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Nuclear Desalination Complex with VK-300 Boiling-Type Reactor Facility

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Abstract

With regard to the global-scale development of desalination technologies and the stable growth demand for them, Russia also takes an active part in the development of these technologies. Two major aspects play a special role here: they are providing the desalination process with power and introducing new materials capable of making the production of fresh water cheaper and of raising the technical reliability of desalination units.

In achieving these tasks, the focus is on the most knowledge-intensive issues, to which Russia is capable of making its contribution based both on the experience of developing national nuclear power and the experience of developing, manufacturing and operating desalination units, including the use of nuclear power (the experience of BN-350 in Aktau (formerly Shevchenko), Kazakhstan).

In terms of design, the Nuclear Desalination Complex (NDC) with a VK-300 reactor facility is a modification of a nuclear power unit with a VK-300 reactor developed for application at Russian nuclear cogeneration plants. A power unit with a VK-300 reactor has a design power of 250 MW(e) with the turbine unit operation in the condensation mode. In modes with the heat supply for desalination needs, up to 400 Gcal/h of thermal energy can be used as steam from turbine extractions with the simultaneous electricity generation by the turbine generator of about 150 MW.

The report considers a VK-300 reactor based NDC with multi-stage evaporation principle (MED) based distillation desalination units with horizontal-tube film evaporators. Russia has an extensive experience of commissioning and long-term commercial operation of domestically built desalination units with horizontal-tube evaporators of different power (from 0.1 to 700m^3/h). Seawater desalination units built on their basis are more economic than evaporators of other types - by a factor of 1.5-2.0 in terms of the energy consumption and by a factor of 1.5-1.8 in

terms of the specific quantity of metal and the development area. With regard to the power unit capabilities of supplying heat for desalination (200-400 Gcal/h) as part of an NDC with a VK-300, it is expedient to use distillation units with a higher unit capacity.

The most attractive option is coupling the VK-300 energy source with distillation desalination units based on the multi-stage evaporation principle (MED). This is the effective NDC structure allowing the use of turbine steam extractions for heat supply (via the intermediate circuit) to the desalination system producing high quality distillate. As it provides with thermal energy a desalination complex with a capacity of 300 000m^3 per day, a nuclear plant consisting of two VK-300 power units allows production of distillate with the cost of US$0.58 per m^3. In this case, the electricity supply to the power system is 357 MW(e). The electricity cost is US$0.029 per kWh.

1. Introduction

Climatic conditions in most of the Russian territory are severe, which stimulates the development of nuclear reactors not only for electricity production but also for heat generation for district heating. Thus, since 1974 Russia has been operating the Bilibino Nuclear Cogeneration Plant, providing safe nuclear electricity and heat supply of the city of Bilibino and the surrounding area (1). Power plant settlements near nuclear power plant are also supplied with heat and hot water from NPPs. Therefore, Russia has an experience of safe nuclear heat generation for public services (more than 2 million Gcal/year).

With regard to the global-scale development of desalination technologies and the stable growth demand for them, Russia also takes an active part in the development of these technologies. Two major aspects play a special role here: they are providing the desalination process with power and introducing new materials capable of making the production of fresh water cheaper and of raising the technical reliability of desalination units. In achieving these tasks, the focus is on the most knowledge-intensive issues, to which Russia is capable of making its contribution based both on the experience of developing national nuclear power and the experience of developing, manufacturing and operating desalination units, including the use of nuclear power (the experience of BN-350 in Aktau (formerly Shevchenko), Kazakhstan).

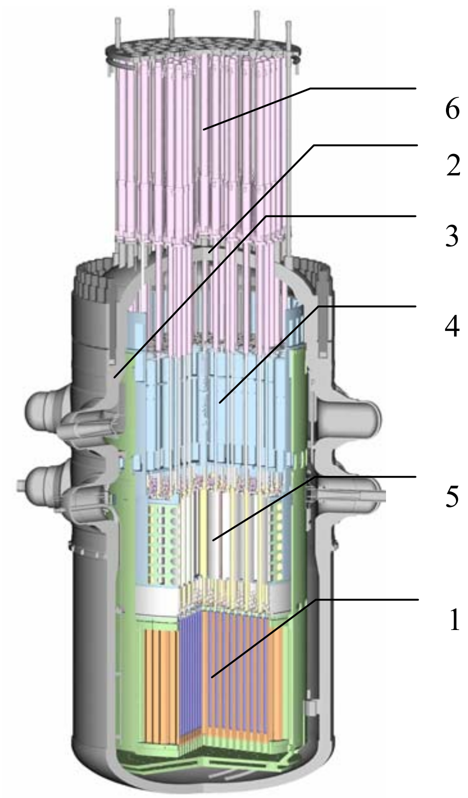
In terms of design, a desalination complex with a VK-300 reactor facility is a modification of a nuclear power unit with VK-300 reactor (2) developed for application at Russian nuclear cogeneration plants. A power unit with a VK-300 reactor has a design power of 250 MW(e) with the turbine unit operation in the condensation mode. In modes with the heat supply for desalination needs, up to 400 Gcal/h of thermal energy can be used as steam from turbine extractions with the simultaneous electricity generation by the turbine generator of about 150 MW.

