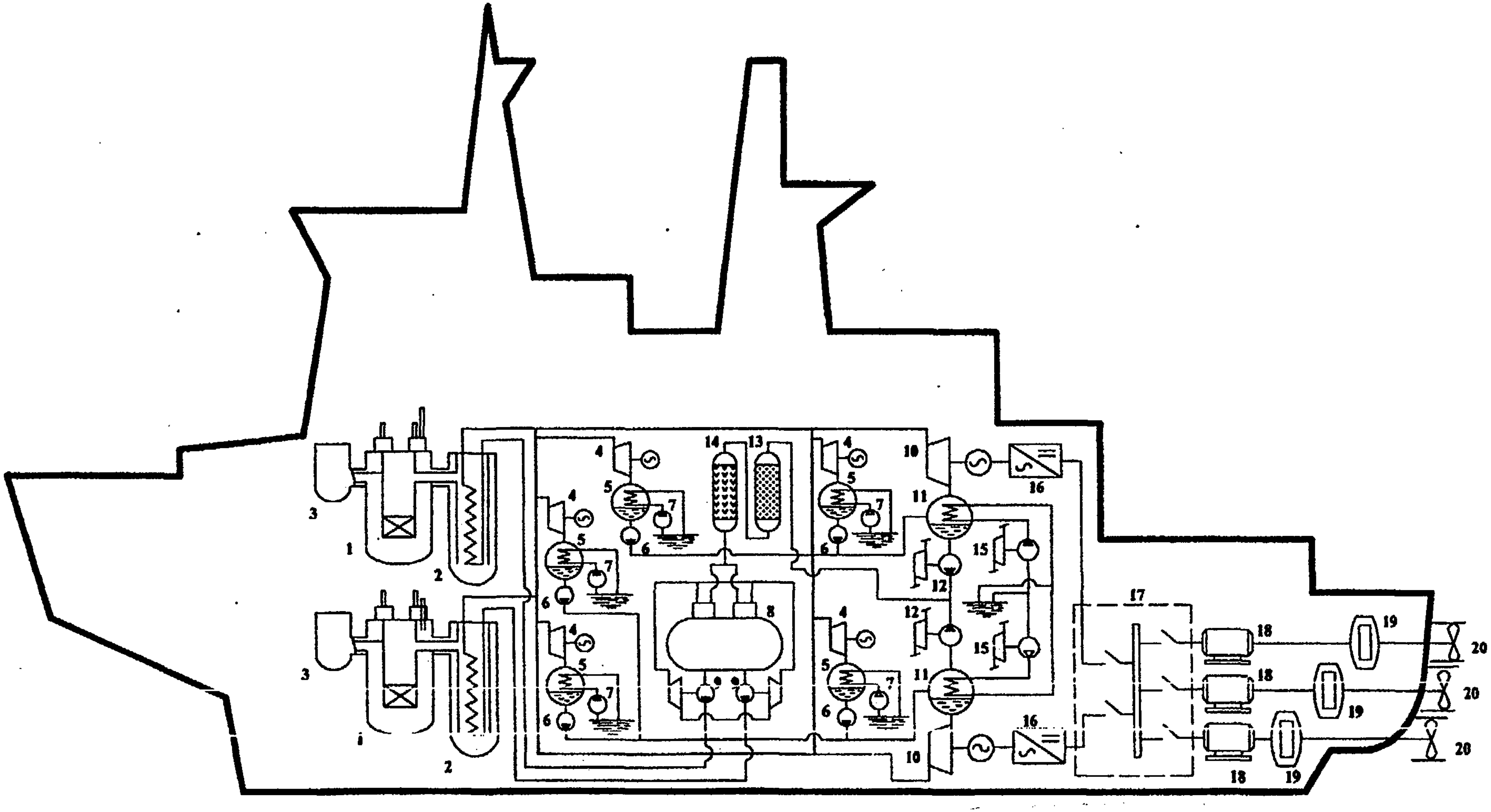

FIG. 2. "Arctica"-type icebreaker's nuclear power plant configuration
1-reactor, 2-steam generator, 3-reactor coolant pump, 4-auxiliary turbine generator (ATG), 5-ATG condenser, 6- ATG condensate pump, 7-deaerator, 8-turbine-driven feedpumps, 10-main turbine generator, 11-main condenser (MC), 12-MC turbine-driven condensate pump, 13-mechanical filter, 14-ion-exchange filter, 15-MC turbine-driven circulating pump, 16-converter, 17-propulsion motor power station, 18-propulsion motor, 19-deadwood bearing, 20-propeller

