A NEW GENERATION OF RESEARCH REACTORS FUELLED WITH LEU

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Abstract

A number of countries have recently shown interest in new research reactors. In response to such willingness to develop nuclear technologies, we have prepared technical proposals on typical research reactors (RR) which will be built as part of nuclear research centres (NRC) according to base design principles. The requirements for such research reactors are defined to represent their competitive service parameters, including capabilities to support a wide spectrum of studies in various areas of theoretical and applied researches. Analysis of the current and projected uses of research reactors and assessment of the external market demands have prompted two design options of a pool-type reactor at a nuclear research centre, namely, a small (up to 0.5 MW) reactor with natural coolant circulation through its core and a reactor with forced coolant circulation scaled up to 10-15 MW. The research reactors under development will run with commercially available and well-proven fuel of low enrichment.

1. INTRODUCTION

The beginning of this century saw significant abatement of the last century’s global trend for a decrease in the number of operating research reactors as well as an emerging interest in new facilities shown, *inter alia*, by countries that have no nuclear infrastructure.

Admittedly, advancement of research reactors will not be as vigorous as it used to be in the 1960s, but they are still the cheapest and most readily available sources of high neutron fluxes and will therefore hold the interest of experimenters for many years to come.

In the past, research reactors normally operated on uranium enriched to more that 20 % (HEU), which is a real threat from the viewpoint of illicit proliferation of fissile material. Work has long been in progress to reduce RR fuel enrichment in uranium-235 to less than 20% (to use LEU fuel). Despite certain headway made already in this direction, many issues are yet to be resolved and much has to be done before the final goal is attained and all civil research reactors are converted to LEU. It should be noted though that all new research reactors are designed to run with fuel of low enrichment.

2. R&D PURPOSES AND AREAS

NIKIET pursues research and development in the following directions:

- Participation in the activities to develop and produce competitive Russian LEU-fuel;
- Preparation of technical proposals for design of future research reactors (100 kW to 25 MW in capacity) keyed to potential foreign demand.

The new research reactors will be designed to have competitive service parameters and to support a broad spectrum of studies in:

- Nuclear physics;
- Solid-state physics;
- radiation material science;

- Neutron-activation analysis;
- Neutron radiography of various products;
- Silicon doping, production of medical and industrial isotopes (^{99}Mo, ^{131}I, ^{125}I, ^{35}S, ^{32}P, ^{90}Y, ^{166}Ho, ^{60}Co, ^{153}Sm, ^{192}Ir).

Research reactors can be used as training facilities and neutron sources for neutron therapy.

3. PRINCIPLES OF DESIGNING ADVANCED RESEARCH REACTORS

Development of new research reactors in line with international rules should be guided by the following conceptual design provisions and principles of use at nuclear research centres.

3.1. Reliability

- Application of design approaches and components well-proven during reactor operation in Russia and abroad;
- Choice of coolant flow rates and pressure drops in the core to provide the required boiling margin and heat engineering index.

3.2. Safety

- Core arrangement deep in a pool of water;
- The reactor designed to keep the core under water in the event of leaks in pipelines;
- Leak monitoring, collection and return to the pool during accidents;
- No surface boiling at fuel elements and core components;
- Adequate worth of CPS rods;
- Passive safety systems;
- Negative reactivity feedbacks;
- Presence of beryllium in the reflector to ensure safe reactor control during startup;
- Use of reference IRT-4M and VVR-M2 fuel assemblies with LEU fuel;
- Development of new VVR-KN assemblies with LEU fuel;
- Handling operations under water.

3.3. Efficiency

- High neutron flux in the reactor experimental devices;
- High burnup of discharged fuel assemblies;
- High “reactor merit” (Φ/N);
- Large variety of experimental positions.

3.4. Flexibility

- Reconfigurability of the reactor core;
- Variability of the number and location of experimental channels.

