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THE USE OF ENGINEERING FEATURES AND SCHEMATIC SOLUTIONS OF PROPULSION NUCLEAR STEAM SUPPLY SYSTEMS FOR FLOATING NUCLEAR POWER PLANT DESIGN

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Abstract

In the recent years many countries and the international community represented by the IAEA have shown a notable interest in designing small and medium size nuclear power plants intended for electricity and heat generation for remote areas. These power plants can be also used for desalination purposes. As these nuclear plants are planned for the use in the areas without well-developed power grid, the design shall account for their transportation to the site in complete preparedness for operation.

Since the late 80s Research and Development Institute of Power Engineering (RDIPE) has carried out the active efforts in designing the reactor facilities for floating nuclear power plants. This work relies on the long-term experience of RDIPE engineers in designing the propulsion NSSS. Advantages can be gained from the specific engineering solutions that are already applied in the design of propulsion NSSS or from development of new design based on the proven technologies.

Successful implementation of the experience has been made easier owing to rather similar design requirements prescribed to ship-mounted NSSS and floating NPP. The common design targets are, in particular, minimization of mass and dimensions, resistance to such external impacts as rolling, heel and trim, operability in case of running aground or collision with other ships, etc.

DESCRIPTION OF DESIGN FEATURES

2.1.The NSSS is equipped with an integral water-cooled water-moderated reactor with inherent safety and the following unique features:

- negative coefficients of reactivity in the whole operating range of parameters;
- high rate of natural circulation of the coolant which affords effective cooling and heat removal from the core during design-basis and beyond design-basis accidents;
- high heat storage capacity of metal structures and a large mass of coolant in the reactor which result in a relatively slow progression of transients during accidents with upset heat removal from the core.

Figs. 1 and 2 show general view of the reactor and schematic of primary coolant motion. As is clear from the figures, all components of the primary circuit (i.e., the core and control rods, steam generator, main coolant pumps, pressurizer) are located in a single cylindrical vessel.

Primary coolant circulation is provided by main coolant pumps (MCP) with canned asynchronous motors that are installed on the reactor cover. As an additional benefit, simple configuration and short length of the primary circuit path permit to sustain high flow rate of

