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Low-power lead-cooled fast reactor for education purposes

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Abstract

The possibility is examined to develop fast reactor for the purpose of implementation of research, education of undergraduate and doctoral students in handling innovative fast reactors and training specialists for atomic research centers and nuclear power plants. Main characteristics of liquid lead-cooled reactor using commercially implemented uranium dioxide with 19.7% enrichment with ^{235}U isotope as the fuel load are examined. Hard neutron spectrum achieved in the fast reactor with compact core and natural lead coolant and, in longer term perspective, cooled with lead enriched with ^{208}Pb isotope will allow addressing a number of research tasks under fast neutron flux densities of the order of 10^{13} neutrons/(cm^2 s). Relatively low thermal power equal to 0.5 MW is envisaged for the purpose of safe handling of the reactor. Possibility of prompt neutron runaway of the reactor is excluded due to the low reactivity margin which is less than the effective fraction of delayed neutrons. The studies are implemented based on the experience of development of low-power reactors available at the INPE NRNC "MEPhI", as well as on the experience gained at the Joint-Stock Company "SSC RF-IPPE" in the field of development of fast reactors cooled with heavy liquid metal.

Keywords: Research fast lead-cooled reactor for education purposes; Low thermal power; Low reactivity margin; Hard neutron spectrum.

Current status of research

Low power nuclear reactors, in particular, IRT reactor at the NRNU "MEPhI" [1] and the design of ELECTRA reactor [2], are used for educational and research purposes by a number of higher education institutions offering courses in nuclear engineering.

Main characteristics of inherently safe fast reactor (BRUTs) cooled with liquid lead and using commercially available uranium dioxide with 19.7% enrichment with ^{235}U isotope as the fuel composition which is intended to be used for education purposes are examined in the present study. Relatively low thermal reactor power equal to 0.5 MW is considered for the purposes of ensuring safe handling of the reactor. Possibility of reactor runaway on prompt neutrons is excluded due to low reactivity margin which is less than the effective fraction of delayed neutrons. The studies are implemented based on the experience available at the INPE NRNC "MEPhI" of development of low-power reactors, in particular, MASTER-IATE heat supply reactor with up to 0.3 MW thermal power [3], experience of substantiation of safety of liquid metal cooled nuclear power installations [4], as well as on the experience gained at the Joint-Stock Company "SSC RF-IPPE" in the field of development of fast reactors cooled with heavy liquid metal designed for different purposes.

Elements of the proposed design of the BRUTs reactor

Main elements of the proposed design of the BRUTs reactor and its performance characteristics are presented in Table 1.

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Table 1
Main technical characteristics of the BRUTs reactor core.

Characteristics, measurement unit	Value
Thermal power, MW	0.5
Number of fuel assemblies in the core, items	7
Number of fuel pins in the fuel assembly, items	252
Reactor core diameter, mm	618
Reactor core height, mm	620
Fuel pin diameter along the smooth part, mm	12.7
Fuel pin diameter over the spacer ribs, mm	13.9
Fuel pin lattice spacing, mm	14.0
Fuel composition	UO_2
^{235}U enrichment, %	19.7
UO_2 fuel load, kg	1176
^{235}U load, kg	205
Fuel residence in the core, years	20
Interval between fuel reloading, years	20

Table 2
Neutronics and thermal hydraulics characteristics of the BRUTs reactor.

