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AN INTEGRATED NUCLEAR REACTOR UNIT FOR A FLOATING LOW CAPACITY NUCLEAR POWER PLANT DESIGNED FOR POWER SUPPLY IN REMOTE AREAS WITH DIFFICULT ACCESS

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Abstract

The paper describes the conceptual design of an integrated advanced safety nuclear reactor unit for a low capacity floating NPP designed for power supply in areas which are remote with difficult access.

The paper describes the major structural and lay-out components of the steam generator and reactor units with main technical characteristics.

Conceptual design of a reactor facility with enhanced safety for a low capacity floating and environment friendly NPP has been developed in Research and Development Institute of Power Engineering to provide electricity supply to areas which are remote with difficult access.

The most advanced technical solutions well mastered during recent years in designing of navy nuclear power facilities have been used.

The following technical solutions provide high safety level of the reactor facility:

- application of well mastered technology of water-cooled reactors with developed inherent safety features;
- location of the total primary circuit equipment into one vessel of an integrated nuclear steam supply system (NSSS);
- provision of defence - in-depth barriers to prevent ionizing radiation and radioactive fission products release into environment, realization of technical measures to protect confining barriers and maintain their effectiveness;
- application of safety systems, mainly based on passive operation principle;
- independence from external power sources.

The Development of the reactor facility (RF) for floating NPP was carried out in compliance with current Russian rules and requirements to provide safety of stationary and floating nuclear power plants and ship nuclear power facilities and in accordance with the modern notion of prospect enhanced safety NPPs, elaborated so far by the world community. It was considered that RF met safety requirements, if its radiation effect on personnel, population and environment in normal operation and design-basis accidents did not lead to excess of specified dose rates, and limits this effect in beyond design-basis accidents. Technical and organizational measures were assumed to ensure safety with any design-basis initial event with superposition of one failure independent of the initial event of any of the following safety system components: active or passive component having mechanical movable parts or one personnel error independent of the initial event. Besides one failure independent of the initial event, a nondetectable failure of components, not monitored during operation, which influences accident propagation, and results in violation of safe operation limits is taken into account.