TABLE II OPERATION EXPEREINCE OF PROPULSION REACTORS

	Name of ship								
Characteristics	i.-br. 'Lenin'	i.-br. 'Arctica'	i.-br. 'Sibir'	i.-br. 'Russia'	i.-br. 'Sov. Souz'	i.-br. 'Tyamir'	i.-br. 'Vaygach'	i.-br. 'Yamal'	1.-cr. 'Sev-morput"	i.-br. '50th Anniver-sary of Victory'
1. Year of commissioning	1970	1974	1977	1985	1989	1989	1990	1992	1988	under con-struction
2. Averaged duration per year, days	230	225	232	258	232	255	252		291	
3. Total reactor operating record , h	106740* 106350**	123575 124276	94785 94043	60572 60011	52596 52239	57627	48305	35704 35081	59453	
4. Total energy produced , 10^3MWh	6523 6398	8091 7500	6095 6933	4294 4472	3254 3433	4495	4153	2602 2601	3378	
5. Distance sailed, miles										
1) total	654400	825177	740786	391761	305857	331995	213421	229819	232650	
2) incl. Through ice	560600	721644	472787	361283	258341	308134	196712	204648	77191	
6. Number of ships conducted	3700	2830	1711	1121	425	919	576	572		

i.-br. = ice breaker, 1.-cr. = lighter carrier
* for reactor No. 1, ** for rector No.2

However, single failures were taken place in individual equipment pieces of the propulsion NSSSS, including small leaks of primary coolant into the environs and interfacing systems. The failures emerged as a rule following expiration of specified service life. Analysis of operating conditions and metallographic study of damaged elements in a primary circuit have shown that faults are governed by the following processes:

- thermocyclic loads;
- corrosion wear;
- irradiation;
- overpressurization.

Main reasons of thermocyclic effect are:

- operational transients (plant heating, cooling down, changes in power level, etc.); cyclic mass exchange between cold and hot coolant flows;
- disordered mixing of coolant flows with significantly different temperatures;
- non-steady pattern of coolant flow at heat exchange under significant temperature gradient conditions.

Thermocyclic cracks were revealed in pipes connecting a reactor with pressurizers, in internal headers for water supply from purification system to reactor coolant pumps, in internal shells of pumps' flow chambers, etc. The indicated defects became the reason for in-depth analytical and experimental studies of equipment operating conditions in the propulsion and test reactor plants, particularly thermal and strain parameters monitoring.

Corrosion wears effect associated, as a rule, with deterioration of a primary water chemistry regime (as compared to a specified one). In particular, the steam generators were operated with excessive salt content in feed water that could be the reason of failures of some steam-generating tubes and other items of SGs.

Resulting from irradiation of reactor internals increase in forces to be applied for movement of reactivity control members was observed by the end of a specified lifetime.

The operating experience has shown that abrupt changes in a primary pressure can be the reason of damages in internal structures made as semi-closed plena which walls were not designed for the primary coolant pressure. That was the reason of failure of a partition in the reactor coolant pump of icebreaker "Arctica".

Guides on optimal running of operational transients were developed for improvement of equipment operating conditions, and some modification was introduced in the equipment structures.

4. DESIGNER SUPERVISORY ACTIVITY, INSPECTIONS, LIFE EXTENSION

During the entire period of the NSSSs operation a supervisory activity has been carried out by the design organization as concerned reactor-related equipment and systems. Each failure or mis-operation event was thoroughly analysed, and recommendations for their elimination were then developed. Remarks of the plants personnel on operation of individual equipment items and systems were analysed and quickly removed; new improved arrangements were tested; the plants operating modes were optimised, etc. Inspections of equipment were carried out, weak points were identified and then removed in both operating and newly designed NSSS. Resulting from the supervisory activity actual operation models were determined, according which more precise calculations were carried out aiming at damage parameters corrections and residual service life prediction.

Due to systematic activity on improvement of equipment and systems, optimizations of their operating modes the reactor plant main equipment specified lifetime has been increased from (25-30)x 10^3hrs for the first NSSSs up to (100-120)x 10^3hrs for the modern ones.

