NUCLEAR HEAT APPLICATIONS IN RUSSIA: EXPERIENCE, STATUS AND PROSPECTS

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Abstract

The extensive experiece gained with nuclear district heating in Russia is described. Most of the WWER reactors in Russia are cogeneration plants. Steam is extracted through LP turbine bleeders and condensed in intermediate heat exchangers to hot water which is then supplied to DH grids. Also some small dedicated nuclear heating plants are operated.

1. INTRODUCTION

Low temperatures during the greater part of the year is characteristic for a majority of regions in Russia. Heating period for town dwellings lasts usually from 7 to 10 months a year. Contemporary dwellings are also provided with centrally-supplied hot potable water for sanitary and hygienic purposes. Moreover, hot water is supplied to public buildings for air conditioning. Average per capita heat consumption in households amounts to about 24 GJ a year and has been increasing over the years.

Fast growth of towns and gradual improvements in the quality of dwellings in the Sixties and Seventies resulted in a dominant share for fossil fuel in the production of heat. By the end of the Eighties it attained 42%, i.e. 1.72 times higher than that for electricity production.

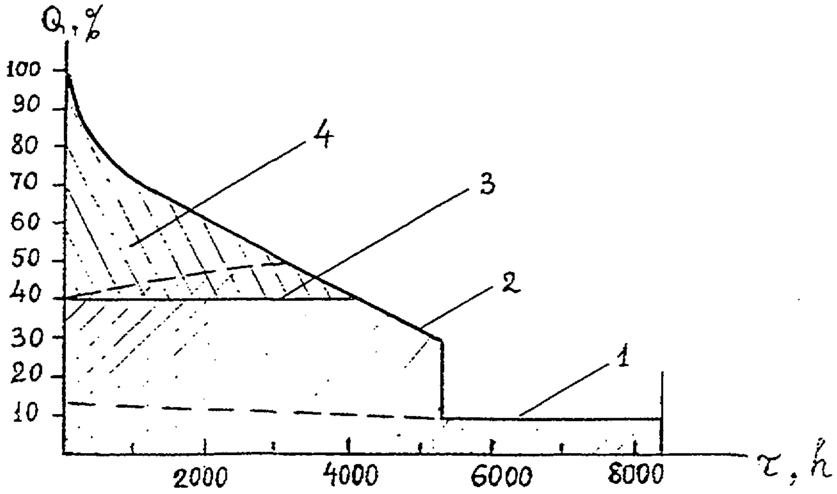
The town-building concept adopted in the country has been based traditionally upon the utilization of centralized heating, i.e. large systems for transport and distribution of heat from co-generation plants and boiler stations to blocks of buildings and to separate multiflat houses. About 70% of total low-grade heat consumed in household sector and in industry (approx. 8.7×10^9 GJ/year) is provided by powerful sources of heat through centralized heating systems, and about half of this value is being produced by co-generation plants [1]. Total heat output capacity of co-generation steam turbines amounted to 175GW (1990). The remaining 30% of heat is generated by decentralized sources, i.e. small boilers and individual fire devices. The share of electric heating is negligible.

A growth in concentration and value of heating demands in towns and availability of hot water transport and distribution, systems create, in principle, favorable prerequisites for utilization of nuclear plants as sources of heat in centralized district heating systems. In regions suffering from shortage of fossil fuel, where expensive fuel is used for heating and/or where environmental conditions do not allow the use of conventional fossil-fuelled boilers, nuclear plants are more attractive.

2. HEAT LOADS IN CENTRALIZED HEATING SYSTEMS

The level of heat demand in a centralized district heating system (CHS) varies depending on ambient air temperature. On the contrary, potable hot water supply does not depend significantly on the season and variations during a day are similar to those in household electrical demand. A typical CHS load diagram is presented in Fig.1.

Heat supply in a CHS is usually provided by a number of heat sources, one of which is a large co-generation power plant or boiler station bearing a base load in the CHS, while rest of the sources are being connected successively to the base as heat demand builds-up, i.e. as ambient air temperature drops. Co-generation power plants are used as a base heat source in CHSs with maximum heat loads exceeding 2500 GJ/h.



1 - hot water demands, 2 - heating demands,
3 - base heat source, 4 - peak heat source

Fig.1 CHS annual heat load variation diagram

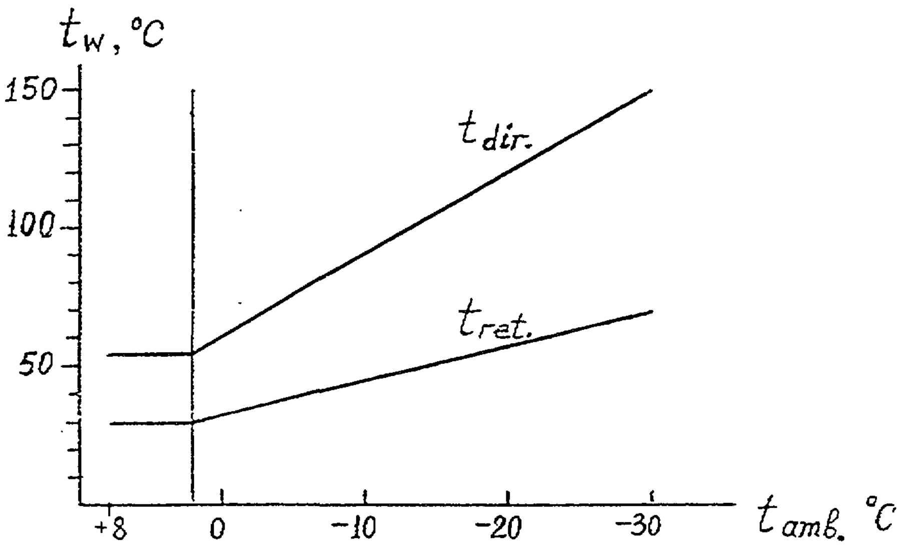
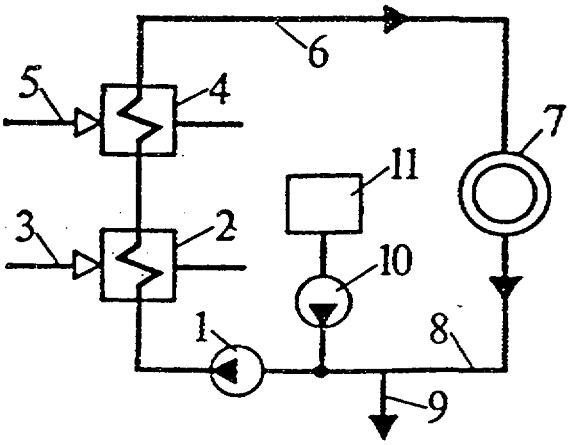


Fig. 2. Heating grid water temperature variation vrs. ambeint air temperature



1 - grid pump, 2 - main grid HX, 3,5 - steam from turbine bleeders, 4 - peak grid HX, 6 - direct water, 7 - heat consumer, 8 - return water, 9 -grid bleed, 10 -grid make-up pump, 11 - make-up water preparation facility.

Fig.3 NPP's heating facility and related CHS flow diagram

Due to the short duration of the period with lowest ambient temperatures a base plant's rated capacity has to be determined not by the maximum heating load in the CHS, but to maximize the plant operation factor,. A base source, therefore, has to supply a heating load which is required by consumers during a major part of the year. Share of the base source in provision of the CHS maximum heat demand is characterized by $_t$-factor, which value should be optimized on the basis of techno-economic analysis during CHS design development. If, for instance, co-generation power plant (CPP) is used in the CHS, it is necessary to take into account in the $_t$-factor optimization, that a reduction in steam flow extracted from a turbine plant when ambient air temperature rises will result in turbine efficiency deterioration. Usually, $_t$-factor adopted is in the range from 0.4 to 0.6.

Maximum temperatures of direct and return water (t_{dir} and t_{ret} respectively) in a full load heating mode of CHS operation are standardized and adopted as follows:

For large towns:	t_{dir}^{max} 150°C	t_{ret}^{max} 70°C
for small heating grids:	t_{dir}^{max} 130°C	t_{ret}^{max} 70°C

Fig.2 shows a typical graph of temperature variation in a heating grid (HG). A HG regulation by changing grid water flowrate ("quantitative" control) is adopted only for a narrow range of positive temperatures of ambient air (+2 -+8 °C). In the rest air temperature variation range "qualitative" regulation is provided by changing both grid water temperatures and temperature difference between direct and return water. Total gird water flowrate is determined for the maximum heat consumption mode of the CHS operation and remains constant over the whole range of ambient air temperature variation. Reduction in direct water temperature is provided by mixing with colder return water.

3. HEAT SUPPLY FROM CONDENSING NPPS IN THE RUSSIA FEDERATION

Even though historically heat supply was not formulated as an objective for nuclear power industry, first steps in that direction, had been made in the very beginning of the industry development. It is worth reminding that even the first NPP, operating since 1954, served for many years as a heat source for the Obninsk town's CHS. All operating NPPs are equipped with heating facilities including grid water heaters and provide heat for space heating, air conditioning and hot water supply to both the atomic station and related towns. Such towns have a population of 40,000 to 50,000, situated usually 3-15 km away from a NPP site and have heat demands ranging from 100 to 200 MW (360-720 GJ/h) or higher.