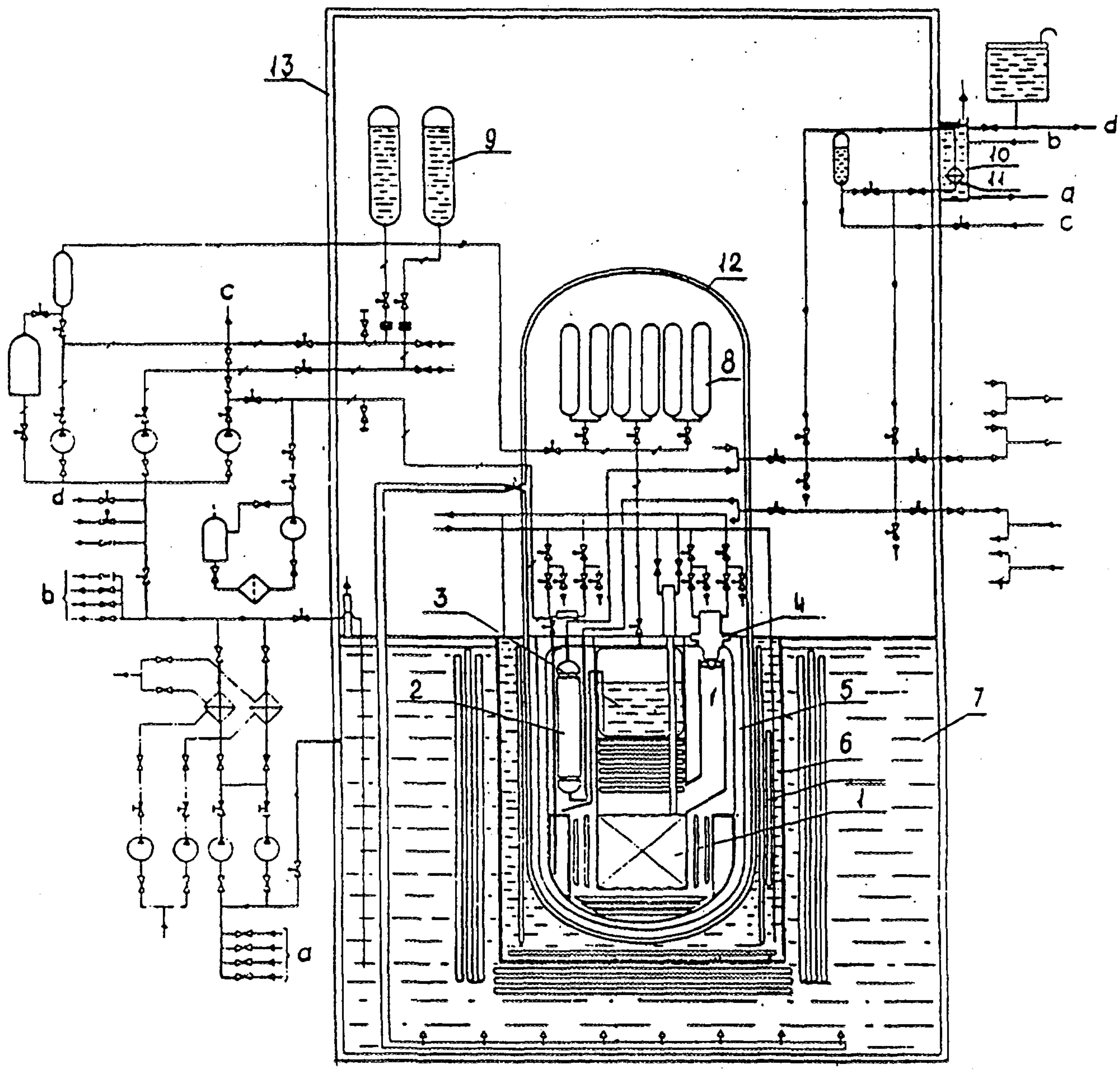

Fig.1. Reactor facility flow diagram:

1 - core; 2 - steam generator; 3 - pressurizer; 4 - primary circuit electric circulation pump; 5 - steam-generating system vessel; 6 - iron-water shielding tank; 7 - bubbling tank; 8 - high pressure gas cylinder; 9 - emergency flooding cylinder; 10 - emergency cooldown tank; 11 - heat-echanger-condenser; 12 - safeguard housing; 13 - containment.