4. RUSSIAN LEU FUEL

Two types of fuel assemblies commercially available in Russia were chosen for the reactors, namely: VVR-M2 for the smaller research reactors and IRT-4M for the 10–15 MW reactors, as was also the newly developed VVR-KN fuel assembly for the latters. The general view of the fuel assemblies is given in Figures 1–3, and their technical characteristics are summarized in Table I.

The VVR-M2 fuel assemblies have successfully operated in Vietnam, Hungary and the Ukraine, and the IRT-4M assemblies have shown equally good performance in Bulgaria, Czechia and Libya.

The VVR-KN assembly was chosen for near-term applications. Its engineering design is completed, the manufacturing process has been tried out, and 3 full-size assemblies are available for tests in the VVR-K reactor in Kazakhstan. Production of the assemblies is to be launched in 2013.

TABLE 1. Technical characteristics of fuel assemblies made in Russia

Parameter	VVR-M2	IRT-4M with 6/8 fuel elements	VVR-KN with 5/8 fuel elements
Fuel portion height, mm	600	600	600
Fuel material	UO_2-Al	UO_2-Al	UO_2-Al
Enrichment in ^{235}U, %	19.7	19.7	19.7
^{235}U content in fuel assembly, g	50	263.8/300	201.9/252.6
U concentration, g/cm^3	2.5	3	2.8
Fuel cladding	SAV-1	SAV-1	SAV-1
Structural material of end pieces	SAV-6	SAV-6 (AMg_2)	SAV-6 (AMg_2)
Reference reactors	DRR(Vietnam), BRR(Hungary), VVR-M Kiev (Ukraine)	IRT-1(Libya), IRT-Sofia (Bulgaria), VR-1, LVR-15(Czech Republic), VVR-CM Tashkent (Uzbekistan)	Manufacture is to start in 2013

5. R&D RESULTS ACHIEVED

5.1 Development of technical proposals for research reactors of three power levels

The power range of advanced research reactors in demand in international market was defined at Phase 1. This comprises three baseline designs for the thermal power levels of 1, 10 and 20 MW. Technical proposals for the above research reactors were also developed as part of Phase 1.

Pool reactors with forced coolant circulation through the core were considered. Demineralized water is used as the coolant, moderator, axial reflector and radiation shielding material.

The pool reactor has been reasonably selected given its long-term history of safe and effective operations. Pool reactors are both highly safe and ensure high thermal neutron fluxes which are sufficient for carrying out nearly all kinds of studies involving use of thermal neutrons.

The core configurations offering optimal service characteristics (see Table 2), with the best possible combination of the reactor power level and the FA type employed, have been selected by calculations.

