Low-power modular lead-cooled nuclear reactor

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The concept of a low-power nuclear power reactor based on the use of the passive principle of natural circulation of lead coolant in the core cooling loop is presented. A simplified technological scheme and a numerical assessment of the thermal-hydraulic parameters of the reactor cooling system in normal mode are presented to substantiate the possibility of using such a system in a low-power power reactor with increased safety parameters. The simplicity of the proposed heat removal system allows it to be used to create standard modular low-power fast neutron reactors.

Keywords: NUCLEAR SAFETY; LOW POWER REACTORS; NATURAL CIRCULATION; FAST REACTORS; PASSIVE COOLING SYSTEM.

Introduction

One of the main directions of modern development of nuclear energy is the creation of small modular reactors. Small modular reactors installed in single or multi-unit power plants make it possible to combine nuclear and alternative energy sources, including renewable sources.

However, the problem of optimal choice of the type of coolant for such reactors remains unresolved. Despite the seemingly obvious choice, the use of water as a coolant carries significant risks of a heat transfer crisis in the core in emergency situations, and the possibility of an exothermic zirconium vapor reaction has led to catastrophic consequences at the Fukushima-Daiichi NPP [1]. The use of gas, organic heat transfer fluids or salts causes no less problems and risks. Liquid metal coolant - liquid sodium requires special care in handling it due to its fire and explosion hazard, and the use of a lead-bismuth coolant leads to the formation of a large amount of hazardous radioactive polonium-210, which, in case of accidents with depressurization, can escape into the environment and lead to serious radiation consequences in the adjacent territories. Therefore, perhaps the most acceptable coolant option for small-sized modular reactors may be ordinary lead.

Small Modular Fast Reactor Concept

To ensure increased safety and economic efficiency of low-power nuclear power reactors, special requirements that are atypical for conventional nuclear power plants should be met:

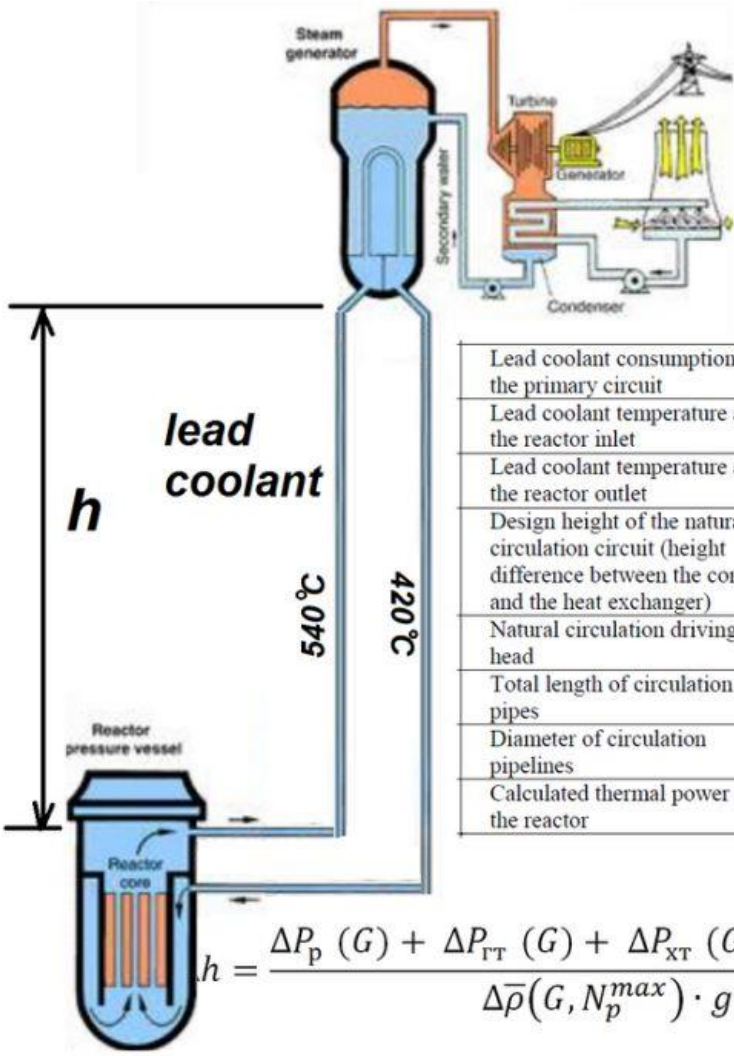
- extreme simplicity of the design of the reactor plant;
- passive heat removal from the reactor according to the principle of natural circulation in all modes, including emergency;
- absence in the primary cooling circuit of mechanical moving elements subject to an increased risk of breakdowns at high temperatures (pumps, check valves, shut-off and control valves);
- maximum possible temperature of the heating medium in the primary circuit (taking into account the properties of structural materials) to ensure high efficiency of the reactor plant;
- minimized cost of erection and dismantling of construction
- structures taking into account adverse external influences (aircraft crashes, hurricanes, earthquakes, explosions during man-made accidents at nearby facilities);
- no fire and explosion hazard of the coolant (exclusion the use, for example, of such heat carriers as sodium) and organic heat carriers such as ditolylmethane;
- providing simple and reliable physical protection of the object, minimal risk of a terrorist threat;
- the possibility of ensuring the safe operation of the reactor plant with a minimum number of operating and maintenance personnel;
- internal self-protection of the reactor plant, limiting the ability to negatively affect the work with erroneous or malicious actions of personnel;