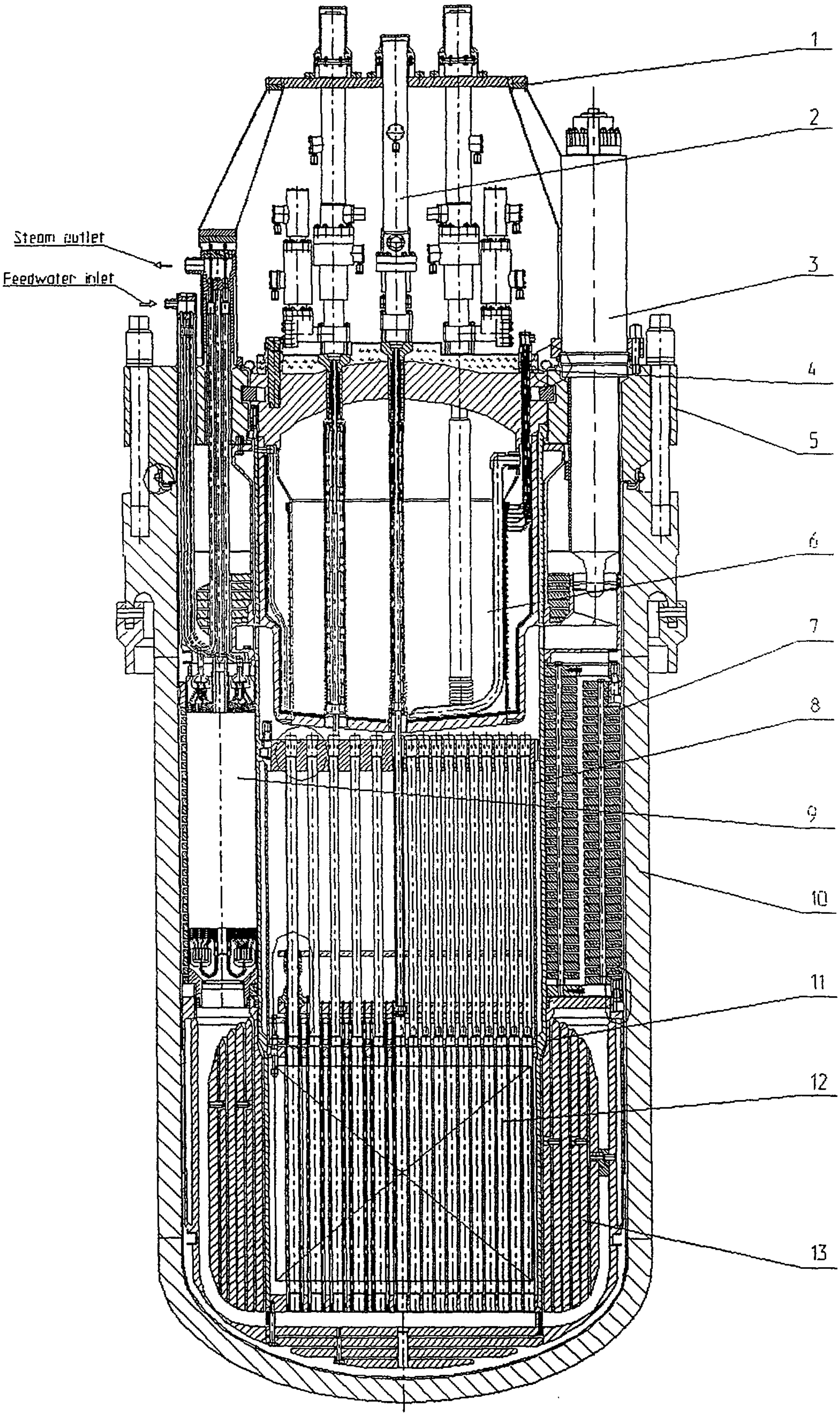

Fig.1. General view of the reactor

1 - drive fastening frame; 2 - shim rod group drive; 3 - MCP; 4 - thermal insulation; 5 - annular cover; 6 - pressurizer; 7 - displacers; 8 - metalwork with control rod clusters; 9 - SG; 10 - vessel; 11 - core barrel; 12 - fuel assembly; 13 - side shield.

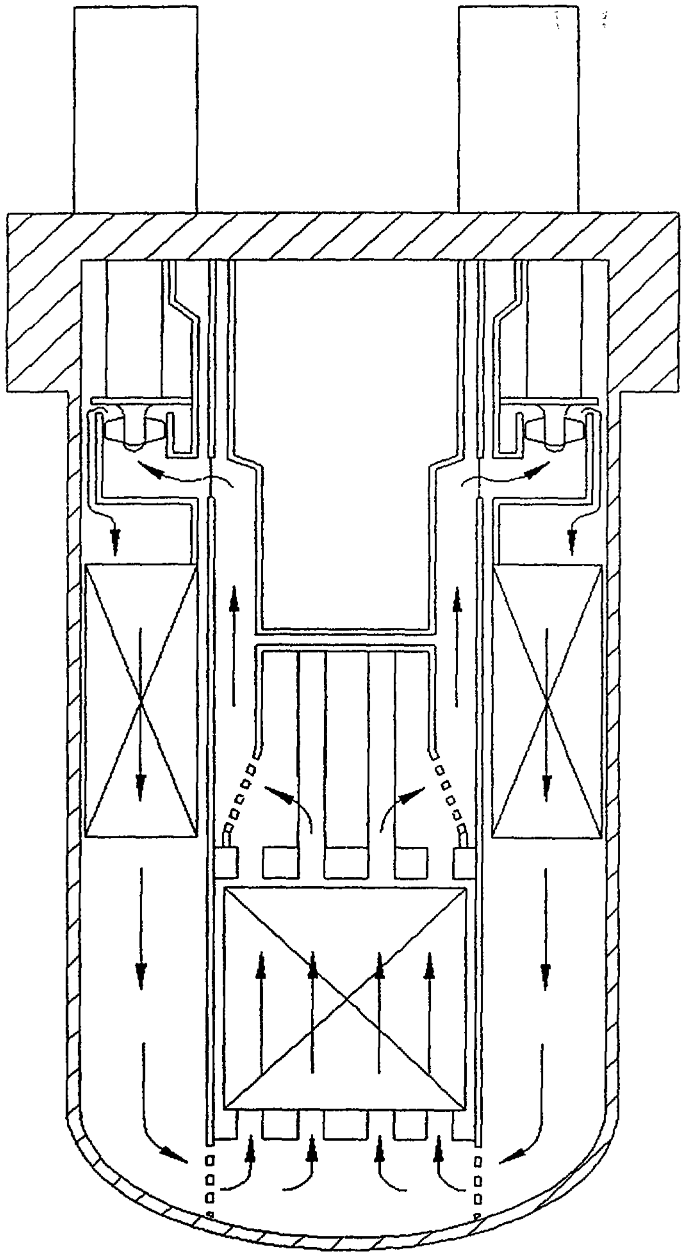

Fig. 2. Primary coolant flow diagram

natural circulation in the reactor and a capability for NSSS operation at power not lower than 25% of nominal when MCPs are stopped.