Heating facilities of NPPs are being operated from non-regulated steam bleeders of turbine plants and usually have two- or three-stage flow configuration (Fig.3). Heat production characteristics of operating NPPs are given in Table 1. A significant increase in NPP heat supply capacity may be seen as nuclear power units become more powerful.

TABLE I. OPERATING AND MODERNIZED NPPS HEAT OUTPUT PERFORMANCES

Characteristic		Reactor	types	
	VVER-440	BN-600	VVER-1000	RBMK-1000
1. Rated electric power, MW(e)	400	600	1000	100
2. Heat capacity of turbine plant steam bleeders, GJ/h	2 x 100	3 x 240	840	2 x 310
3. Heat capacity of modernized turbine bleeders, GJ/h	840		1900	
4. Steam pressure in turbine bleeders, Mpa				
* upper		0.3	0.6-0.8	
* lower		0.13	0.2-0.3	

NPPs operate under base electrical and heat loads, practically without regulation of energy extracted from steam bleeders. Steam from the turbine is extracted in the range of a turbo-generator power variation from 100 to 60 percent of rated power. Because steam pressure in turbine bleeders reduces proportionally to electric load of a turbo-generator at lower power, steam is supplied to heating facilities from a main steam collector through a pressure-reduction device. To cover the winter maximum demands, a special peak heater may be connected additionally to main heaters.

When NPPs supply heat to large CHSs conventional co-generation power plant plays the role of a load-following source of heat, as well as the town's peak load boilers which come on-line at the lowest ambient temperatures. A co-generation power plant also serves as a back-up source of heat in case the NPP is under a shut-down.

Radiological safety of nuclear heat consumers is provided by continuous monitoring of secondary coolant radioactivity. If radioactivity exceeds the permissible level, fast-acting isolation valves will automatically stop grid water supply to the NPP's heating facility. An additional protective barrier has to be used such as pressure difference between grid water (grid pumps head is 1.6-1.8 MPa) and heating steam in grid heaters. According to regulatory requirements maximum dose to an individual of the wrounding population from NPP-related heating grid must not exceed 0.01 mSv/year [2].

Significant savings of fossil fuel, from 50 to 100 thousand tons oil equivalent per year for one 1000 MW(e) power unit, is the first positive effect of heat extraction from condensing NPPs. Improvement of environmental conditions (less pollution) in NPP-satellite towns and settlements is the second positive factor.

Experience available in operation of relatively small CHSs at the working atomic stations, demonstrates the high reliability and safety of such systems, as well as technical feasibility for creation of more powerful and more effective CHSs connected to NPPs. Design studies of advanced steam turbines have confirmed the possibility to increase significantly heat capacity of non-regulated steam bleeders of NPP turbines - up to 1400 MW (~5000 GJ/h) from one 1000 MW(e) turbine plant [3]. It allows to create large CHSs covering several districts and towns with a big concentration of heat demands. A number of techno-economic studies have been carried out lately for such NPP-related CHSs consolidating heating grids of towns and settlements in a radius of up to 150 km from NPP sites [3,4]. Specific designs of CHSs powered from NPPs which are planned to be constructed at the Kola and Novovoronezh atomic stations have been studied recently [5]. Characteristics of heat loads for these CHSs with different radius of enveloped heat consumers in the vicinity of the NPPs are given below (Table 2).

Fig.4 shows the results of the analysis of showings for CHSs connected to NPPs (both operating and under construction) with VVER-440 and VVER-1000 PWRs, compared to separate production of heat and electricity from conventional plants and boilers (under conditions of central regions of Russia) [3]. One can conclude that utilization of the NPPs for heat supply to CHSs is economical over the entire range of considered heat load variation: the savings vary from 7-25% at moderate heat loads up to 37-48% for the largest CHSs.

Economic impact of such systems is primarily due to significant savings of fossil fuel (up to 5-6 million tons a year), elimination of numerous small low-efficient and polluting heating boilers, transfer of larger boilers to peak or stand-by mode of operation with a low operating factor, and a reduction in economic detriment from polluting releases of conventional energy sources. Economic competitiveness of nuclear-powered CHSs increases substantially as fossil fuel cost rises and NPP investment cost reduces. Thus, a significant rise in economic effect at heat loads below 5000 GJ/h in Fig.4 is explained by transition to larger units of VVER-1000 which have 1.6 times less specific cost than VVER-440 units.

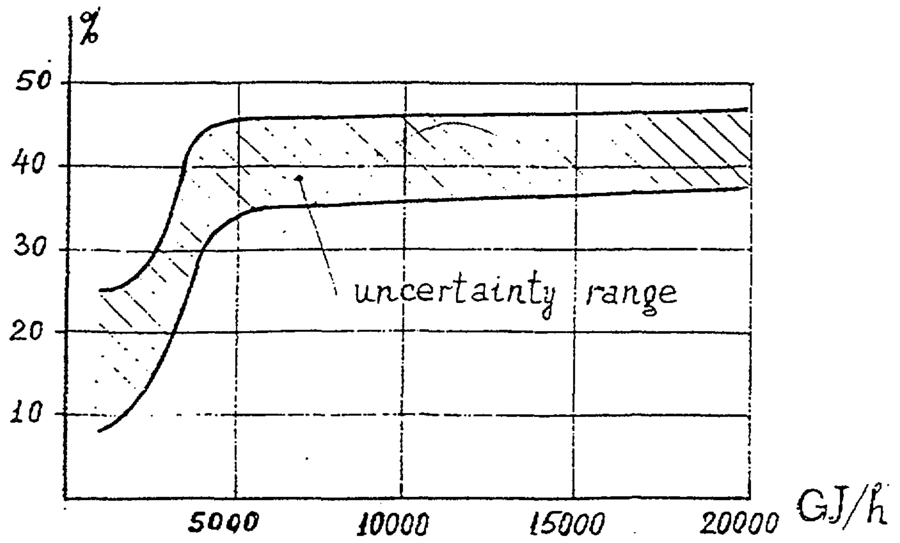


Fig.4. Relative economy of CHS expences vrs. maximum heat demands

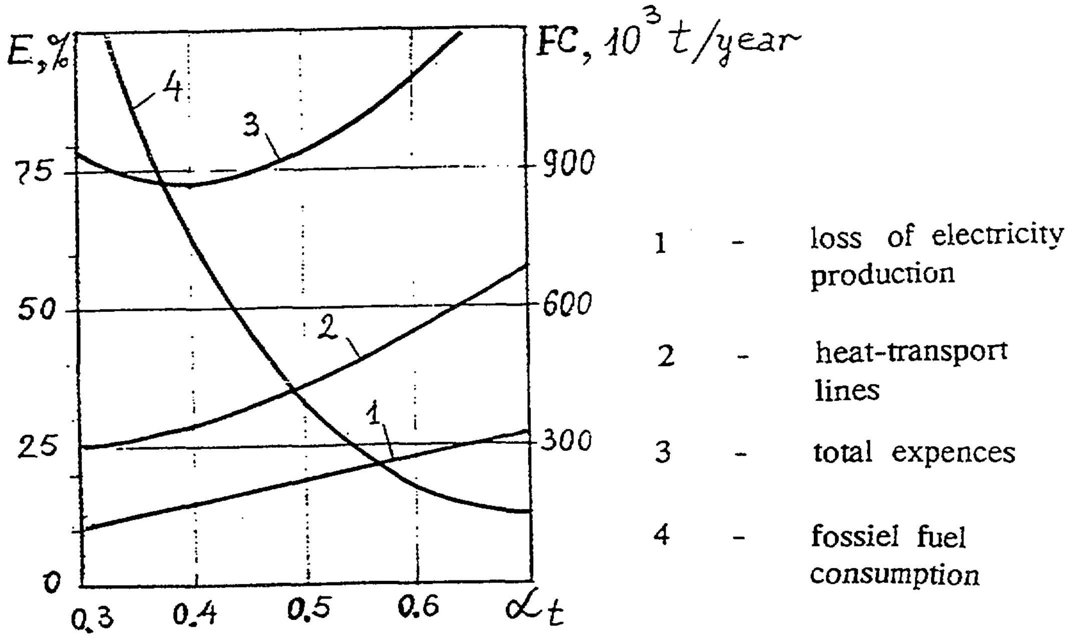


Fig.5 Reduced expences in NPP-based CHS (E) and fossil fuel consumption(FC) vrs. nuclear heat contribution factor α_t

Fig.5 gives an idea about variation of main components of expenses in a CHS with the nuclear heat contribution $_t$-factor [4]. Investigations showed that in large CHSs with heat load more than 5000 MW and large length of heat transport networks, the optimal value of $_t$-factor ranges from 0.3 to 0.5. In smaller CHSs, the optimal $_t$-factor rises to 0.6-0.7.