The development of the VK-300 reactor facility for nuclear cogeneration plants was started in 1997 to replace the operating plutonium production reactor of the Krasnoyarsk Nuclear Complex of Russia. It was caused by Russia's international obligations to limit the production of weapons grade plutonium. The Russian Ministry for Atomic Energy suggested a task of developing a nuclear reactor facility based on proven technologies assimilated in Russia with the aim for the industry to manufacture the equipment and reactor components with the use of a small scope of R&D work as possible.

2. Technical characteristics of the VK-300 reactor facility

The VK-50 reactor in operation in Russia is considered as the prototype of the VK-300 reactor. The experience of designing and operating a small-power VK-50 boiling-type reactor in Dimitrovgrad has been useful in developing the VK-300 reactor. International achievements in the field of designing and operating boiling-type reactors have been also taken into account, primarily as far as the design of passive safety systems. The VK-300 design features are based on the use of equipment components developed and manufactured for other reactor types. For example, it is the vessel of the VVER-1000 reactor. It is evident that the design and commercialization of a new pressure vessel for a power reactor is a complicated, time-consuming and expensive task. So the use of a ready component (a power reactor vessel) facilitates the task of development of the VK-300 reactor. Russia possesses production facilities for manufacturing such pressure vessels. VVER-1000 fuel elements, RBMK neutron flux sensors and fission chambers are used in the VK-300 reactor core. Cyclone separators that were designed and experimentally optimized for being used in vertical steam generators of VVER-1000 are installed in the reactor. Therefore, the design of the VK-300, an innovative boiling-type reactor, uses many equipment components technologically optimized and having the experience of operation. The same principles were used also in the design of other plant equipment (turbine, heat exchanging equipment, pumps) that also has operating prototypes. The general view of the VK-300 reactor is shown in *Figure 1*.

Figure 1.



General view of the VK-300 reactor:
1 – fuel assemblies; 2 – reactor lid; 3 – reactor vessel; 4 – steam separators;
5 – natural circulation guide tubes; 6 – control rod drivers

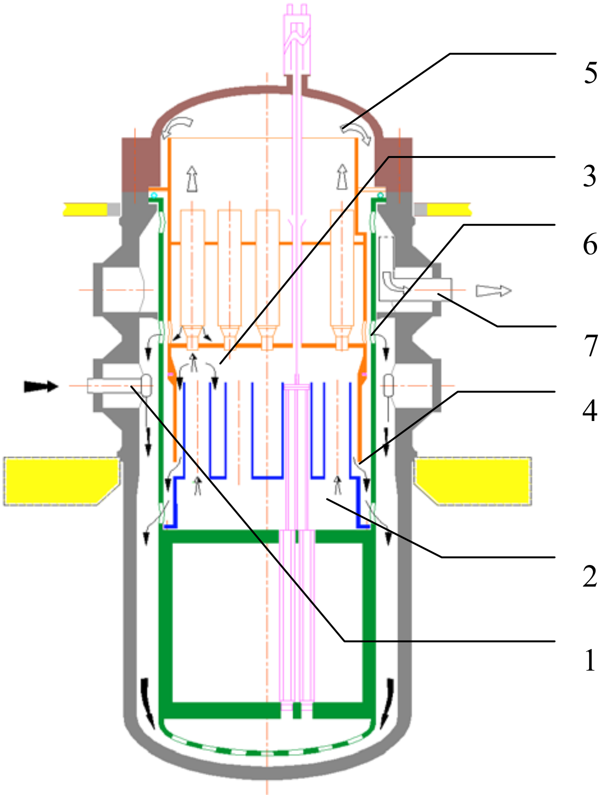
The main technical characteristics of the reactor are shown in the following table:

Nominal thermal power of the reactor, MW	750
Nominal evaporative capacity, t/h	1370
Reactor steam pressure, Mpa	6.8
Reactor outlet steam temperature, ^{o}C	285
Reactor outlet maximum steam humidity, %	0.1
Feedwater temperature, ^{o}C	190
Average mass steam content at the FA outlet, %	15.6
Core dimensions (height × equiv. diameter), m	2.42 × 3.16
Fuel enrichment, %	3.6
Fuel burnup, MW·day/U kg	41.4
Fuel campaign life: effective days calendar days (at the capacity factor of 0.8)	 437 546

3. Simplified diagram of the natural circulation and separation in the reactor

The reactor core is cooled during normal operation of the reactor and in any emergency by natural coolant circulation. The VK-300 design uses a unique system of coolant circulation and multi-stage separation in the reactor. We know that the entire steam-water mixture flow upstream of the core in most of the boiling-type reactors with internal steam separation goes to the separators (normally, cyclone type) where moisture and steam are separated. With a high flow rate of the steam-water mixture, the hydraulic resistance of the separators turns out to be significant. By preliminarily extracting moisture from the flow and delivering it back to the core inlet, we can reduce the mass flow rate via the separators and thus ensure a lower hydraulic resistance of the circuit and, as a consequence, raise the natural circulation rate. The arrangement of the circulation and separation circuit in the reactor is shown in *Figure 2.*

Figure 2.