The reactor core is composed of fuel rods with square cross-section. At the corner there are fins that are spiral with respect to longitudinal axis of the fuel rod. Fuel composition is uranium-zirconium alloy with - 20 % enrichment by U235 . Fuel cladding is made of zirconium alloy. Fuel rods are grouped in fuel assemblies (FA). Burnable rods placed in FAs and absorber rods moving outside fuel channels are used to compensate for reactivity change in the core.

In-vessel once-through steam generator is designed as surface-type helical heat exchanger with tubing made of titanium alloy. Heat exchange area of steam generator is divided into cylindrical cassettes that are placed in the reactor annulus formed by a cylindrical part of the reactor vessel and core barrel. From steam and feedwater sides the SG cassettes are connected via pipelines to form four independent sections that can be isolated by valves outside the reactor vessel.

CEDM incorporates a rotary step motor used for motion of control rods under all normal and emergency modes of NSSS operation. The step motor is backed up with a spring-type actuator that inserts the rods in the core in case of loss of power to the step motor or control system under any position of the reactor, including its capsizing. Implementation of this engineering solution is especially important having in view that the reactor is to be mounted on a ship.

Unlike the known designs of integral reactors being under development in many countries where either steam or steam-gas pressurizer is applied, the integral reactors developed by RDIPE use a gas pressurizer. Selection of such solution was motivated by several reasons, firstly, the intention to simplify and, consequently, enhance safety of the primary circuit pressure compensation system by elimination of heaters and sprinkler system. Secondly, this approach is based on our 40-year experience in designing and operation of ship-mounted NSSS with gas pressurizers in the primary circuit. It should be pointed out, however, that in the previous cases the pressurizers were placed outside the reactor vessel.

In-vessel and out-of-vessel gas pressurizers operate under different operating conditions, especially, temperature conditions. Out-of-vessel pressurizer is in the region of low temperature, therefore water and gas temperatures therein are not higher than 100° C. In-vessel pressurizer that is placed in the upper part of the reactor is exposed to high temperatures. If cooling is not provided temperatures of water and steam-gas mixture will be almost equal to coolant temperature at core outlet. So, instead of gas type this pressurizer will become steam-gas one, which is poorly investigated in operation.

When gas pressurizers are used, it is important to consider gas transport in the primary circuit. It is well known that solubility of nitrogen taken as a working medium in the pressurizer rises as temperature increases. Under 15 MPa nitrogen solubility in water reaches its maximum at temperature of -270° C. As a result, possible gas transport from the pressurizer to the primary circuit, subsequent gas release and formation of gas bubbles in various regions of the circuit will cause certain difficulties as well as some changes in heat transfer conditions in the core and steam generator.

Theoretical justification of in-vessel gas pressurizer design can become the subject of a separate paper. Here we only want to point out that through the use of certain design features in-vessel pressurizer can operate under the conditions and parameters that are similar to those for out-of-vessel pressurizer.

Schematic diagram of in-vessel pressurizer of the integral reactor (Fig. 3) illustrates specific features of its design.

The pressurizer is designed as a cylindrical vessel, its cover being the central cover of the reactor vessel. The pressurizer is separated into two cavities: central where the "water-gas" phase separation level is set in all power modes of operation, and annular peripheral cavity housing a heat exchanger connected to NSSS component cooling system. The annular cavity is connected by pipelines with upper part of the reactor and with the central cavity. Inner surface of cylindrical