TABLE II. DESIGN CHARACTERISTICS OF CHSS BASED ON NEW NOVOVORONEZH AND KOLA NPPs (VVER-1000)

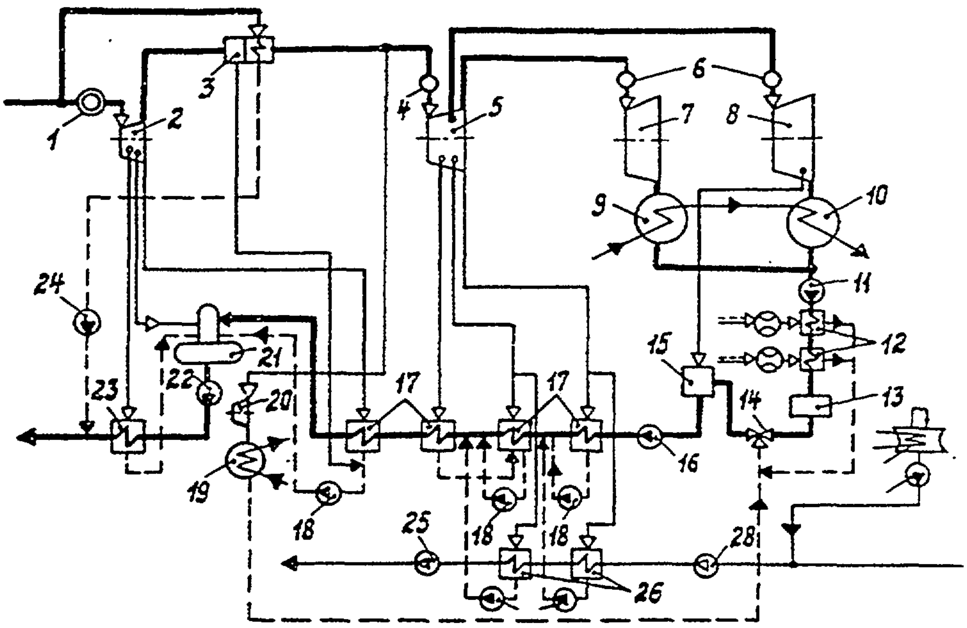
Consumers	Heat load	Distance from	NPPs site, km
	MW	Up to town's boundary	up to most remote consumer
1. CHS from Novovoronezh NPPs			
Total load	6950		
Contibutors:			
- Voronezh city	6310	40.0	55.0
- Novovoronezh town	640	50.0	7.0
2. CHS from Kola NPPs			
Total load	2665		
Contributors:			
- Apatit	2926	51.0	56.5
- Kirovsk	571	64.0	72.0
- Kandalaksha	446	22.5	28.0
- Polar Zori	360	7.0	10.0

4. Heat Supply From Nuclear Co-generation plants (CPPs)

Co-generation of electricity and heat with extraction of significant amount of heat from regulated bleeders of turbine plants is widely used in the power industry of Russia : CPPs give about a third of the total production of heat in the country. This method of reducing losses of heat in a steam cycle permits cutting the expenditure of fuel per kWh. For conditions in Russia, co-generation systems are more economic than separate production of electricity and heat in regions with density of heat demand more than 200 GJ/h per km^2 and maximum heat demand more than 2500 GJ/h [6].

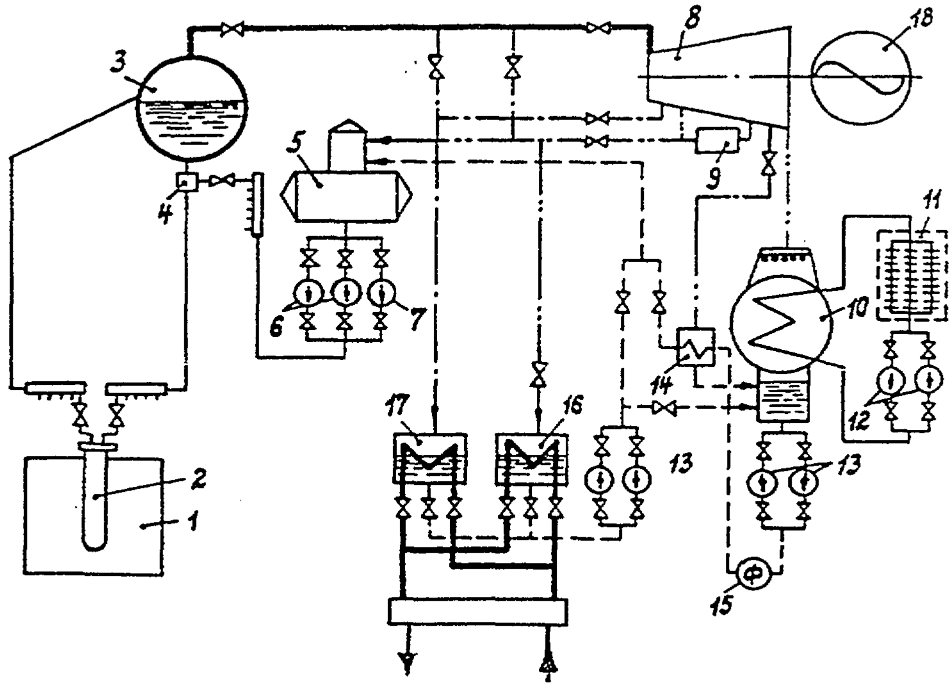
Economic efficiency of co-generation for NPPs, in general, is less than for conventional CPPs, due to lower initial parameters of steam. Large steam supply to a heating facility complicates saturated-steam turbine structure. Moreover, compared with conventional CPPs situated close to a town cost of heat transport and losses in hot water transmission lines are larger for nuclear co-generation power plants (NCPP). Therefore, pressure in steam bleeders of a turbine plant should be higher than increases under production of electricity. Nevertheless, as it was shown in the seventies, utilization of NCPPs might be economically effective in CHSs with large heat loads (more than 4000 GJ/h) at value of $_t$-factor in the range of 0.6-0.7 [6,7].

In the beginning of the eighties in ex-USSR, construction of two large NCPPs with VVER-1000 reactor plants was started near large cities of Minsk and Odessa. For those NCPPs specifically a steam turbine was developed with heat extraction capacity of 1800 GJ/h lower by a factor of 2 than that for bleed turbines of conventional CPPs). The turbine had two regulated steam bleeders and several non-regulated ones, that might be used for additional heating of grid water up to 200 C. In condensing mode of operation the turbine power is 500 MW(e), while in steam-extraction mode at full heat load the power reduces to 450 MW(e). Figu.6 shows the principal flow diagram of the NCPP and its heating facility.



1- stop valve, 2 - medium pressure cylinder, 3- intermediate separator-superheater, 4 - shut-off valve, 5, 7, 8 -low pressure cylinders, 6 - control valves, 9,10 - condensers, 11, 16 - condensate pumps, 12 - ejectors/seals steam coolers, 13 - condensate purification system, 14 - condenser level control valve, 15 - mixing reheater; 17 - low pressure reheater, 18 - drain pumps, 19 - drive turbine condenser, 20 - drive steam turbine, 21 - deaerator, 22 - feedwater pump, 23 - high pressure reheater, 24 - reheater condensate pump, 25 - second stage grid pump, 26 - grid heaters, 27 - grid heaters condensate drain pumps, 28 - first stage grid pump, 29 - grid make - up pump, 30 grid make-up system deaerator.

Fig.6 NCPP's turbine plant principal flow diagram



1 - reactor, 2 - fuel channel, 3 - steam drum, 4 - mixing device, 5 - deaerator, 6 - feed pumps, 7 - emergency feed pump, 8 - turbine, 9 -separator, 10 - condenser, 11 - air coolers, 12 - circulating pumps, 13 - condensate pumps, 14 - low pressure reheater, 15 - ion-exchange filter, 16 - main grid heater, 17 - peak heater, 18 - generator.

Fig. 7 Bilibino NCPP principal flow diagram

Though both projects were canceled after the Chernobyl accident under the pressure of public opinion, the interest and prerequisits for further development of nuclear co-generation are still retained in Russia due to the following reasons:

(i) There is a solid positive experience with operating NCPPs, such as Bilibino, as well as Tomsk and Krasnojarsk NCPPs based on weapon-grade plutonium production reactors.

(ii) Growth in heat load concentration in towns and a significant rise in fuel prices (both fossil and nuclear) enhance the economics of nuclear co-generation.