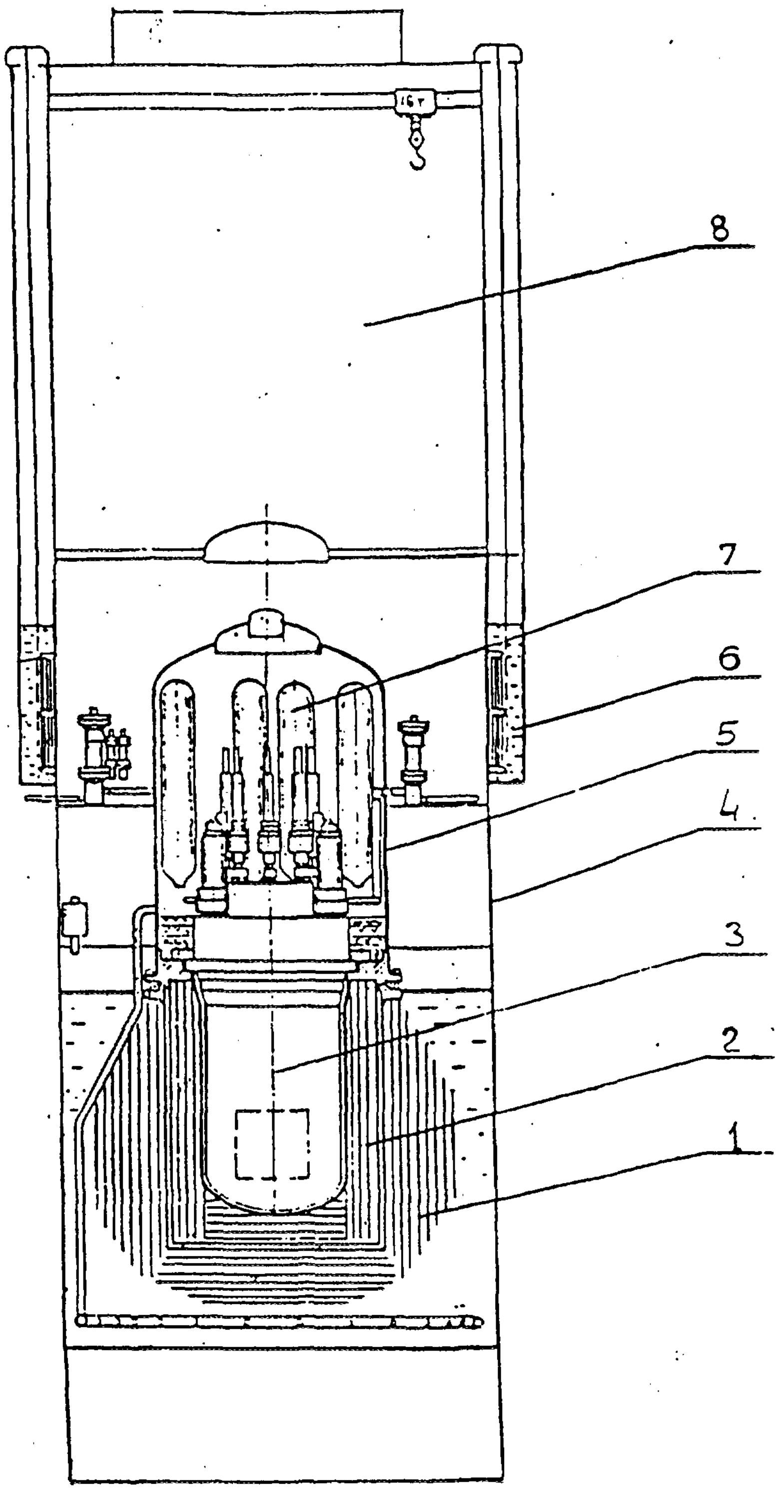

Fig.2. Reactor facility general arrangement. Elevation:
1 - bubbling tank; 2 - iron-water shielding tank; 3 - steam-generating system; 4 - containment; 5 - safeguard housing; 6 - emergency cooldown heat-echange - condenser; 7 - high pressure gas cylinder; 8 - refuelling and repair room.

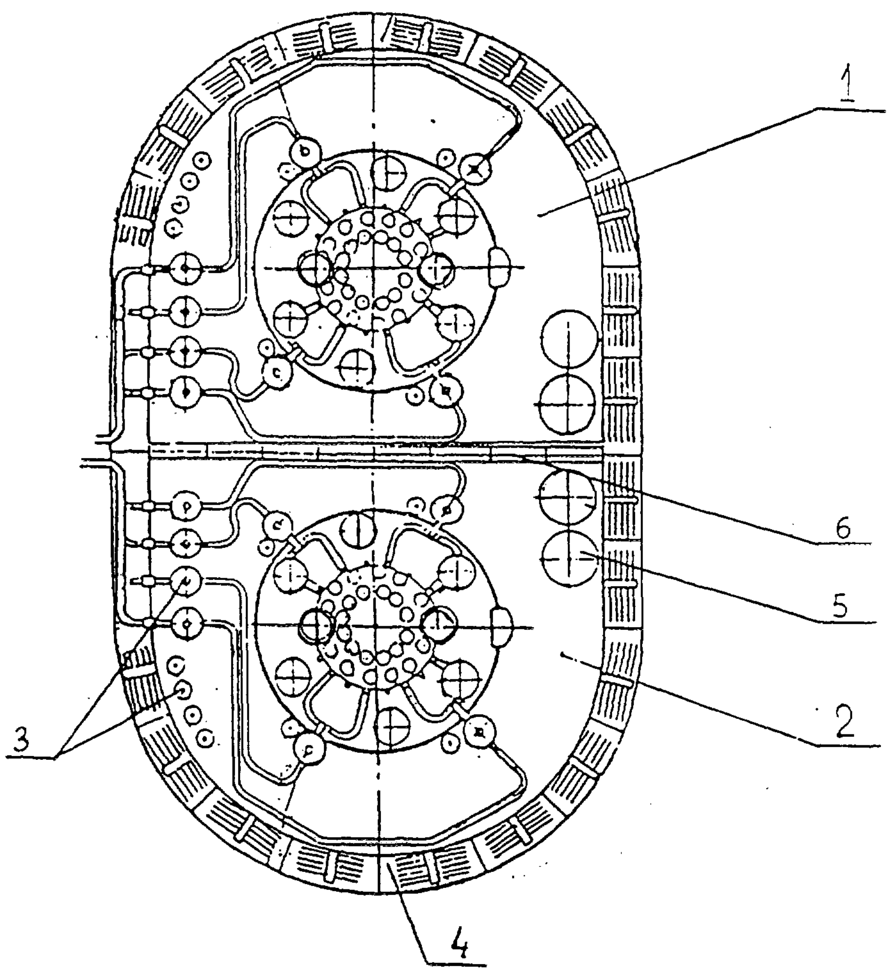

Fig.3. Reactor facility general arrangement. Plan:
1 - steam-generating system No.1; 2 - steam-generating system No.2; 3 - isolating valves for steam and secondary circuit feedwater; 4 - emergency cooldown tank; 5 - emergency flooding cylinder; 6 - strong leaktight partition.