VK-300 circulation and separation diagram:
1 – feed water; 2 – out-core-mixing chamber; 3 – preliminary separation chamber; 4 – pre-separated water outlet; 5 – steam; 6 – major separated water; 7 – stream outlet

An important component of the natural circulation circuit is a lifting tube unit that performs a number of functions:

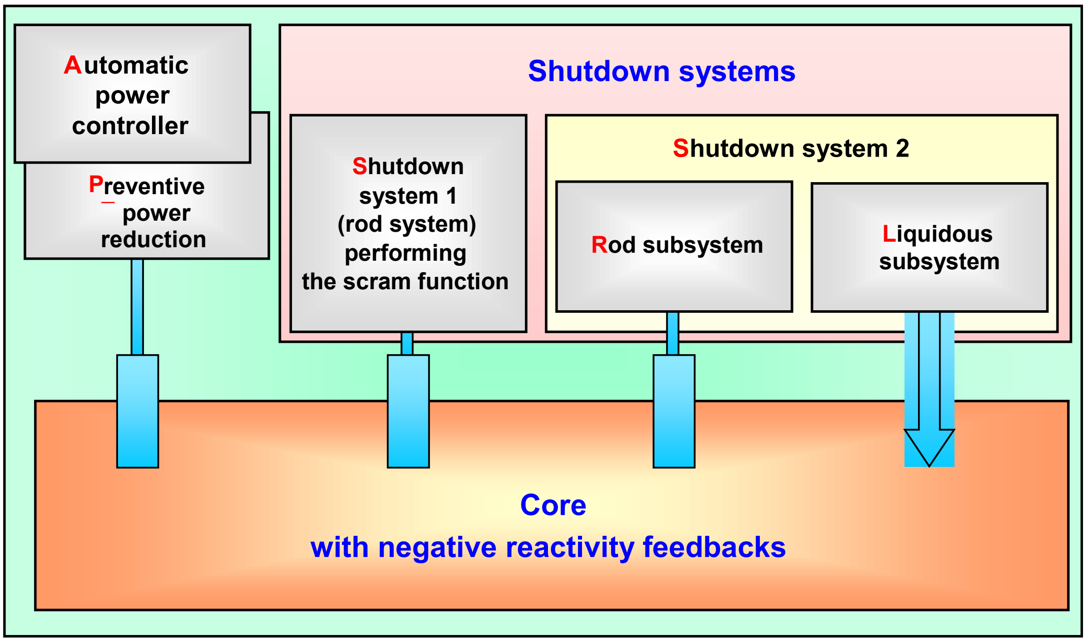
- forms the raising and downstream coolant flows in the reactor;
- preliminarly separates moisture (the possibility of moisture separation after the steam-water mixture exits from the lifting tube unit has been proved experimentally);
- buildup of the water inventory (between lifting tubes) that immediately goes back to the core in the event of the reactor shutdown or during accidents;
- creates a guiding structure for the reactor control rods (which is very important at the upper location of the CPS drives).

4. Control of the chain fission reaction

Very important for the successful control of the chain fission reaction are reactivity effects and factors that form the basis for the guaranteed controllability and stable operation of the reactor. The VK-300 reactor has just a small reactivity margin for nuclear fuel burn-up thanks to partial overloading and use of burnable absorbers. Minimization of the reactivity margin creates pre-conditions for designing a simpler CPS system with "light" rods, which mitigates the consequences of accidents with the CPS rod withdrawal.

The reactor is provided with two reactivity control systems *(see Figure 3)* that use different principles of action. The first of the system is a traditional rod system including 90 drives of the CPS. Each of the drives simultaneously moves control rods installed in three adjoining fuel assemblies of the core.

***Figure 3.* Reactor facility protection in terms of the power control function**



The second reactivity control system is a liquid system intended for introducing boric acid solution to the reactor coolant at failures of the rod reactivity control system. The system consists of pressurized hydraulic accumulators with a boric acid solution.

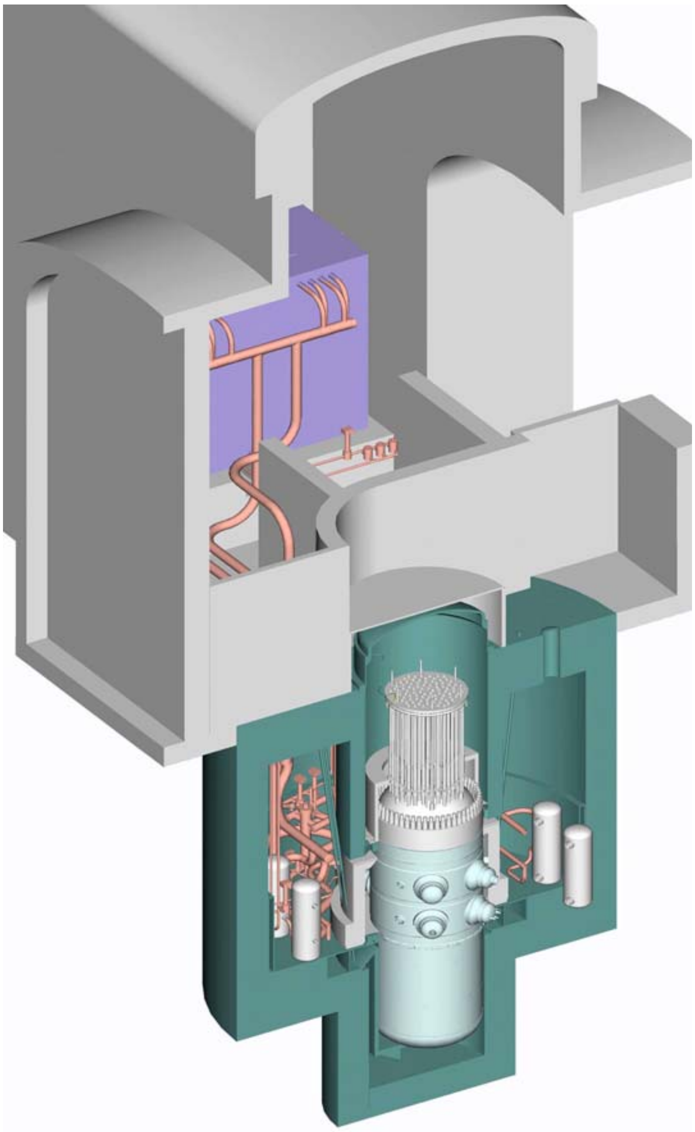
5. Primary reactor containment and passive safety assurance during accidents