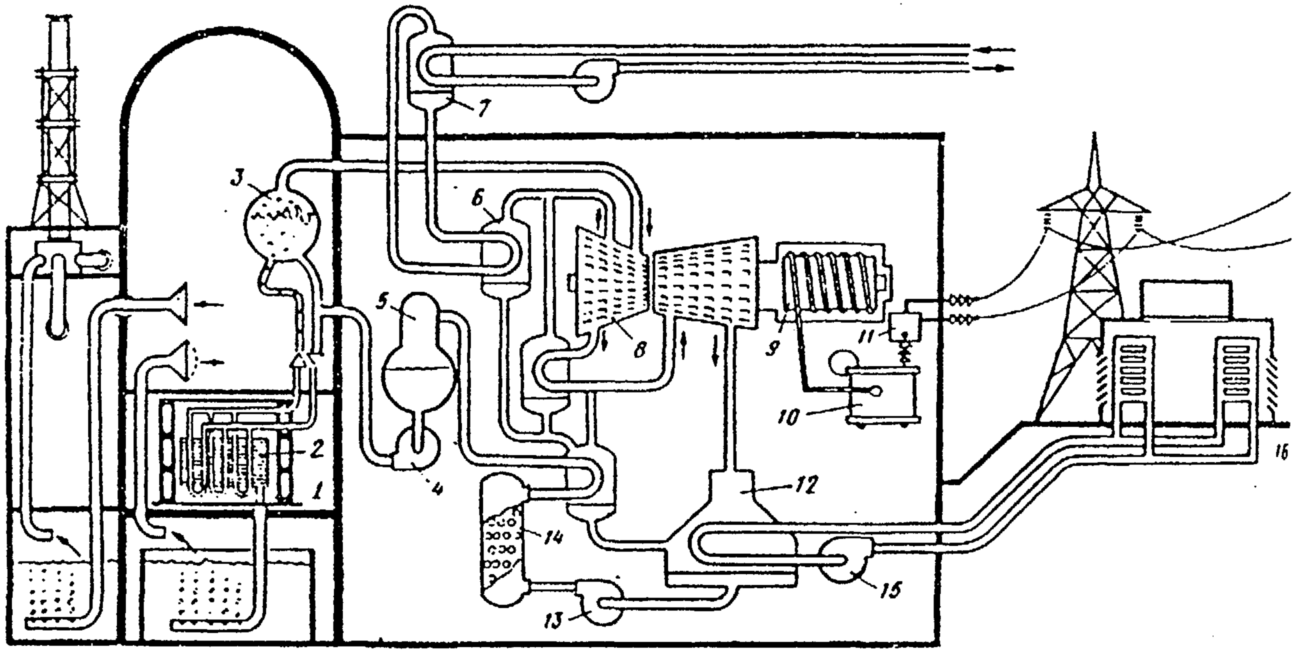
Long-term successful operation of the Bilibino NCPP convincingly demonstrated the economic efficiency and social significance of nuclear heating under specific conditions of the extreme North. Bilibino is the administrative center of important gold-mining region in Chuckot peninsula, far away from the Polar Circle. Severe climatic conditions with extremely low air temperature in winter (down to -60 C) are characteristic for this region, as well as long lasting heating period. Proceeding from the necessity to meet the relatively large demands in heat a NCPP has been adopted as the base energy source for the region. The NCPP comprises of four power units of 12 MW(e) each, that were commissioned in 1974-1976 [8]. At rated electric power, up to 280 GJ/h of heat can be extracted, while maximum heat output (with electric power reduced to 40 MW) is equal to 480 GJ/h (Table 3).

12 MW(e) steam turbines with two regulated and two non-regulated steam bleeders are used in the NCPP. Fig.7 shows the heat transport flow diagram : steam from the turbine bleeders heats water of transmission line (secondary circuit) in the heating facility up to 150 C. This water is supplied to grid HXs located 3.5 km away in a district heating post of the town. Town's heating and potable hot water (65 C) supply grid forms the third heat-transfer circuit. Pressure in heat transmission line is maintained higher (P_{min} = 0.2 MPa) than pressure of heating steam, thus radiological safety of heat consumers is provided. Many years of experience show that the specific radioactivity of grid water is the same as of input water from the local water pond.

TABLE III. BILIBINO NCPP DATA

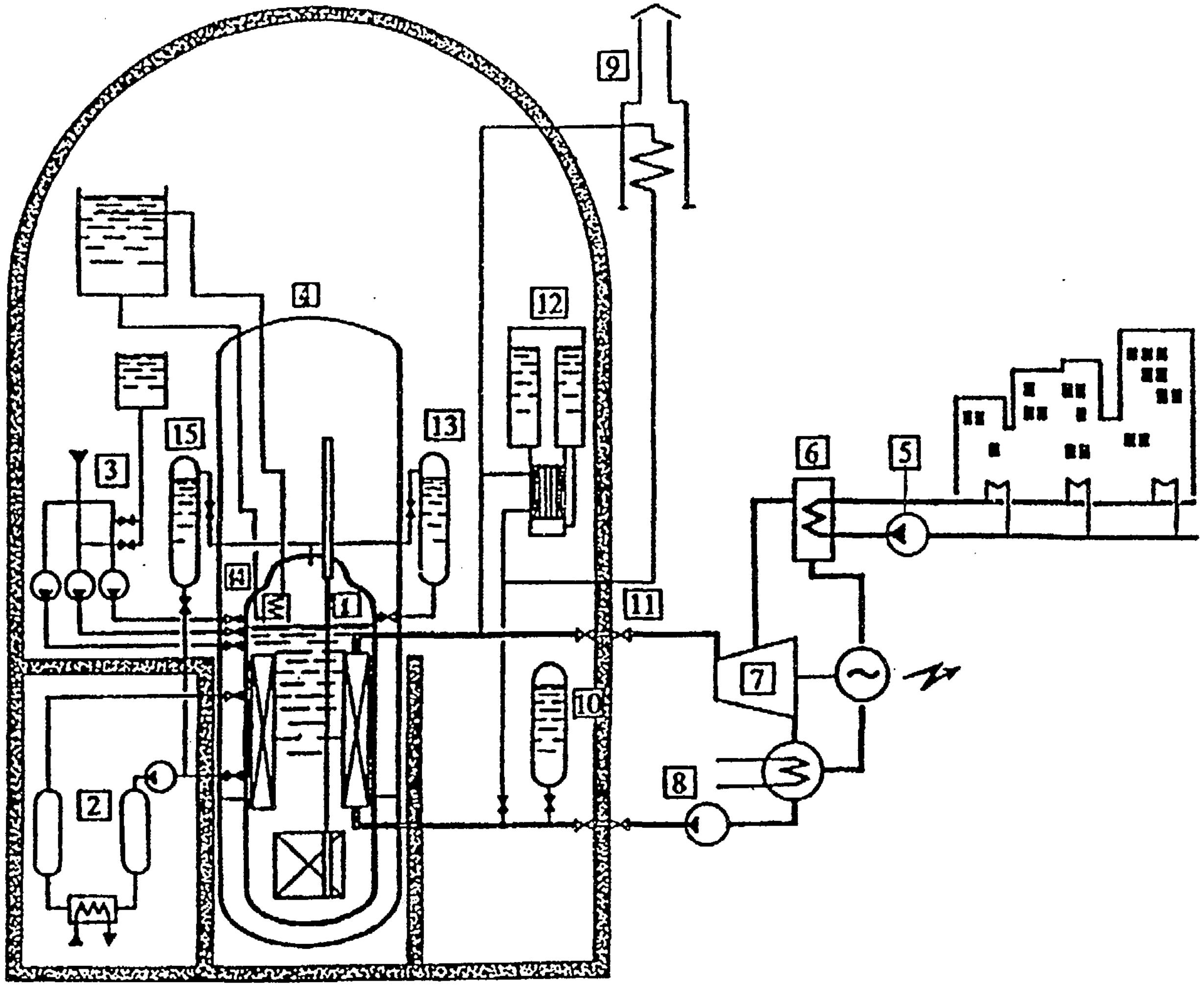
Number of reactor plants	4 (EGP-6)
Reactor type	Channel, uranium-graphite, boiling water, director cycle
Nuclear fuel	UO_2+Mg dispersion, tube configuration
Reactor thermal power MW	62
NCPP rated electric power	48 (4 x 12)
Electric load variation, %	280-480
Reactor coolant parameters	50-100
- pressure, Mpa	6.4
- temperature, ^{o}C	275
Transmission line direct	
water temperature, ^{o}C	150
- direct	95
- return	70
Steam pressure (max) to water heaters, Mpa	1.5
Heat transmission line pressure, Mpa	1.8
Heating grid pressure (max), Mpa	0.6

The NCPP economic indicators turned out to be much better than those for conventional energy sources operating in the region, e.g. cost of heat is 2-2.5 times lower than that from local heating boilers.



1 - channel-type reactor, 2 - reactor core, 3 - steam drum, 4 - feed pump,
5 - deaerator, 6 - heating facility HX, 7 - grid HX, 8 - turbine, 8 - generator,
10 - transformers, 11 - 110 kV switchgear, 12 - condencer, 13 - condensate pump,
14 - condensate clean-up facility, 15 - raw water pump, 16 - air coolers.

Fig.8. Advanced CNPP with ATU-2 nuclear reactor



1 - reactor unit, 2 - reactor coolant purification facility, 3 - water/boric acid make-up system, 4 - guard vessel. 5 - grid pump, 6 - grid HX, 7 - turbo-generator, 8 - feed pump, 9 - air cooler, 10 - secondary coolant storage tank, 11 - containment, 12, 14 - ERHR trains, 13 - emergency core cooling system, 15 - boric acid injection system

Fig. 9. ATEC - nuclear co-generation plant principal flow diagram

The plant solved the fuel and energy supply problem - it saves some 230,000 tons of fossil fuel a year, thus providing for the economic development of the region and creating qualitatively new conditions of life for the local population (reliable heating and hot water provisions, swimming pool, large greenhouse, improved environmental conditions in the town, etc.).

Taking into account, the high efficiency and positive operational experience of the Bilibino nuclear reactors, the design of advanced nuclear reactor (also of channel type) ATU-2 (40 MW(e), heat capacity of 210 GJ/h) has been developed recently [9]. The new NCPP is designed in compliance with the updated requirements for safety, e.g. an additional heat-transport circuit is introduced between heating steam and a grid HX in the nuclear plant flow diagram (Fig.8). Three such reactors were supposed to substitute the existing nuclear reactors of the Bilibino NCPP which are to be removed from operation in 2001-2004.