Structurally the RF is divided into two separate and independently operating steam generating facilities with identical principal flow charts and equipment (see Figs. 1-3).

The RF employs water-moderated, water-cooled reactors with inherent safety and control features due to negative power and temperature reactivity coefficients. The core physical characteristics are so selected that the above coefficients be negative in the entire range of temperatures during core life. This eliminates spontaneous reactor power excursion in normal startup and heatup and stabilizes operation in steady-state conditions and transients.

The adopted core structure rules out the possibility of forming local critical masses both in normal and emergency modes. Formation of secondary critical mass in hypothetical accidents, resulting in partial or full core melting is also excluded.

All equipment of the primary circuit (the core with reactivity compensation components, steam generator, electric circulation pumps, pressurizer) except gas cylinders are located in cylindric vessel of the integrated nuclear steam supply system (NSSS) (see Fig. 4).

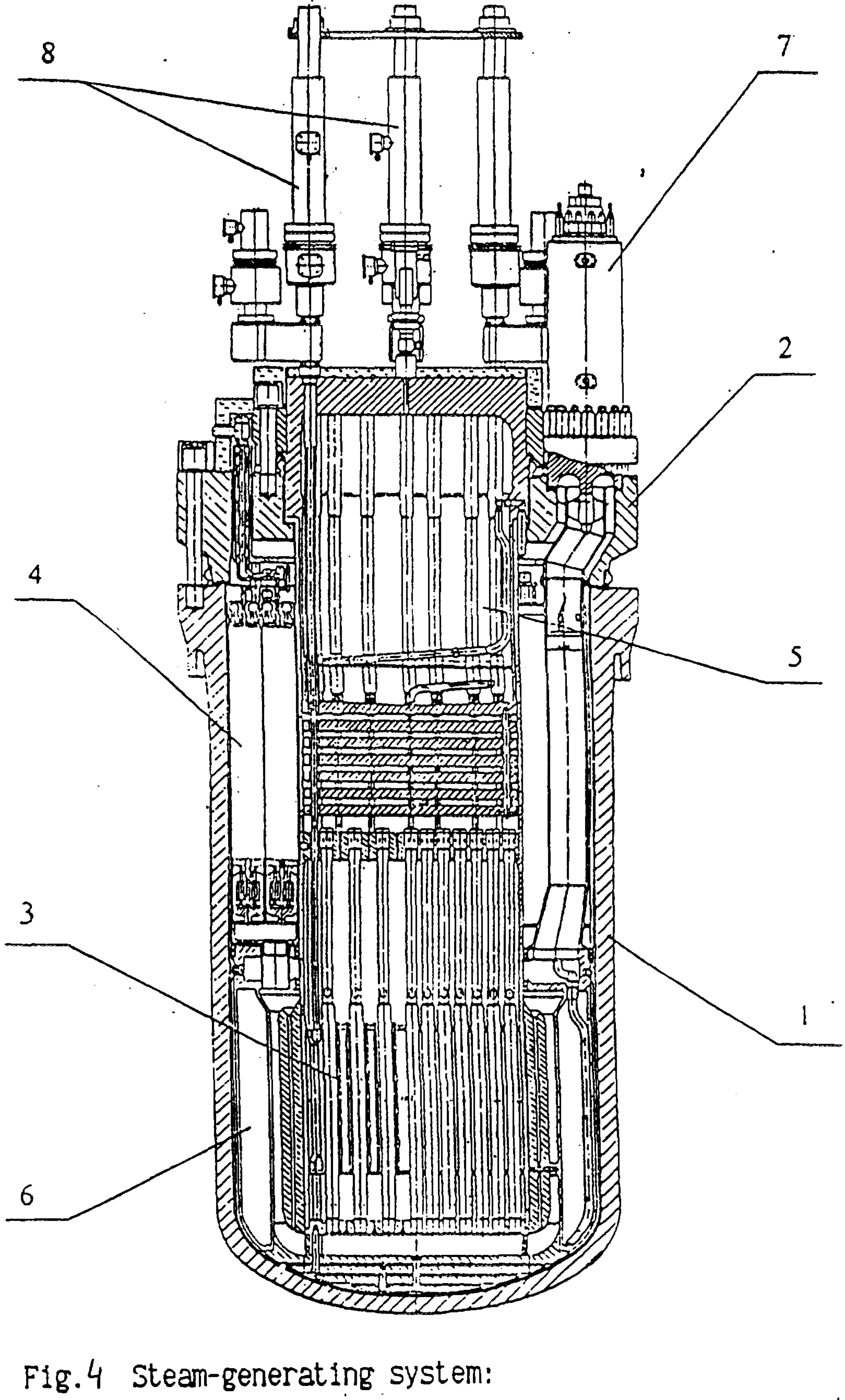

Fig.4 Steam-generating system:

1 - vessel; 2 - ring-type cover; 3 - core; 4 - steam generator; 5 - pressurizer; 6 - intermediate capacity; 7 - electric circulation pump; 8 - control and protection members drives.

The pipeline between gas cylinders with pressurizer and make p system pipelines is connected to the NSSS cover and ends at this point.

Such NSSS structure allows:

- to reduce the number and extent of external primary circuit lines down to minimum and reduce probability of its depressurization;
- to provide high level of natural circulation for the primary circuit coolant;
- to increase water volume above the core and to improve its cooling conditions in a hypothetical accident related to primary circuit depressurization and water cut-off from the NSSS.

In order to decrease the leak and mitigate accident consequences in case of pipeline rupture which connects pressurizer with receiving cylinders, a constricting device is installed on it. Check valves are installed on makeup pipelines (in places of its attachement to NSSS cover).

RF employs defence-in-depth principle, based on barrier system to prevent ionizing radiation and radioactive substances release into environment supported by technical procedures to protect these barriers and maintain their efficiency.

In accordance with this the RF safety systems provide for:

- reactor emergency trip and keeping it subcritical;
- emergency heat removal from the core;
- confining of radioactive products within specified boundaries.

Flow chart and design of these systems are based on their passive action as much as possible. In order to ensure reactor emergency trip and keeping it subcritical the following systems have been designed:

- main emergency protection;
- additional emergency protection;
- liquid absorber injection system.