Another innovative feature of the VK-300 project is the application of a metal-lined primary containment (PC) of reinforced concrete. The PC helps to solve the safety assurance problem economically and reliably using structurally simple passive safety systems. The PC is rather small (about 2000m^3). It performs the functions of:

- a safeguard (additional) reactor vessel;
- a protective safety barrier limiting the release of radioactive substances during accidents with ruptures of steam, feedwater and other pipelines immediately near the reactor;
- providing the possibility of the emergency core cooling by the reactor cooling water making additional water inventory unnecessary.

Figure 3 presents a simplified diagram of the reactor plant hydraulics. The figure shows components of the safety systems inside the PC as well as emergency cooldown tanks (ECT) and heat exchangers for heat removal from the ECTs to the end absorber (atmospheric air) outside the PC. *Figure 4* shows the arrangement of the PC components inside the PC and the ECT location in leak-tight rooms of the reactor plant.

Figure 4. **Reactor facility equipment arrangement**



The emergency cooldown tanks contain the water inventory for emergency reactor flooding and core cooling during steam or water line ruptures within the PC. Besides, the ECTs perform the functions of:

- accumulating the reactor energy with the potential of transferring it to the end absorber for an unlimited time period;
- compensating the cooling water inventory in the reactor during accidents by returning the condensed coolant to the reactor;
- receiving steam or steam-water mixture (for example, the exhaust of the reactor safety valves installed inside the PC).

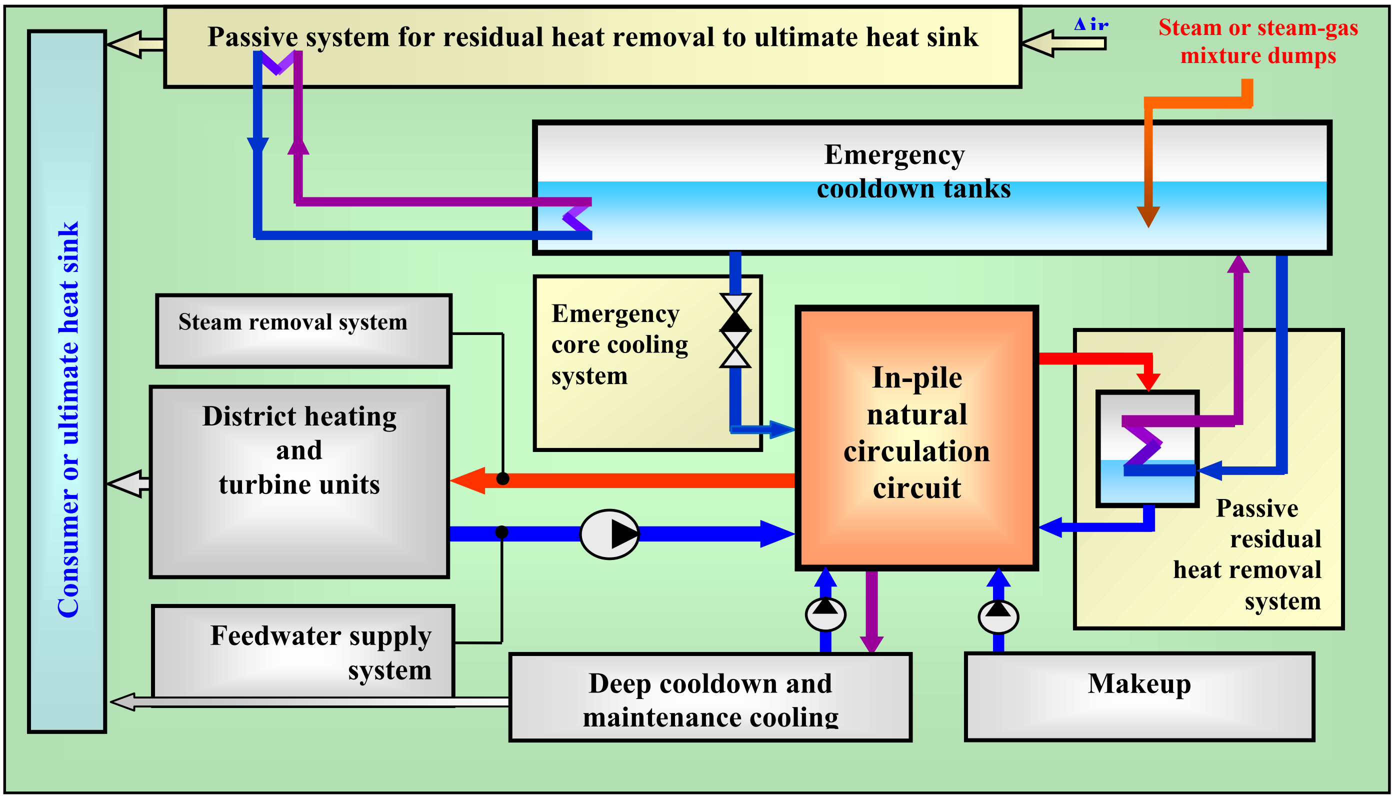
Pressure grows inside the PC during accidents caused by a rupture of a steam line or feedwater pipeline adjoining the reactor within the containment, which serves as a signal for actuation of the reactor scram and passive closure of shutoff devices (valves) cutting the reactor off the external steam-water lines. A pressure reduction in the reactor as the result of the coolant leak through the rupture creates conditions for the water delivery from the ECTs to the reactor via a special pipeline under the action of hydrostatic pressure. The steam-air mixture goes via discharge pipelines from the containment to the ECTs where it is condensed. As a result, a circulation circuit of the ECT – reactor – PC – ECT is formed and its function ensures long-term passive cooling of the reactor.