A number of medium size power units ATEC-80, -150 and -200 for nuclear co-generation plants has been developed recently on the basis of integral PWR [10]. Proven technical decisions and established technology of marine nuclear reactors are used in the designs, along with engineering features and technology of heat-only reactors created in the eighties (see next chapter). The level of safety attained in the design meets the requirements applied to advanced nuclear reactors and removes the sanitary restrictions on deployment of such reactors in heat-consuming centers. Table 4 gives main design characteristics of ATEC- type NCPP, Fig.9 shows its principal flow diagram.

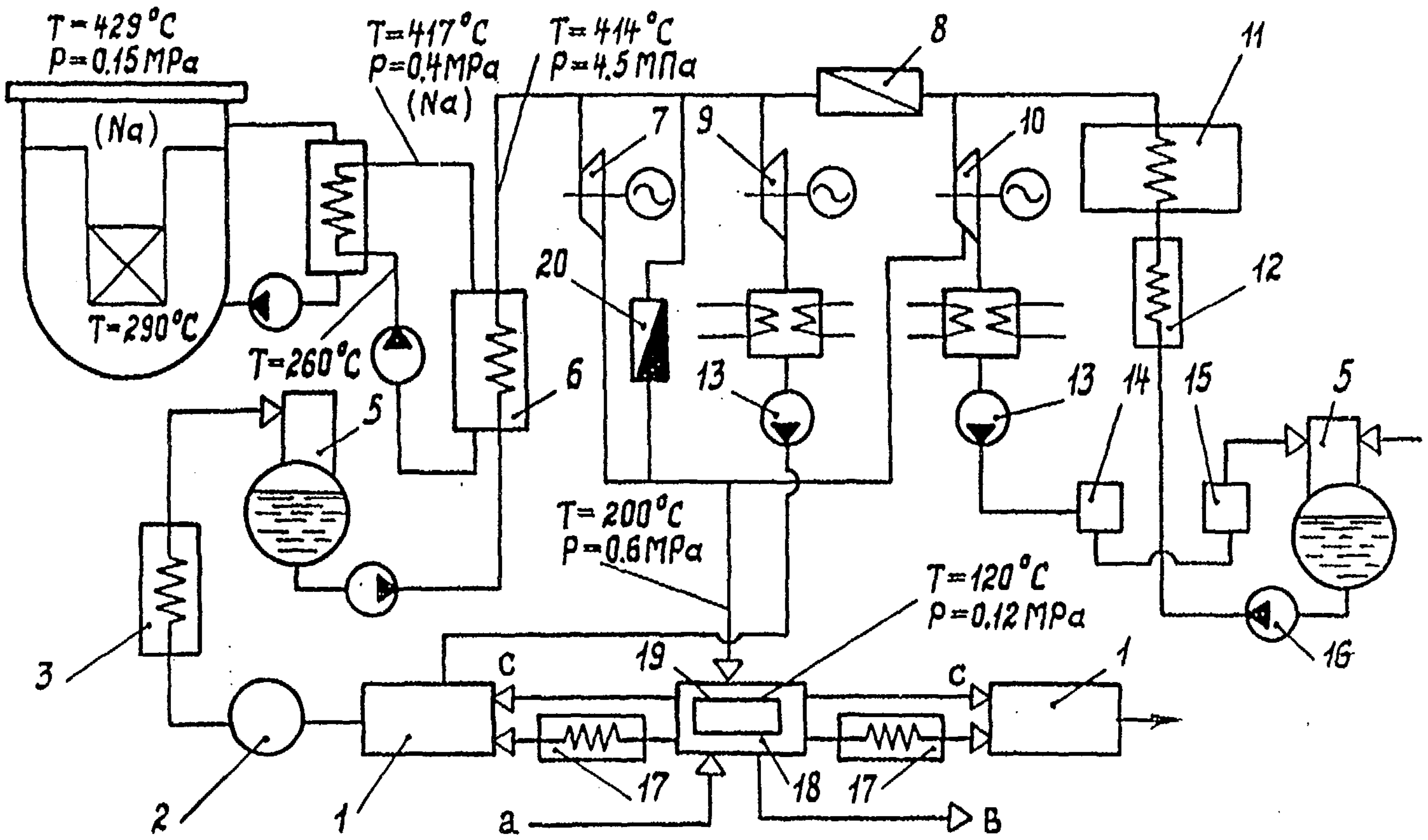
TABLE IV. ATEC-200 DESIGN CHARACTERISTICS

Reactor thermal power, MW	750
Electric power, MW	
- maximum (condensing mode)	250
- heat extraction mode	180-50
Heat output range, GJ/h	1575-2520
Main steam parameters	
- pressure, Mpa	4.4
- temperature, ^{o}C	290
Grid water temperature, ^{o}C	
- direct	150
- return	70
Max. distilled water output (*),m^3/day	290,000
Power demand for water desalination	20 MW(e)

(*) This amount of potable water could be produced when there is no heating load.

These power units have been designed as universal power sources capable of producing electricity and heat in different proportions, to desalinate sea water, to provide steam for industry according to specific demands of the consumers.

At present, the project for deployment of the ATEC-200 units on the site of a large nuclear fuel cycle enterprise in Krasnojarsk region is under consideration. Main objective of the project is to substitute a NCPP operating there for a long time on the basis of a plutonium-production reactor, which has to be decommissioned in 2000. The present demands in heat and electricity of both the enterprise and the town (3150 GJ/h) can be provided by two ATEC-200 power units. Underground location of the new units is planned in existing rock caverns, as well as utilization of available hot water transmission line to a satellite town (5 km). Taking account of its deployment on a site of the large production works, it is proposed to use the NCPP for process steam (1.2 MPa) production as well. The design of a boiling water reactor VK-300 is also considered as an alternative.



1 - water preparation facilities, 2 - vacuum deaerators, 3 - desalted water heater , 4 - feed pumps, 5 - 0.7 MPa deaerators, 6 - steam generators, 7 - back-pressure turbines, 8 - 10/4.5 pressure reduction device, 9 - condensing turbine, 10 - conventional CPP's turbines, 11 - CPP's boilers, 12 - high pressure reheaters, 13 - condensate pumps, 14 - condensate purification facility, 15 - low pressure reheaters, 16 - CPP's feed pums, 17 - heating steam condensate coolers, 18 - desalination facility, 19 - desalinator, 20 - 4.5/0.5 pressure reduction device, a - sea water, b - brine removal, c - distillate.

Fig.10. BN-350 nuclear power - desalination complex principal flow diagram

5. PROCESS HEAT SUPPLY FROM NUCLEAR REACTORS AND SEA WATER DESALINATION

In Russia, industry consumes approximately two times more low-and medium-grade heat than the household sector. More than 60% of the heat is provided by low-pressure steam (dominant pressure level from 0.5 to 1.8 MPa). About 40% of heat consumed by industry is used immediately in technological processes, as well as for heating, air conditioning and hot water supply. Large enterprises have usually their own sources of energy, such as CPPs. Hot water supply for small enterprises can be provided from the town's CHS. In the case, when NPP operates as a base source of heat in a CHS, it bears usually an industrial heat load as well.

The first design of a nuclear plant developed specifically for production of process heat (steam) was realized in a NCPP that has been operating in Shevchenko (nowadays Actau, Kazakhstan). This region represents a lifeless stony desert on the eastern shore of the Caspian sea, rich in various minerals (incl. uranium ore) but deprived in potable water sources. From 1972, the first nuclear power-desalination complex in the would has been operating there with a NCPP ussing the fast reactor, BN-350, and a large seawater desalination plant [11]. Table 5 gives main characteristics of the NCPP and desalination facility, Fig.10 shows the complex flow diagram.

TABLE V. BN-350 NUCLEAR REACTOR AND DESALINATION PLANT CHARACTERISTICS

Reactor thermal power, MW	520 (750)
Electric output, MW(e)	125
Primary sodium temperature, ^{o}C	
- outlet	437
- inlet	288
Main steam parameters	
- temperature, ^{o}C	405
- pressure, MPa	4.5
Desalinator type	multi-stage evaporator
Number of desalinators	9
Desalinators capacity, t/day	5 x 15000
	3 x 14400
	1 x 12000
Total distilled water output, t/day	~100.000
Specific production of distilled water, t water/t steam	7.8-8.1

Back-pressure bleed turbine plants (N=37.5 MW(e)) and one condensing turbine are used in the NCPP. Exhaust steam after the back-pressure turbine (0.6 MPa, 200± 20 C) is supplied to desalinating facilities which represent multi-stage tube-type evaporators operating on the principle of multiple evaporation of sea water. Distilled water produced in the facilities is used to prepare water of drinkable quality. There is a conventional CPP in the complex, which is used as a back-up source of heat for the desalination facility. During 23 years of operation, the plant has demonstrated the reliable and safe performance of nuclear desalination complex playing the essential role of a water source for the population, industry and agricultural enterprises in the region. Availability of well developed sea water desalination technology proved by long-term operation of the prototypes gives grounds for development and creation of various power-desalination complexes of required capacity.