- the requirements for the qualifications of personnel should be lower than large nuclear power plants with their complex and branched systems;

- lack of power supply to the reactor plant should not lead to dangerous emergencies, resulting in depressurization of fuel elements.

- emergency shutdown of power supply at the reactor facility should not lead to deterioration of heat removal from the reactor core and dangerous emergencies leading to depressurization of fuel elements.

It is possible that these requirements are met by the concept of a reactor plant with a lead coolant, in which, in the absence of a circulation pump, it is possible to achieve an increase in the intensity of circulation through the reactor due to the difference in the hydrostatic head in the ascending and descending directions of the sections of the pipelines of the circulation loop. For this, the difference in height between the reactor core and the lead-cooled steam generator must be maximum, which can be achieved if the reactor vessel is located deep underground and the steam generator is located at ground level. At the same time, this arrangement of the reactor provides protection from external influences and dramatically reduces the cost of dismantling the reactor plant after decommissioning. As an example, we can consider a simplified scheme of such a reactor with the parameters of heating the lead coolant, similar to the parameters of the primary circuit of the BREST-OD-300 reactor [2]. Refueling of fuel assemblies in the reactor occurs at a reduced level of lead coolant, which makes it possible to replace fuel assemblies with a loose reactor head. The coolant level in the primary circuit decreases and increases with the help of a heated monjus (Fig. 1).



Lead coolant consumption in the primary circuit	G	2600	m^3/h
Lead coolant temperature at the reactor inlet	Tin	420	°C
Lead coolant temperature at the reactor outlet	Tout	540	°C
Design height of the natural circulation circuit (height difference between the core and the heat exchanger)	H	63,4	m
Natural circulation driving head	$\Delta\rho \times g \times h$	89,5	kPa
Total length of circulation pipes	L	230	m
Diameter of circulation pipelines	D	0,85	m
Calculated thermal power of the reactor	N	134,0	MW

$$h = \frac{\Delta P_{\text{р}}\ (G) + \Delta P_{\text{ГТ}}\ (G) + \Delta P_{\text{ХТ}}\ (G) + \Delta P_{\text{ТО}}\ (G)}{\Delta\bar{\rho}\left(G, N_p^{max}\right)\cdot g}$$

Fig. 1. Simplified diagram of a low-power power reactor at fast neutrons with lead coolant

As confirmation of the possibility of implementing the proposed reactor plant in table. 1 show the main design parameters of the liquid-metal core cooling loop with natural circulation of lead melt.