Another class of the reactor plant normal operation violations is connected with the loss of the heat removal from the reactor as the result of failures or false operation of components of the system for steam removal to the turbine or feedwater supply to the reactor. The primary task following the scram actuation is to receive the residual heat from the shut down reactor and ensure its normal cooldown.

This function is performed by the residual heat removal system (RHRS) that passively removes heat from the reactor in special heat condensers located inside the PC. The condensers are connected to the reactor by pipelines that are filled with water during normal operation of the reactor. As the water level decreases in the reactor, the upper pipeline opens for the steam passage from the reactor to the condensers and the resultant condensate goes back to the reactor. The RHRS condensers are cooled with water from the emergency cooldown tanks. The system is fully based on passive principles of action and ensures natural heat transport from the reactor to the emergency cooldown tanks.

Therefore, heat from the reactor is accumulated in the emergency cooldown tanks in emergencies. The water inventory in the tanks has the thermal capacity that is sufficient for taking up the residual heat of the shut down reactor during 24 hours autonomously (i.e. without heat removal from the tanks and without personnel interference) without boiling. It is possible to make this time interval as long as appropriate thanks to the operation of the system for heat removal from the tanks to the end absorber (RHRS EA). This is a simple and reliable system, being a natural circulation water circuit including heat exchanging apparatus sunk in the ECT water at the one end and atmospheric air cooled heat exchangers beyond the reactor department rooms at the other end. The RHRS EA maintains the ECT water temperature mode by removing heat from the tanks during normal operation of the reactor and is capable of ensuring long-term passive reactor cooldown in emergency conditions. *Figure 5* schematically shows the interaction of the main systems ensuring nuclear fuel cooling in the reactor during normal operation of the power unit and in emergency conditions.

Figure 5. **Interaction of the main reactor facility and power unit systems providing nuclear fuel cooling**



6. Power unit containment

As noted above, the reactor is encircled by the PC that ensures reactor isolation during accidents. And to exclude the activity escape to beyond the PC during reactor accidents, the containment leak-tightness is evaluated by the value of 1% of the volume per day with the maximum design pressure in the containment of 0.65 MPa. Therefore, the PC is one of the main barriers preventing the spreading of radioactivity beyond the reactor facility.

At the same time, taking into account the necessity of deploying the reactor within the city limits, with regard for the single-circuit layout and the necessity of raising the reliability of the environmental protection during accidents, the power unit design stipulates that all of the power unit will be within a leak-tight enclosure (the containment). The containment accommodates the PC with the VK-300 reactor, emergency cooldown tanks, turbine, spent fuel storage pools, refueling machine and central hall crane. The electric generator is installed in a separate annex outside the containment using a shaft that passes through the containment wall to beyond the containment. The containment leak-tightness is 50% of the volume per day with the design pressure of not more than 0.15 MPa. The containment is an attended room whose primary function is to protect the reactor from external impacts such as aircraft fall, terrorist acts, etc. Thanks to new layout concepts for the main equipment of the VK-300 power unit, the containment dimensions do not exceed the dimensions of the VVER-1000 reactor containment.

It should be noted that a single-circuit plant during normal operation (as any other modern NPP) undoubtedly generates active elements that are transported by steam from the reactor and further to the stack via the turbine condenser ejectors. To limit such releases, activity suppression units widely applied at single-circuit plants both in Russia and abroad are used. Besides, the VK-300 reactor uses more expensive fuel than traditional NPP and requires compliance with tougher regulations for fuel element leak-tightness. A set of reactor plant safety features and the concept of defence-in-depth protection from radioactivity escape allow plant arrangement in the vicinity of a residential district limiting the control area around the VK-300 cogeneration plant by the dimension of the NPP site.