For production of process heat of medium (up to 500 C) and high (up to 950 C) temperatures a number of high temperature gas-cooled reactors (HTGR) was developed in ex-USSR in the 1980s [12]. Different combinations of those reactors with most energy-intensive industrial processes in chemistry, oil-refinery, petrochemistry, oil production industries etc. were deeply studied [13]. Fig.11 shows spheres of possible heat applications. The following were considered as the most promising ones: production of

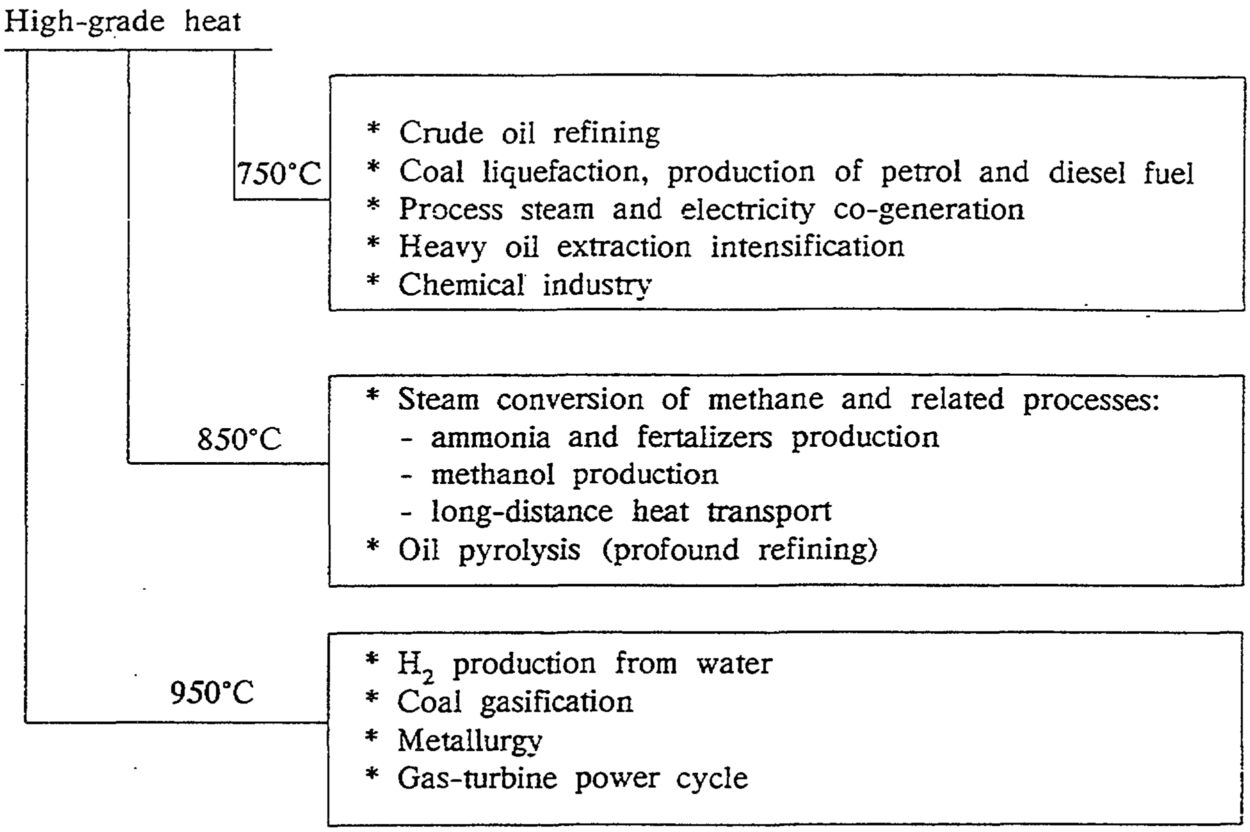


Fig. 11. HTGR process heat applications

ammonia, fertilizers, methanol (synthetic fuel), hydrogen and pyrolysis of oil. An interesting feature of high-temperature heat transmission in chemically bounded form over very long distances (up to 200-300 km) were pointed out. In this case, heat from a HTGR is used initially for steam conversion decomposition) of methane. Mixture of the decomposition products (H_2, CO, CO_2) in "cold" state under excess pressure are pumped through pipes to remote consumers, where a reverse reaction of methane synthesis is performed. The reaction goes on with heat release at temperatures up to 500-600 C. The methane is then returned to the NPP. Advantage of this methodlies in the possibility to cover a large number of dispersed heat consumers by a single large (and consequently economic) nuclear source. Cost of heat transport can be reduced significantly - at least 2.5 times compared with hot water transmission lines.

6. NUCLEAR DISTRICT HEATING STATIONS

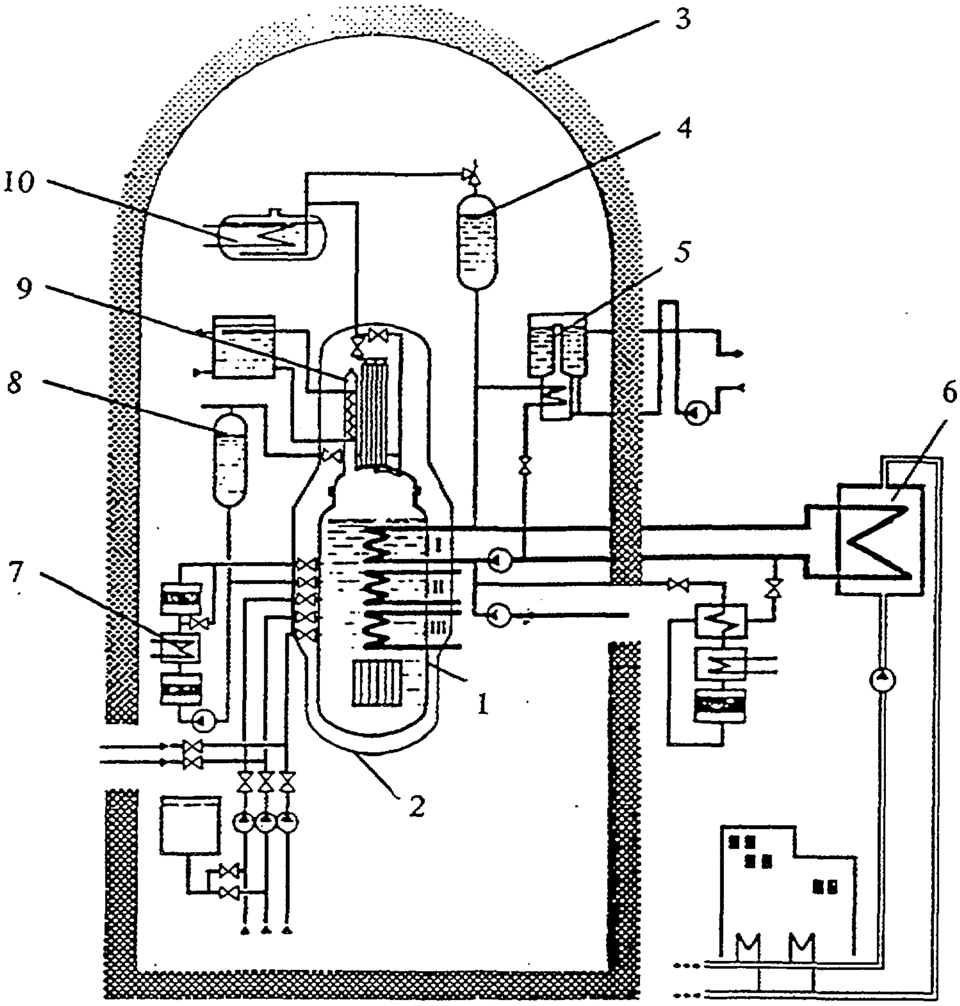
For heating of large towns with significant heat demands and expensive fossil fuel, a heat only low-temperature reactor AST-500 was developed in the late 1970s [14]. From the very beginning, the reactor had been developed as a heat source of enhanced safety to exclude practically any risk to the population from a nuclear heating station (NHS) situated near the center of heat loads. Minimal alienated area and small needs in raw water facilitate NHS siting in the vicinity of towns and in densely populated regions. This simplifies heat transport, while reduced parameters of a reactor coolant and elimination of energy-conversion system give possibility to simplify the structure of a heating reactor and to reduce capital cost of NHS and costs to the CHS.

In the early eighties, construction of two pilot 1000 MW NHSs was started in the cities of Gorky and Voronezh. The NHSs was considered, in that period, as the first stage of an extensive nuclear heating development programme in the country. Significant R&D work was carried out to validate the AST-500 design. Fabrication of the reactor components was established and assembly of the first reactor was almost 90% complete by 1989. Comprehensive safety review of the AST-500 was carried out by an IAEA team in the framework of a Pre-OSART mission, with a positive conclusion in respect of both design decisions and its implementation in Gorky NHS.

According to the design, a twin-unit station in combination with conventional peak sources of heat is capable of providing heat for a CHS with maximum heat demands of up to 2300 MW (8280 GJ/h), which corresponds to a town with 350-400 thousand inhabitants [15]. Radiological safety of consumers is provided by three-circuit heat transport scheme, with a pressure barrier between the second (intermediate) and third (grid) circuits (Fig.12). The NHS enables closing about 300 small heating boiler plants which are sources of significant air pollution. At base load operation for the entire heating period (4500-5500 h/a), the NHS provides about 78% of annual heat consumption of a town, producing more than 16 million GJ of heat, equivalent to burning some 700,000 tons of fossil fuel (oil equivalent). Substitution of such quantity of fuel means that the NHS reduces emission of SOx by 20,000 t and NOx by 2000 t a year. However, in spite of significant anticipated socio-economic benefits and positive conclusions of the IAEA review team on the safety level of the plant, construction of all NHSs in the country has been suspended in the early nineties under the pressure of political factors.