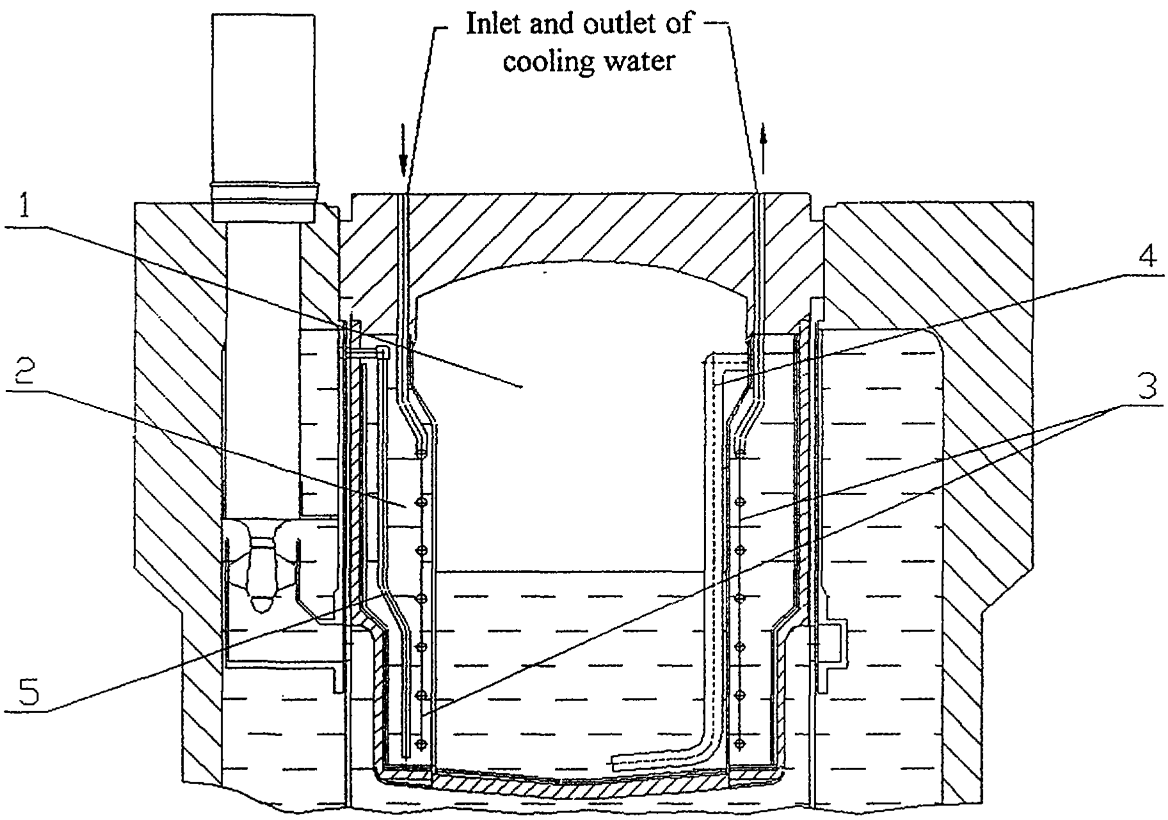

Fig.3. Schematic diagram of the pressurizer
1-central cavity; 2- annular cavity;
3-heat exchanger; 4,5- pipelines

part of the reactor vessel and pressurizer bottom are coated with thermal insulation which is designed as multi-layer set of sheets made of titanium alloy.

When NSSS is in operation, temperature in the central cavity of the pressurizer is settled at ~ 120° C, i.e. these are conditions of minimum nitrogen solubility in water. Besides, sequential connection of the reactor annulus and peripheral and central cavities allows to operate the pressurizer as hydraulic siphon: gas being accumulated in the upper part of the reactor or in peripheral cavity of the pressurizer will flow under fluctuation of the primary temperature to the central cavity and adds to total mass of gas.

Fig. 4 shows arrangement of NSSS components and biological shielding. The figure illustrates a general principle which sets the basis for the design concept of a nuclear power facility. In compliance with this principle, all components of the NSSS are placed in two volumes formed by strong leaktight shells, i.e. the safeguard vessel and containment that act as successive barriers preventing from release of radioactive medium.

Primary coolant components are placed inside the safeguard vessel and under all designbasis accidents the possible release of radionuclides would be retained within the safeguard vessel. Only under beyond design-basis accidents when pressure exceeds the allowable limits the radioactive medium could be released from the safeguard vessel into the containment through the bubbling device.