Table 1 – Basic parameters of a low-power pressure vessel on fast neutrons with lead coolant

Parameter	Meaning
Heat capacity of lead coolant	**147.3** *J / kg K*
Kinematic viscosity	**0.000000195** m^2/s
Heat carrier flow rate in the primary circuit: - *volumetric* - *massive*	 **2 600** m^3/h; **0.72** m^3/s **7.580** *kg / s*
Heat carrier temperature: - *at the entrance to the reactor* - *at the outlet of the reactor*	 **420** *°C* **540** *°C*
Temperature difference in the lifting and lowering sections of the circulation circuit	**120** *°C*
Coolant density: - *at the entrance to the reactor* - *at the outlet of the reactor*	 **10 568** kg / m^3 **10 424** kg / m^3
The difference in the density of the coolant in the lifting and lowering sections of the circulation circuit	**144** kg / m^3
The calculated height of the natural circulation contour (difference heights between the core and the heat exchanger)	**56.0** *m*
Natural circulation driving head	**79 048.6** *Pa*
Circulation pipelines parameters: - *total length* - *diameter* - *flow area* - *roughness* - *average speed* - *friction head loss* - *Reynolds criterion* - *coefficient of friction*	 **150** *m* **0.85** *m* **0.567** m^2 **0.0001** *m* **1.273** *m / s* **19 502** *Pa* **5 547 871** **0.013**
Circulation circuit parameters: - *coefficient of local resistance* - *loss of pressure on local resistance* - *total calculated head loss*	 **7.1** **59 546** *Pa* **79 049** *Pa*
Reactor power: - *thermal* - *electric*	 **134** *MW* **55** *MW*

In the event of an accident with a rupture in the second circuit, the water level in the steam generator drops sharply, after which the reactor is cooled due to the natural circulation of air near the upper part of the reactor vessel. Then the heated air passes into the channel, in which the vertical pipelines of the primary circuit are located, and, having passed through the filters, enters the atmosphere. Gradually, with a decrease in the level of residual energy release, the resistance to air circulation in this circuit increases, closing the damper, the flow rate of natural air circulation decreases in order to maintain the temperature of the melt in the optimal range. In this case, the circulation of the lead coolant in the primary circuit does not stop, but its speed is much lower than in normal operation.

To unload the fuel assemblies, the lead coolant is poured into a heated monjus, which makes it possible to unseal the reactor vessel lid and replace the fuel assemblies.

In situations with a rupture of the primary circuit pipeline or with a routine decrease in the coolant level in the primary circuit for refueling fuel assemblies, cooling is carried out by transferring heat to the circulating air in the upper part of the reactor vessel. The heated air then passes into the vertical channel, where the vertical pipelines are located, and creates the necessary natural circulating thrust, while the vertical channel with the pipelines acts as a chimney, in which the air flow can be adjusted by increasing or decreasing the hydraulic resistance to the flow to maintain the temperature of the lead coolant in the reactor vessel at a level of 400–450 ° C. In this case, a shortened contour of natural circulation through the core is preserved in the vessel itself, since the heater is located in the lower part of the reactor vessel, and the cooler is located in the upper part.

After routine refueling of fuel assemblies in the core and sealing of the reactor lid, all circulation pipelines of the primary circuit are heated to a temperature of at least 350 ° C and the entire natural circulation circuit is filled with a lead coolant. The circuit is filled by squeezing the lead melt out of the heated monjus with compressed gas. The reactor is ready for operation, and when the power rises, the steam generator is started. Since the power of the reactor is relatively small, the duration of the campaign between refueling is several years.

Conclusion

The presented concept of a low-power nuclear power reactor with natural circulation of a lead coolant located deep below ground level has a number of advantages over similar (in terms of power) light water reactors:

- simplicity of the design of the reactor plant, which allows it to be mass-produced at relatively low cost;
- a significant increase in safety due to a number of factors: natural protection from external influences, a sharp decrease in the number of possible emergencies associated with equipment breakdowns, power outage of the installation and erroneous actions of personnel;
- Possible reduction of capital costs during the construction of low-power nuclear power plants and the decommissioning of the reactor plant;
- absence of liquid radioactive waste;
- reducing the requirements for the qualifications of personnel, which is important in the case of widespread use of installations of this type;
- convenience in providing physical protection of the reactor facility;
- efficiently burn minor actinides obtained from the spent nuclear fuel of large power pressurized water reactors.

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