The influence on NHSs economics of such factors as the level of heat loads in a CHS, cost of fossil fuel, operating factor etc. has been investigated lately [16]. As it was shown, NHS efficiency rises with increases in heat loads in a CHS and fossil fuel cost.

It was concluded that the following decisions might be adopted to enhance economic efficiency of NHSs: increase in rated thermal power, connection to a NHS additional heat consumers, production of process steam and electricity, that would enable use of underloaded heat capacity of a NHS in summer, when main (heating) load is not in demand. A study of the potential of NHSs showed that up to 120% increase in rated power can be attained in periods of seasonal rising ambient temperature by lowering the return grid water temperature. There is also a possibility to use a NHS to provide potable hot water demands in summer.



1 - reactor, 2 - guard vessel, 3 - containment, 4 - pressurizer, 5 - RHR HX, 6 - grid HX, 7 - reactor coolant purification system, 8 - boric acid storage tank, 9 - RHR condenser, 10 - bubbler tank

FIG. 12. AST-500 principal flow diagram

To produce electricity a NHS is coupled with a turbine plant operating on saturated steam with pressure of 0.12-0.13 MPa. Maximum electric capacity of one AST-500 unit ranges from 15 to 50 MW(e) depending on the turbine type (condensing or back-pressure one). Selection of a configuration for each design depends on the specific structure and value of heat demands and other particular conditions.

Even though the nuclear heating programme has suffered due to adverse public opinion in the post-Chernobyl period, the prospects for NHSs are still encouraging. State review of ecological safety completed this year for Voronezh NHS, resulted in a favorable conclusion on the possibility to resume construction of the station. Moreover, a special decision of the local authorities has been released removing the hold on construction. On receipt of the official permission from the state regulatory body GAN, the station construction will be resumed in 1996.

Besides, a project for construction of a twin-unit NHS on the site of a Siberian chemical plant is under consideration now. The main objective of the project is to substitute an operating heat source at Tomsk (18 km away, heat output of 2000 GJ/h) consisting of two plutonium-production nuclear reactors which will have to be decommissioned by 2000 in compliance with the Treaty for strategic weapons reduction. To shorten the station construction period it is supposed to use available components of the AST-500 reactor plant erected on the canceled NHS in Nizhny Novgorod (former Gorky).

Besides, the AST-500, a number of small heating reactors is under development in Russia with distinctive design approaches and features. One of the designs - "Ruta" represents a number of pool-type nuclear reactors of atmospheric pressure with heat capacity of 10, 20 and 55 MW [17]. A feasibility study is being carried out now for construction of a NHS with these reactors in transpolar town Apatit on Kola peninsula.

7. SMALL NPPS FOR HEAT AND ELECTRICITY PRODUCTION

Activity on small nuclear plants (SNPs) for implementation in remote and difficult-to-access regions to provide electricity and heat supply to isolated consumers has been started in the ex-USSR as long ago as the fifties. Particular interest in this energy source is traditionally connected with the existence in the North and North-East of Russia, vast territories (more than a half of the country's total area) where production and delivery of energy are especially difficult tasks. It is connected with the necessity in large-scale seasonal transportation of fuels over distances of thousands of kilometers under severe natural conditions. Therefore, cost of fuel in some regions of Extreme North is determined almost completely (80-90%) by transport cost, and the cost of electricity and heat turned out to be 10-20 times higher than that in other regions of the country.

Due to the very low density of population and relatively small demands in energy, remoteness of consumers from centralized energy-supply systems, small self-balancing power grids and autonomous energy sources are prevailing there. So, in the northern regions of Russia more than 10,000 small power plants (200 kW capacity in average) mainly of a diesel type are being operated, along with many thousands of heating plants of several GJ/h average capacity. Under such very specific conditions SNPs can be considered as an economically acceptable alternative to traditional sources of energy.

Practical utilization of nuclear fuel for energy production in the Far North was started in Russia by putting into operation the Bilibino NCPP (1974). In the mid eighties a comprehensive study had been carried out by a large group of specialists, concerning prospective demands in electricity and heat for settlements over the northern regions of Russia and energy sources necessary to meet those demands [17]. It was concluded in the study, that for some 90 settlements SNPs could be considered as an acceptable alternative, and co-generation nuclear plants of 6, 12, 25 and 40 MW(e) unit power were selected as the most appropriate sizes for this purpose. The first programme planned for the period until 2000 envisaged construction of SNPs on 33 sites in the North, but it was canceled after Chernobyl accident.

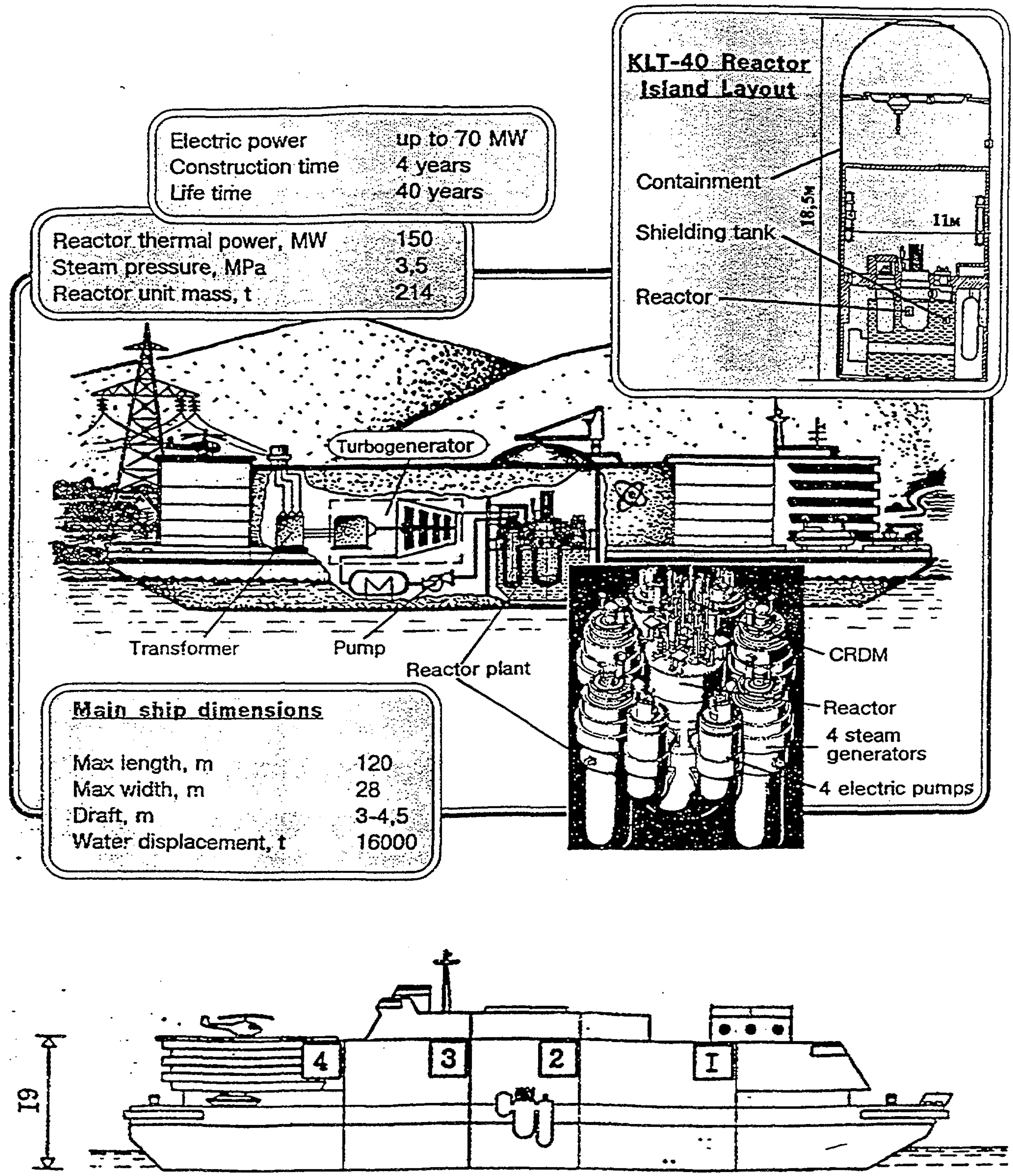


Fig. 13. Twin-KLT-40 floating NCPP

In 1989 a new proposal was validated on construction of SNPs on nine sites situated nearby large gold-mining enterprises in the regions of northern and eastern Siberia [18]. In that period, development of a number of advanced nuclear reactors was started specifically for SNPs to meet the updated safety requirements and to correspond better to the specific conditions of operation in northern regions. A common feature these designs is universality in application options by virtue of the capability to provide energy supply to various consumers with widely different levels and structure of electrical and heat demands. The designs ready for implementation are based on utilization of marine nuclear reactor technology, especially well developed in Russia [19].