7. Desalination unit

The power unit with the VK-300 reactor facility is intended for combined electricity and heat generation. Therefore, as we speak of building a VK-300 nuclear desalination complex (NDC), we can consider in principle the use of different desalination technologies including distillation systems MED, MSF, MVC with different patterns of thermal energy transfer from the reactor to the distillation desalination units and reverse osmosis (RO) with initial water preheating or with purely electrical interconnection between the nuclear and desalination units. Also hybrid patterns are feasible (MED+RO, MSF+RO).

The report considers a VK-300 reactor based NDC with MED based distillation desalination units with horizontal-tube film evaporators. Russia has an extensive experience of commissioning and long-term commercial operation of domestically built desalination units with horizontal-tube evaporators of different power (from 0.1 to 700m^3/h) on the Aral and Caspian Sea water and on waste water of chemical industries. These evaporators have considerable advantages over other evaporator types (3). Seawater desalination units built on their basis are more economic than evaporators of other types - by the factor of 1.5-2.0 in terms of the energy consumption and by the factor of 1.5-1.8 in terms of the specific quantity of metal and the development area. With regard to the power unit capabilities of supplying heat for desalination (200-400 Gcal/h) as part of an NDC with a VK-300, it is expedient to use distillation units with a higher unit capacity.

Besides the option of an NDC with distillation units, feasibility studies have been conducted for using a VK-300 power source for power supply (without thermal hydraulic connections with the reactor) of reverse osmosis units with HF-membranes.

8. Conjugation of nuclear power unit with VK-300 reactor and desalination unit

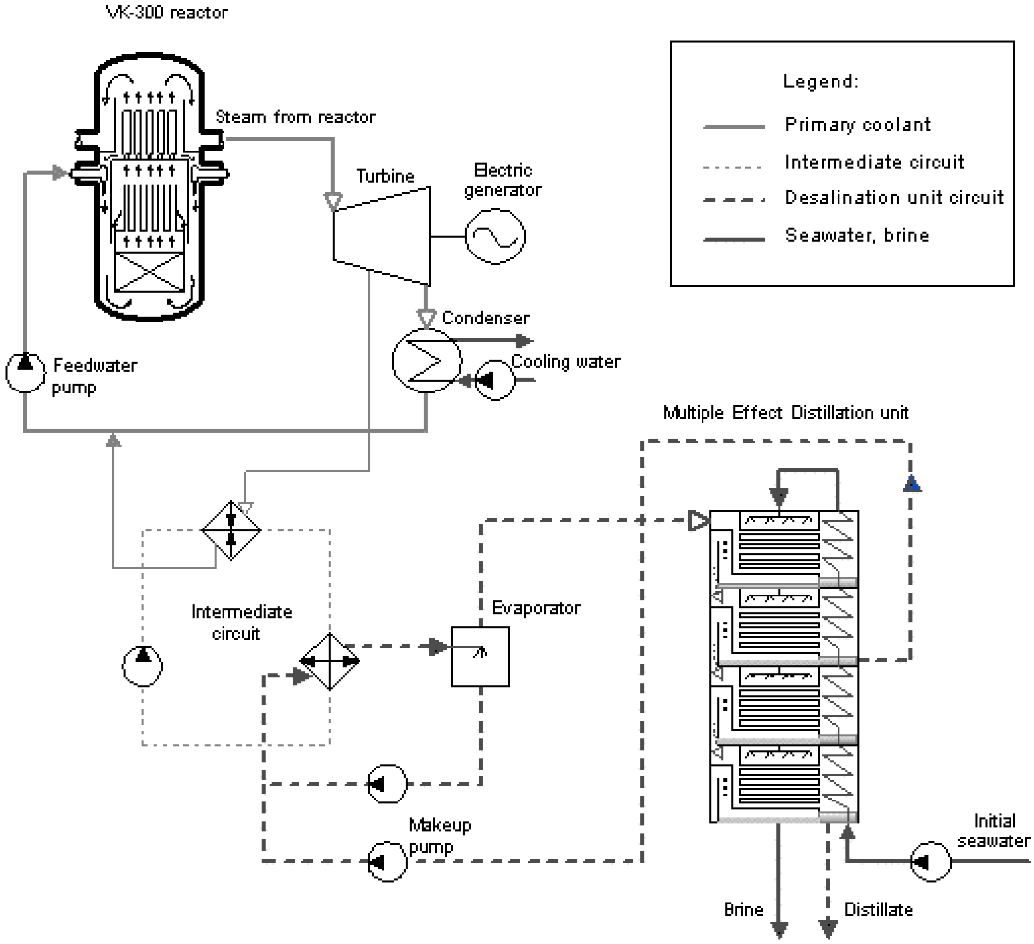
A power unit with a boiling-type VK-300 reactor has a single-circuit arrangement. The unit is equipped with a cogeneration turbine unit that includes the controlled steam extraction ensuring heat supply to the heat consumer via the intermediate circuit. The extraction parameters (the pressure of 0.4 MPa and the steam flow rate to the intermediate circuit low-pressure boiler of 400 t/h) ensure the thermal load of 200 Gcal/h. An increase in the thermal load of up to the limiting value of 400 Gcal/h is provided by the high-pressure boiler CHPB to which steam is delivered from the uncontrolled extraction. The reduced live steam supply to the HPB is also possible from the main pipeline downstream of the turbine stop and control valve. The steam pressure in the high-pressure boiler is not more than 0.95 MPa. The water pressure in the intermediate circuit (1.2 MPa) exceeds the heating steam pressure in the boilers, which prevents the penetration of radioactive substances to the intermediate circuit water.