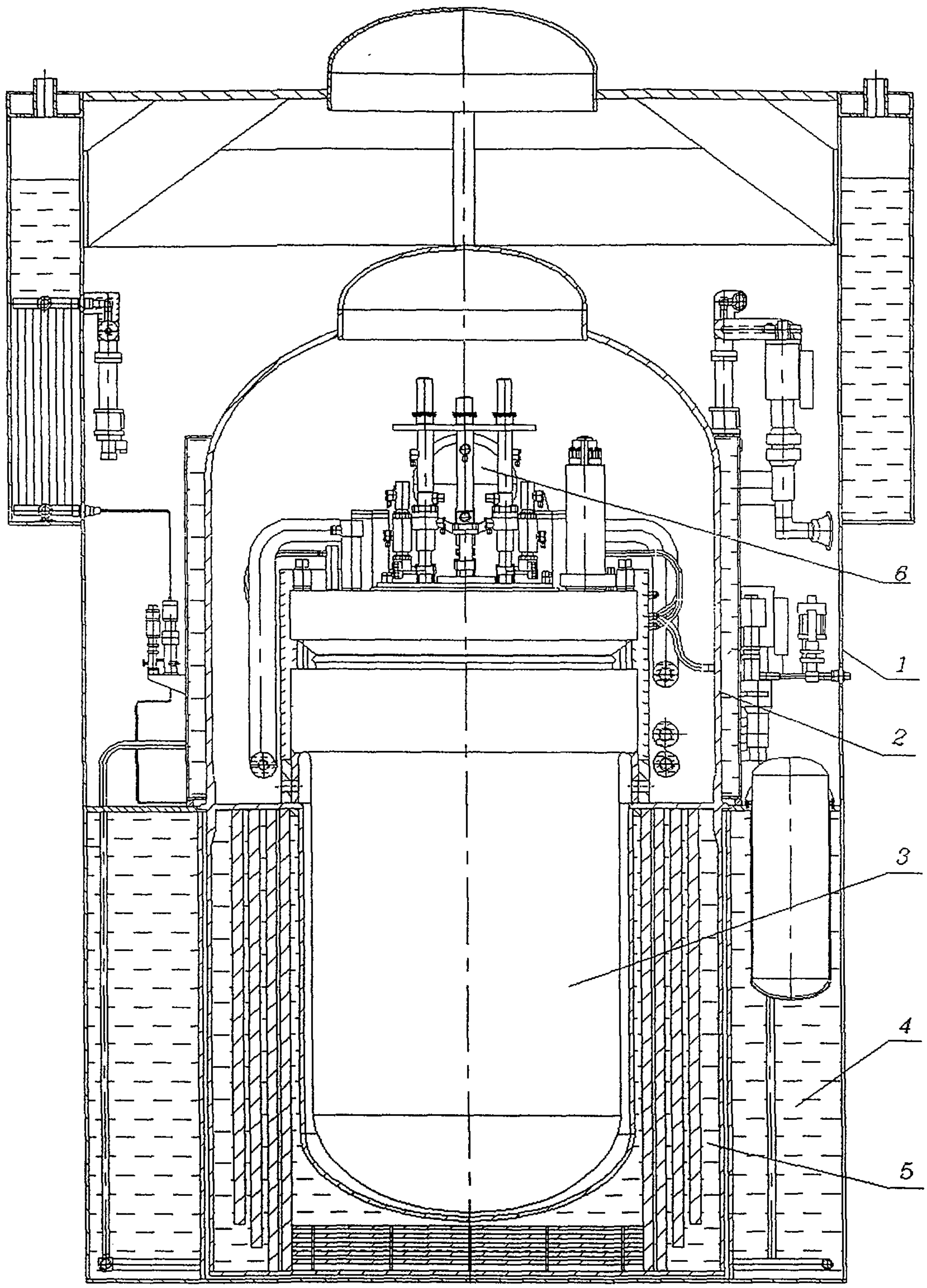

Fig.4. Arrangement of NSSS

1 - containment; 2 - safeguard vessel; 3 - reactor; 4 - biological shielding external tank; 5 - biological shielding internal tank ; 6 - entrance hatch

A regular cylindrical shape of the reactor vessel permits to use the biological shielding optimized in terms of its efficiency and mass and dimension characteristics. Metal-water biological shielding is arranged as two annular concentric tanks. An air gap is provided between the reactor vessel and internal biological shielding tank for the purpose of thermal insulation.

Under the accidents caused by primary coolant leak this gap is filled with water thereby providing adequate heat removal from the reactor vessel. That excludes the probability of reactor vessel meltdown under postulated beyond design-basis accidents involving the core dryout.

Among the safety-related design features it is important to point out the extensive use of passive systems and safety features whose operation is based on natural processes with no need for external power supply.

Such systems include:

- CPS drives whose design assures insertion of control rods into the core by gravity and drop springs;
- passive systems for emergency residual heat removal;
- a safeguard vessel which ensures core coverage with coolant and heat removal under all severe accidents, and guarantees radioactivity confinement in case of a leak in the primary circuit;
- a containment which limits radioactive releases from an open safeguard vessel and under beyond design-basis accidents;
- metal and water biological shielding which apart from its direct functions serves as bubbler tanks with cooling water and provides heat removal from the reactor vessel to avoid its meltdown under a postulated beyond design-basis accident with core dryout.