The main and additional emergency protections have different activation principles. They are activated automatically by CPS and complex system for technical means control (CSTMC) signals or by power cut-off.

Liquid absorber is injected by remote control.

Design of all compensating group (CG) activation devices is based on insertion of shim rods into the core using dump springs or the rods weight during power cut-off from actuators and CPS; the design also ensures keeping shim rods in inserted position in case of the unit turning-over.

The shim rods ensure reactor tripping and keeping it subcritical in all operational modes in case of one (any) CG failure (stuck in the extreme position) by means of CGs remaining in operation.

Additional emergency protection is activated automatically by a signal from CPS in response to failure of two or more CGs.

Besides activation by CPS signals the additional emergency protection becomes operational without any external signal under increase of primary circuit coolant temperature up to specified ultimate value. This is achieved by the additional emergency protection design.

Liquid absorber is injected into integrated NSSS only when the reactor has not been transferred to subcritical state due to failures of the main and additional emergency protections, but such situation is hardly probable.

Availability of the listed means for reactor emergency protection and keeping it subcritical can provide safety reactor trip not only in case of design-basis accidents, but also in hypothetical accidents, which are not related to core or NSSS damage.

In order to avoid spontaneous chain reaction during scheduled maintainance or repair works, CG actuator design envisages clutches, which are installed below "cold" startup position. Electromagnetic clutches are opened only by signals, which allow the core start-up.

To provide heat removal from the core in different emergency situations the RF has the following safety systems:

- emergency cooling system;
- emergency core flooding and cooling system.

RF can be cooled down by feedwater pumping into the steam generator by the steam-turbine means in both operational and emergency modes. In case of primary circuit depressurization the makeup system is also involved in heat removal from the core.

In emergency situations, which are not related to steam turbine failure, the RF is usually cooled by feedwater pumped into the steam generator by steam turbine. In case of the steam turbine failure and during power cut-off the integrated NSSS is automatically disconnected from the steam turbine (from steam and feedwater supply) and emergency cooling system (ECS) starts operating. Heat removal from primary coolant is provided for both operating and non-operating primary circuit electric circulation pumps (due to natural coolant circulation). In case of RF power supply loss the disconnection of NSSS from steam turbine and ECS activation are ensured by isolating and cut-off valves, which perform this function in "normal" position.