Coolant, brand	Pb /C00
Coolant volume in the primary cooling loop (estimated), m^3	~6.0
Doppler reactivity effect, $\Delta K/K/K$	$-1\cdot10^{-5}$
Effective fraction of delayed neutrons, %	0.720
Lead temperature at the reactor core inlet/outlet, °C	460/500
Maximum temperature of fuel pin cladding, °C	526
Average coolant velocity in the reactor core, m/s	0.1
Coolant volume fraction in the reactor core, %	26.0
Average linear load on the loaded fuel pin section, kW/m	0.46
Average power density within the reactor core volume, kW/l	2.73
Neutron flux in the reactor core center, n/(cm^2 s)	$2.4\cdot10^{13}$
Neutron fluence in the core center during 200 eff. days, n/cm^2	$5.8\cdot10^{20}$
Fuel pin cladding material	Steel EP 823
Radiation damage of fuel pin cladding during 20 eff. years, dpa	<3
Calculated reactor service life, years	40

Neutronics and thermal hydraulics characteristics of the BRUTs reactor are provided in Table 2.

General design layout of the reactor

Pool-type configuration ensuring arrangement within the same reactor vessel of the reactor core with reflectors, as well as upper shielding plug, heat exchangers, coolant treatment equipment for maintaining thermodynamic activity of oxygen dissolved in the coolant, thermal engineering sensors, in-vessel shielding and buffer plenum above the molten lead free surface was suggested for the examined design of BRUTs reactor.

BRUTs reactor vessel represents rugged steel cylindrical containment with elliptical bottom and lid equipped with bores for installation and fastening the retractable in-vessel devices.

Reactor vessel is mounted inside concrete shaft with gap between the vessel and shaft walls designed for arrangement of natural air circulation circuit for removing residual heat through the vessel in passive mode and releasing this heat in atmosphere. Separating barrel dividing cold and hot coolant flows and ensuring installation of the retractable core support barrel with reflectors and support plate and designed as part of the arrangement of the primary coolant circulation loop is available inside the vessel.

It is expected that circulation of coolant in the primary cooling loop will be achieved by natural convection. Selection of natural circulation for the primary cooling loop allows avoiding the problem of development and substantiation of operability of circulation pump for pumping heavy liquid metal coolant. Calculation estimations demonstrate that for achieving natural circulation of coolant in the primary loop it is sufficient to have riser with height of ~3 m above the reactor core. This ensures the required head for natural circulation equal to about 1400 Pa. With coolant velocity trough the core equal to 0.1 m/s hydraulic pressure drop will amount for the reactor core to 480 Pa. In the assumption that total pressure drop along the loop exceeds the pressure drop in the core by approximately three times the conclusion can be drawn that natural circulation will be sufficient to ensure the required flow rate in the primary loop.

Reactor core

Reactor core consists of seven fuel assemblies, with 252 fuel pins each. Fuel pins are arranged in hexagonal lattice with pitch 14 mm. Technological channels are arranged in the center of each of the fuel assemblies for placement of (rods) of the reactor control and protection system (SUZ) (emergency shutdown system (RO AZ), reactivity compensation system (RO KR) and automatic reactor control system (RO AR)).

Fuel pin incorporates a block of fuel composed of fuel pellets with diameter equal to 11.5 mm; height of fuel column is equal to 620 mm with average density of fuel (uranium dioxide) along the column equal to 9.5 g/cm^3.

There is a gap filled with helium arranged between the fuel pin cladding and the fuel pellet. The size of the gap is equal to 0.05 mm. It was selected in order to prevent thermomechanical contact and direct interaction between fuel and cladding as a result of radiation swelling of the fuel in the process of fuel burnup.

Overall height of the fuel pin is equal to 1200 mm with 400 mm referring to the compensation plenum designed for collection of gaseous fission products.

End sections of fuel pins adjacent to the top and bottom of the reactor core (molybdenum inserts in the upper and lower parts of the fuel pin, fuel pin plugs), fuel pin lattice and support grid, fuel assembly head and bottom, coolant inlet and outlet plenums and other design elements perform the functions of top and bottom reactor reflectors.

Layout of the fuel pin cell of the BRUTs reactor is presented in Fig. 1. Map of separate fuel assembly is shown in Fig. 2. Transverse cross-section of the BRUTs reactor core is provided in Fig. 3. General external appearance of the BRUTs reactor is shown in Fig. 4.