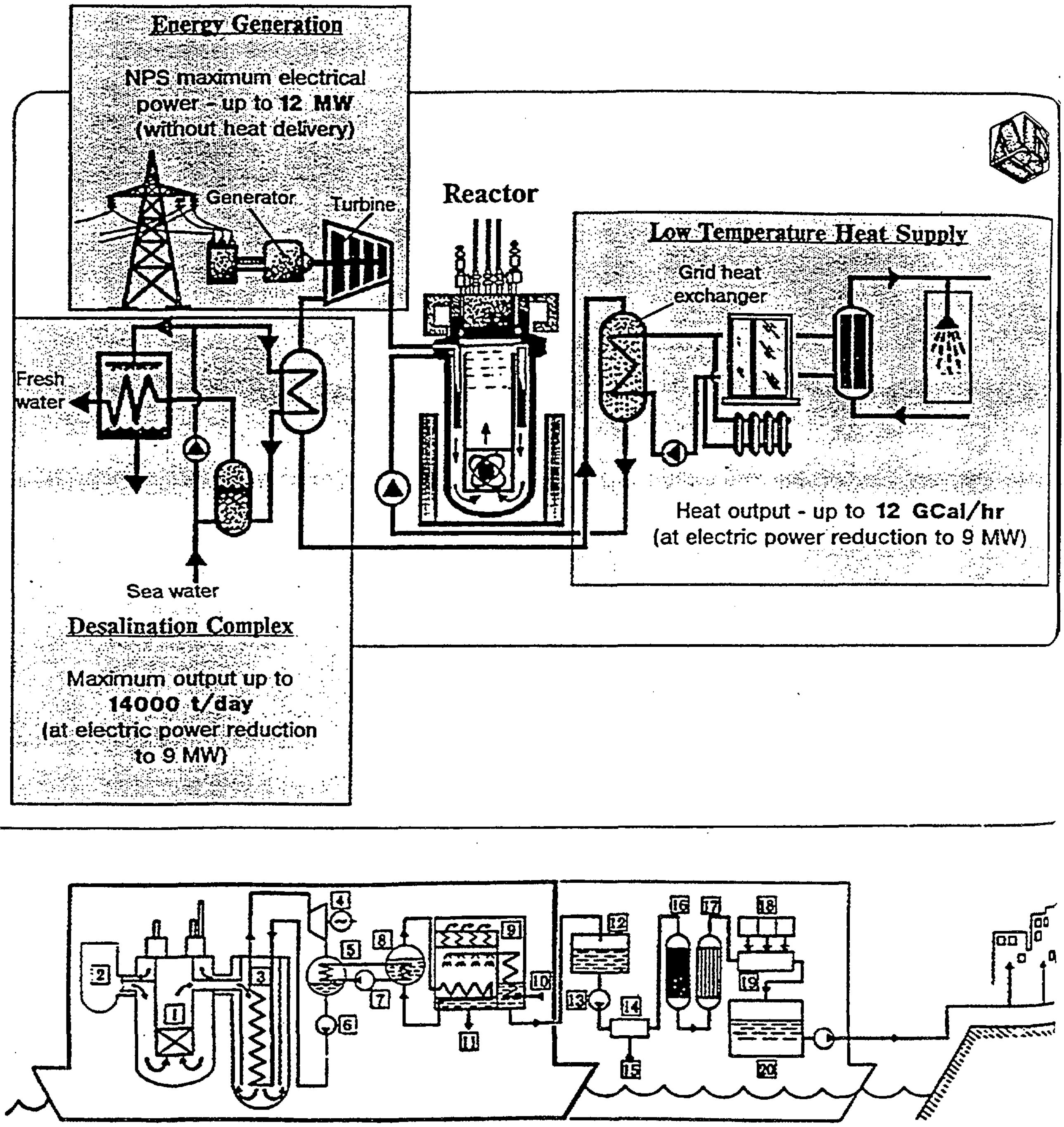
The KLT-40 NPP is based upon serially produced nuclear steam supply systems (NSSS) used in atomic ice-breakers and in ocean-going lighter-carrier "Sevmorput" [20]. Long and highly successful operational experience with this reactor under severe Arctic conditions (total operating record exceeds 140 reactor years), in combination with established technology of nuclear ship construction, operation and maintenance, gave grounds to propose a floating small-power NCPPs with two NSSSs of KLT-40 type.

The floating SNP represents a special non-self-propelled ship (Fig.13) which will be built and equipped with NCPP completely at a specialized shipyard, similar to a nuclear icebreaker. After the completion of trial tests and commissioning on a turn-key basis the floating SNP will be towed by water to the region of deployment. There the plant is connected to shore-based transmission lines (electrical and heat-transport) and can be commissioned quickly. The plant is designed for siting in protected water areas (artificial bay or backwater area) of seas or rivers. There is a possibility to change the plant location, if necessary. The entire complex of maintenance work for floating SNPs, including repairs, refueling of the reactors and evacuation of radioactive waste can be fulfilled by available atomic fleet base-ships using established technology. After expiration of the plant lifetime it will be towed to the atomic fleet base in Murmansk to provide all necessary work for decommissioning. These features allow significant reduction on the capital cost of the plant, faster construction and improvement in construction quality, elimination of the need for a large-scale industrial building and creation of local infrastructure under specific conditions of the extreme North. The construction time of the pilot floating SNP is only four years, and subsequently 2 or 3 units could be built in a year. Main characteristics of the SNP with KLT-40 NSSS are given in Table 6, along with data on an other design of a smaller floating plant based on the ABV integral PWR [21]. This design is also ready for construction.

TABLE VI. MAIN CHARACTERISTICS OF FLOATING SNPs

Characteristic	Reactor type	
	KLT-40	ABV
NSSS rated thermal power, MW	160	6
Number of NSSSs	2	2
Max. electric output, MW	2 x 35	2 x 12.5
Electric output, MW	2 x 25	2 x 8
at simultaneous heat output, GJ/h	2 x 400	2 x 85
Operating range of power variation, %	10-1000	10-100
Average load factor, %	up to 85	up to 85
Draught of ship, m	4.5 (3.5)	2.5
Displacement of ship, t	16000	8700
Oprating personnel	55	45

Both the SNPs are designed to operate over a wide range of loads with various ratios of electrical and heat demands. Along with hot water supply for households, a process steam and potable water production can be also provided. At present, feasibility study is under way for building a pilot floating SNP in a large transpolar port Peveck on a coast of the Arctic Ocean.



1 - reactor, 2 - reactor coolant pump, 3, 8 - steam generator, 4 - turbo-generator, 5 - condenser, 6,7 - secondary and intermediate circuit pumps, 9 - distillation desalination facility, 10 - sea water intake, 11 - brane - removal, 12 - distillate storage tank, 13 - potable water preparation system pump, 14 - mixing device, 15 - H_2CO_3 solution, 16, 17 - filters, 18 - water fluorization, cloriding and stabilization facility, 19 - mixer, 20 - potable water storage tanks.

Fig. 14. APVS-80 nuclear floating sea-water desalination plant

On the basis of KLT-40 NSSS, the design of floating sea-water desalination plant (80,000 m^3/day potable water capacity) has also been developed (Fig.14). This design has been thoroughly reviewed in the framework of the special IAEA programme on nuclear desalination and attracted considerable interest. Small reactors of this type allow large-scale potable water production without off-site power consumption and are independent of the availability of indigenous industrial infrastructure.

8. CONCLUSIONS

Extensive experience has been gained in Russia in the field of nuclear heat applications, particularly for district heating and hot water supply to both household and industrial consumers. Notwithstanding serious restrictions on the national nuclear power development caused by macro-economic and social (public opinion) factors, requirements for nuclear heat applications are still existing in the country. Factors favouring nuclear heat applications are a significant rise in fossil fuel prices, fuel shortages in a number of industrial regions and adoption of more stringent requirements for environmental protection.

Investigations performed lately have validated that the following directions in nuclear heat applications have good prospects for the conditions characteristic of Russia:

1) Further expansion of heat supply from NPPs (both operating and under construction) by increase in steam extraction from nonregulated steam bleeders of condensing turbines. At present it is the most proven and studied method of nuclear heat utilization. Its reliability, safety and economic efficiency have been validated by operational experience in Russia.

2) Building of heat only nuclear stations in towns where acute shortage of heat generation capacities exist. Currently, expensive fossil fuel is used and the environment is polluted heavily. The enhanced safety reactor plant AST-500 has been developed to this end. The plant has proven engineering features and established technology of manufacturing and erection. There is a potential for further improvement of the NHSs economics. The AST-500 design has been reviewed by an IAEA team in the framework of a Pre-OSART mission in 1989. Resumption of building on the Voronezh site of two AST-500 units is awaiting clearance. Some other projects are also under consideration.

3) Creation of universal co-generation NPPs for combined production of electricity and hot water (for household and industry) and/or process steam, as well as for potable water production by sea water desalination.

For this aim advanced reactor plants and nuclear power units can be used which are characterized by enhanced safety, improved reliability and better economics.

Economic viability of either of the nuclear heat sources depends greatly both on the structure of energy demands and level of expenditure on fossil fuel for the given region. For isolated and remote regions with expensive fuel and small decentralized energy requirements (e.g. regions of the North of Russia) even small nuclear co-generation plants (up to a few tens of MW(e) could be an economically attractive alternative.

A number of small CNPP designs has been developed ranging from 10 to 250 MW(e) with heat capacity from 80 to 2000 GJ/h. Most of them are based on well-developed and established technology, have operating or manufactured prototypes and are ready for implementation.

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