Emergency cooling system, consisting of 4 independent sections, can provide NSSS cooling during 24 hours in case of failure of any 2 ECS sections even with the plant blackout. Heat removal from primary coolant and its transfer to water in ECS tanks results from coolant natural circulation in this system. With electric supply availiable the water in ECS is cooled by pumping it through heat exchangers, which are cooled by outboard water. In case of NPP power blackout heat from ECS heat exchangers is removed due to heating followed by evaporation of water from ECS tanks.

Core makeup and core emergency flooding systems provide removal of residual heat from the core and eliminate its drying and further melting in case of primary circuit depressurization and coolant circulation failure. Each of these systems has redundances with respect to equipment and water supply channels to NSSS. The makeup system operates automatically by pressure drop in primary circuit signal from CSTMS and activation of the emergency core flooding system does not require any operator actions or CSTMC activation and occures due to membrane rupture under primary circuit pressure decrease down to specified level.

Taking into account that the makeup system besides RF normal operation assurance is supposed to provide safety, three independent NSSS water supply channels with high pressure pumps in each channel are envisaged in the makeup system. Water for primary circuit makeup is taken from condensate-feedwater system of steam turbine or from water storage tanks, and after water level in bubbling tank reaches specified level the makeup is performed in closed cycle, i.e. water for makeup is taken from bubbling tank, cooled in heat exchangers and delivered into NSSS; the coolant, flowing from NSSS again comes into the bubbling tank.

The emergency core flooding system is based on passive operation principle and comprises two independent channels. Water is supplied into NSSS through these channels due to gas pressure from pressure cylinders.

In case of primary circuit depressurization the feedwater is delivered into steam generator from steam turbine in parallel with operation of makeup and emergency core floodibg systems. This ensures additional removal of heat, released in the core and increases time needed for the core drying in hypothetical accidents due to natural convection of gas and steam in NSSS and partial steam condensation on steam generator surface. Steam turbine failure to supply water into the steam generator activates the ECS.

The availability of cooled iron-water shield around NSSS vessel and favourable conditions for natural circulation of steam-gas medium inside NSSS thereby reduce probability of core melting in hypothetical accidents and eliminate possibility of NSSS vessel melting down in such accidents.

In case of an accident, all actions to localize it are automatic. Control systems (CPS and CSTMC) have three-channel scheme and the control and emergency signals are generated using major principle (2 out of 3) that ensures sufficient operational reliability.

The following safety barriers are envisaged to reduce radioactivity release into environment in design - basis and hypothetical accidents:

- corrosion resistant matrix of fuel elements;
- claddings of fuel elements;
- leaktight primary circuit;
- safeguard vessel;
- containment.

Small number of the equipment, its lifetime characteristics and high automation degree ensure RF operation during one year without maintenance within the containment. This allows to adopt additional technical measures to enhance RF safety. Namely, ventilation system equipment located outside the containment is isolated with isolation valves designed for maximum emergency pressure in safeguard vessel, and is made operational only when it is necessary to make repairs inside the containment (gas is discharged from containment into environment via special filters under control). Conditioning system operates in closed cycle, its total equipment is located in safeguard vessel. Such technical solutions eliminate radionuclides release from containment in normal operation of floating NPP.

Leaktightness of the containment and safeguard vessel and no inside repairs allow to maintain decreased oxygen content (11-13 %) in equipment rooms, thus enhancing their fire safety.

The RF design solutions eliminate a possibility of safeguard vessel and primary circuit damage in case of earthquakes, aircraft crash or other external impacts.

In conclusion, the basic technical characteristics of the reactor facility are as follows:

Thermal power, MWt	2 * 42
Steam output, t/h	2 * 60
Superheated steam parameters:	
temperature, °C	290
pressure, MPa	3.53
Core life as evaluated for nominal power, h	20000
Specific core power rating, kW/l	68.0
Fuel composition	uranium dioxide dispersed in zirconium matrix
Enrichment with U^{235}, %	21
Time period of RF continuous operation without maintenance, h	8000
Mass, including safeguard vessel and containment, t	750

Due to high safety level (probability of severe beyond design-basis accidents, which can result in serious core damage or melting and following radionuclides release into environment does not exceed 2x10я5-8 я0per reactor per year) the RF can be recommended to be used for low capacity floating NPP, and its unique mass-dimension characteristics enable to construct a plant with such a draught (estimated as 2.6 m), which will make it possible to ship it along Nothern rivers to regions which are far away from the coast.