In order to further increase this performance indicator extensive work is currently performed for the inspections of most loaded items in equipment and piping of the decommissioned icebreaker "Lenin" reactor plant. Particularly, samples are cut out from the reactor pressure vessel, nozzle connecting the RPV to steam generator, the pressurizer, heat exchanger, RPV closure head, pressurizing system pipes, etc. It is also planned to inspect items of the SG, RCP, CRDM and other key components. Metallographic tests of cutted-out samples and analysis of obtained results are currently proceeded. Resulting from the comprehensive inspection program fulfillment a decision on extension of running equipment specified lifetime will be adopted, eventually up to the vessel hulls service life.

Presently, the reactor cores are nearing their specified energy production potential of 2.1-2.3TWh. There is a prospect to increase this value, and consequently to improve an economic effectiveness of the reactor plants operation.

Long-term monitoring of the environment (sampling and laboratory tests of snow, soil, air, vegetation, etc.) in the area of the nuclear-powered ship homeport has no revealed any radiological effects of the ships. Obtained data are on the background level. Average annual dose to individuals of the ship personnel does not exceed 5mSv.

Available safeguard barriers and confinement systems practically completely eliminate radioactivity release, even in the most severe design accidents.

The Russian nuclear-powered ships are operated by highly qualified and experienced specialists, which along with their direct duties perform significant scope of research work aiming at enhancement of the reactor plants safety.

Actual level of nuclear and environmental safety of the latest modifications of NSSSs meets modern requirements of domestic and international regulatory documents, and hence removes restrictions on the nuclear-powered ships deployment. It is also demonstrated be the commercial cruises of the icebreakers with passengers.

5. PROSPECTS OF NUCLEAR PROPULSION PLANTS UTILIZATION

The application of progressive solutions for constructional and technological provisions, continuous perfection of safety systems with an Account of updated regulatory requirements for nuclear safety, and improvement of equipment items on the basis of operational experience feedbacks give grounds to recommend the propulsion nuclear reactors as advanced heat sources for co-generation power stations and sea water desalination complexes [2].

Operations along the Arctic Sea route seem to be problematic without vigorous work of the nuclear icebreakers. They provide pilotage of up to **80%** of vessels there. Therefore the decommissioned nuclear icebreaker should be replaced for new ones.

The far north and similar remote regions of Russian occupy more than half of the country's territory where the major part of mineral and energy resources are located, including oil, natural gas, nickel, gold, diamonds and rare metals. However, most places in these regions are not provided with a centralised power supply, have no fuel-energy resources expedient for effective utilization, and while fossil fuel delivery there entails great difficulties and expenses. For these regions, the application of NPPS, especially floating ones, becomes justifiable and prospective.

Creation of nuclear-powered icebreakers, cargo vessels and floating NPPs with standardized reactor plants for servicing Russia's northern regions represents a promising and economically efficient task, since the available integrated maintenance infrastructure can be used for new ships maintenance too.

Creation of floating power-desalination complexes is another prospective application of the propulsion reactor plants. It is a fact that drinkable water production has become an acute problem for many regions of the world, e.g., North Africa, the Near East, India etc. Drinkable water is also expensive in northern regions of Russia.

Among a number of different projects, IAEA is considering floating power desalination complexes, in particular those with the marine nuclear reactor plant of KLT-40 type and desalination facilities of distillation and reverse-osmosis types. The appropriate distillation facilities in Russia are designed by the Sverd NII ChimMash Institute (Ecaterinburg), while reverse-osmosis facilities are produced in particular by the Canadian firm "Candesal Inc".

In 1995 Memorandum on mutual understanding in the development of a desalination complex was signed by "Candesal Inc." and MinAtom of Russia (it was prolonged in 1997). By present a draft prospect on joint power-desalination complex is prepared [3].

High reliability and safety levels of the reactor plants are verified by their long operation experience. Projects of nuclear co-generation stations and power desalination complex based on the propulsion-type reactor plants represent a certain commercial interest and can be attractive for domestic and foreign investors.

6. CONCLUSIONS

(i) Powerful icebreaker - transport nuclear-powered fleet and adequate maintenance infrastructure have been created in Russia by the date.

(ii) Unique multiyear operation experience has been accumulated with the propulsion nuclear reactor plants, and their operational safety and reliability are convincingly confirmed.

(iii) Causes of rare typical failures of equipment and systems have been identified, and proper countermeasures were undertaken for their complete or partial neutralisation.

(iv) The reactor plants have gone through multistage evolutionary modernisation, so that their equipment and systems have now a long specified lifetime.

The KLT-40 NSSSs are still attractive for fast realization in new icebreakers, cargo vessels, floating heat and power co-generation stations and power desalination complexes.

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