It is proposed to use resource-saving tubeless finned tube heat exchangers as heat exchanging equipment for the heat transfer from the primary circuit to the intermediate circuit and from the intermediate circuit to the distillation unit circuit (4). The same heat exchangers can be used as part of the auxiliary heat exchanging equipment. In terms of their thermodynamic parameters, these heat exchangers are not inferior to the most known effective apparatus such as plate-type finned heat exchangers. But they require less man hours for manufacturing, use universal materials, have lower specific weight characteristics, high manufacturability and maintainability. The main advantages of these heat exchangers are:

- the manufacturing material – plate "black" steel 08KP;
- high heat exchange parameters (KNOW-HOW);
- small specific quantity of metal;
- practically non-waste use of rolled metal in manufacturing;
- high corrosion resistance (500 times as high as in carbon steel for water);
- low cost parameters (approximately 2 times as low as for modern products of the same class);
- the manufacturing technology allows production with a 100% mechanization level;
- much lower operating costs.

Figure 6 presents a standard VK-300 power unit and distillation unit (MED) coupling option. To generate heating steam for the first stage of the multi-stage evaporator unit, an evaporating flash chamber is used in which the intermediate circuit water boils up due to decompression after it gets there.

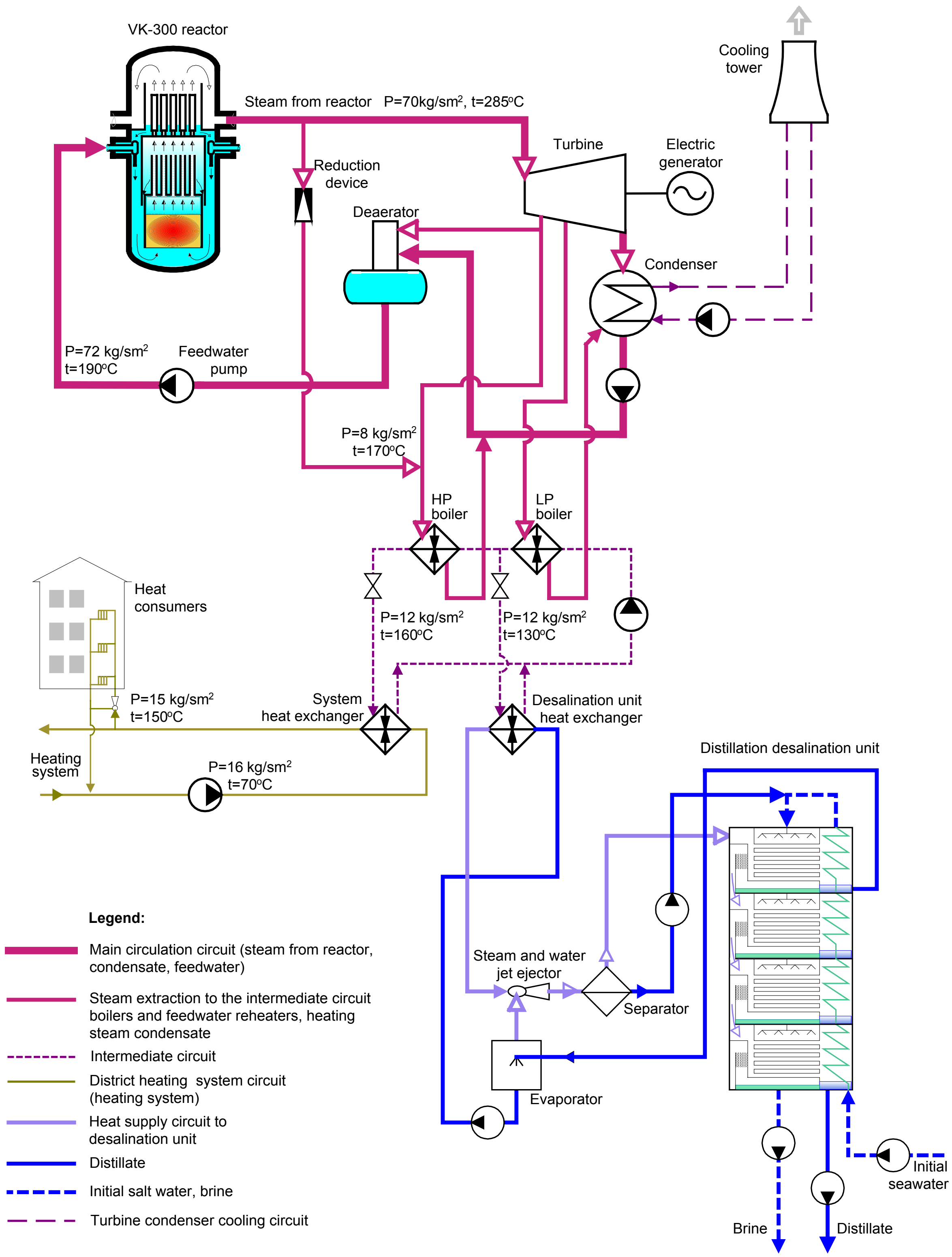
***Figure 6.* Conjugation diagram of the VK-300 power unit and distillation unit with horizontal-tube film evaporators (MED-technology)**



One VK-300 power unit is capable of providing with thermal energy a distillation complex with a total capacity of 300 000m^3 per day. If no high requirements are made to the fresh water quality, membrane apparatus can be installed additionally (or instead of MED facility).

Figure 7 shows a diagram of a multi-purpose VK-300 energy source designed to provide a city or a town with electricity, fresh water and thermal energy for communal needs (heating and hot water supply). Such a multi-purpose energy source can be implemented, e.g. in geoclimatic conditions of Uzbekistan and Kazakhstan having regions with a sharply continental climate with cold winters (the January average temperature in the Kyzyl-Kum Desert is minus 10, as in Moscow) and underground brackish water sources beneath vast arid territories. The layout uses an option of the pattern for the heat supply to the desalination unit proposed by developers of the DOU GTPA-840 unit intended for a floating power unit with a KLT-40 NSSS. Here, the selection of this quite complicated pattern is explained by the temperature operating conditions of the intermediate circuit identical with KLT-40 (130/70^{o}C) – the intermediate circuit in the VK-300 option is common for the district heating system and for the desalination system. The possibility of the reactor power being redistributed with a combined electricity and heat generation and the seasonal (and the daily) redistribution of the heat flow rates between the heating and desalination systems allows reactor (and power unit) operation with the maximum capacity factor value.

***Figure 7.* Simplified diagram of the multi-purpose nuclear power and desalination complex based on VK-300 RF (electricity generation + domestic heating + desalination)**



9. Economic issues

The improved technical and economic parameters of the VK-300 power unit with a relatively small power are achieved through:

– reduced capital costs of the NPP construction thanks to technical approaches ensuring the maximum simplicity of the NPP design and the reactor plant layout (such as natural circulation in the reactor, integral arrangement, etc.);
– a single-circuit layout of the power unit excluding metal-intensive, cumbersome and expensive equipment, less pipelines and valves;
– rational layout decisions ensuring reduced construction scopes and considerably reduced construction costs of the main buildings;
– a higher reliability of equipment and reduced maintenance and repair costs;
– a longer design service life of the reactor (up to 60 years).

Feasibility studies confirm the VK-300 NPP capability to successfully compete with other reactor type NPP.

The required capacity of the desalination complex in each particular case is determined based on the region's estimated demands for fresh water. Besides supply of energy (thermal and electric) for desalination, the energy source power (the number of the VK-300 units on the site) should take into account the region's energy demands, power system capabilities, loading schedules, etc. The optimal solution can be found only with regard for the entire set of technical, economic and social factors.

The conceptual analysis was based on preliminary feasibility studies of the power desalination complex based on two VK-300 units with different desalination systems using DEEP code (5) - distillate technology, reverse osmosis (stand alone unit) and hybrid layout have been considered. The capacity of 300m^3 per day has been assumed in the calculations. The said capacity for the MED option is ensured by the heat supply with steam from uncontrolled heat extractions from the turbines of two power units (via the intermediate circuit). The calculations were based on using the basic initial data on desalination systems recommended by the code developers for the coupling patterns presented in the description (5). The table presents the results of the preliminary feasibility studies for a power desalination complex with VK-300 reactors:

Description of characteristic	Value		
Power source	2 power units with VK-300 RF		
Nominal electric power at the turbine operation in condensation mode, MW(e)	(220 × 2)*		
Power source construction costs**, US$ million	456	440	450
Desalination technology	MED	RO	Hybrid unit (MED+RO)
Desalination system cost, US$ million	326	260	296
NDC fresh water production capacity, m^3 per day	300 000	300 000	300 000, including MED – 100 000

			RO – 200 000
Distillate (permiate) cost, US$ per m^3	0.58	0.51	0.53
Distillate (permiate) TDS, ppm	10	300	220
Excessive electricity supply (sale) to the power system by two VK-300 power units, MW(e)	357	346	352

Notes:
*The nominal power of the turbine generator in the condensation mode of 250 MW(e) to 220 MW(e) in the power unit option for the NDC has been lowered because of higher condensation temperatures and poorer vacuum in the condenser at the power unit deployment in districts with hot climate.
**The difference in the energy source cost for different desalination system options is explained by additional costs of the intermediate circuit in the MED based option.

Conclusion

The innovative pressure-vessel boiling-type VK-300 reactor, being part of a cogeneration unit for electricity and heat production for public services, features higher safety and good economic performance, which makes it attractive with regard to a potential energy source for desalination plants.

The most attractive option is coupling of the VK-300 energy source with distillation desalination units operating on the basis of the multi-stage evaporation principle (MED). This is the effective NDC structure allowing the use of turbine steam extractions for heat supply (via the intermediate circuit) to the desalination system producing high-quality distillate. As it provides with thermal energy a desalination complex with the capacity of 300 000m^3 per day, a nuclear plant consisting of two VK-300 power units allows production of distillate with the cost of US$ 0.58 per m^3. In this case, the electricity supply to the power system is 357 MW(e). The electricity cost is US$0.029/kWh.

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