TABLE 2. BASIC CHARACTERISTICS OF 1MW, 10MW AND 20MW RESEARCH REACTORS

No.	Description of parameter	1 MW RR	10 MW RR		20 MW RR	
1.	FA type	VVR-M2	IRT-4M	VVR-KN	IRT-4M	VVR-KN
2.	Thermal power, MW	1	10	10	20	20
3.	Number of FAs in core	70	16	26	40	45
4.	Core height, m	600	600	600	600	600
5.	Fuel enrichment in ^{235}U, %	19.7	19.7	19.7	19.7	19.7
6.	Maximum thermal neutron flux (E<0.625 eV), $\times 10^{14}$ cm$^{-2}\cdot$s^{-1}:					
	in core	0.44	3.2	3.3	4.1	4.6
	in beryllium reflector	0.2	2	2	1.4	1.2
7.	Undisturbed neutron flux at the silicon doping channel (Ø 205 mm) location, $\times 10^{13}$ cm$^{-2}\cdot$s^{-1}:					
	thermal neutrons (E<0.625 eV)	-	3.8	3.7	6	9
	fast neutrons (E>0.82 MeV)	-	0.03	0.03	0.03	0.1
8.	Neutron flux at horizontal hole outlets, $\times 10^{10}$ cm^{-2}s^{-1}:					
	thermal neutrons (E<0.625 eV)	0.1-0.15	0.8-1.3	0.8-1.3	1.2-2	0.6-1.8
	fast neutrons (E>0.82 MeV)	0.1-0.12	0.004-0.05	0.004-0.05	0.01-0.08	0.003-0.034
9.	Undisturbed thermal neutron flux (E<0.625 eV) at hydraulic rabbit system locations, $\times 10^{13}$ cm$^{-2}\cdot$s^{-1}:	0.02	0.2	0.2	0.4	1.2
10.	Number of horizontal experimental holes (HEH)	4	4	4	4	4
11.	Number of vertical experimental holes (VEH)	4	up to 25	up to 25	up to 20	up to 17
12.	CPS actuator absorber	B_4C	B_4C	B_4C	B_4C	B_4C
13.	Number of control rods, including:	9	11	10	21	16
	shim rods	6	8	6	18	12
	automatic control rods	1	1	1	1	1
	scram rods	2	2	3	2	3
14.	Temperature effect, %ΔK/K	-0.5	-0.3	-0.3	-0.2	-0.15
15.	Average fuel burnup in disharged FA, %	50	50	50	50	50
16.	“Reactor merit” in thermal neutrons (Φ/N), 1/cm^{2}s·W	$4.4\cdot 10^7$	$3.2\cdot 10^7$	$3.3\cdot 10^7$	$2.05\cdot 10^7$	$2.3\cdot 10^7$

5.2 Current progress with designs of advanced research reactors

The two current pool RR versions developed for the NRC based on the initial phase activities and analyzing modern and prospective trends in the RR application and the foreign-market demand are a small reactor (of up to 0.5 MW) with natural coolant circulation via the core and a power-scalable reactor with forced coolant circulation (10–15 MW).

Each reactor is accommodated inside a concrete shield building and comprises a tank, which serves as the pool's outer containment, a core, a beryllium reflector, the control and protection system (CPS) actuators, ionization chamber channels, an upper shielding plate, horizontal hole gate valves and experimental devices. The reactor tank is also used for the interim storage of spent FAs. The reactor's pool design makes it much easier for FAs and irradiated samples to be placed in and withdrawn from the core.

The reactor of 10-15 MW is peculiar in that it has the CPS actuators encapsulated and contained in a subreactor room beneath the reactor support plate. This leads to more space left free over the core for carrying out experiments and handling operations. The CPS actuators are operated with the aid of stepped motors. For safety reasons, the design includes leakage protection.

Table 3 presents the basic service characteristics of the research reactors under design.

TABLE 3. BASIC CHARACTERISTICS OF SMALL AND MEDIUM-SIZE RESEARCH REACTORS

Description of parameter	RR parameter value	
FAs	Tube type, LEU (UO_2 + Al, 19.7 % ^{235}U)	
Thermal power, MW	≤ 0.5	10-15
Core height, mm	600	600
Reflector	beryllium	
Moderator	demineralized water	
Coolant		
Circulation	natural	forced, downward
In-core maximum thermal neutron flux, 10^{14} $cm^{-2}\cdot s^{-1}$, not less than	0.2	3.2
Maximum thermal neutron flux in reflector, 10^{14} $cm^{-2}s^{-1}$, not less than	0.1	2
RR "merit" – thermal neutron flux reduced per power unit, $\times 10^{14}$ $(cm^{-2}s^{-1}))$/MW	about 0.4	0.32
Number of horizontal experimental holes	4	4-5
Number of vertical experimental holes	4	≤ 24
Average fuel burnup in withdrawn FA, %	50	50

The potential reactor core maps are given in Figures 4–6 and 3D reactor models are given in Figures 7 and 8.

The reactors under design are intended for carrying out operations using experimental holes that can be inserted into the core cells, into the replaceable beryllium blocks, into the central trap and into the fixed reflector cells. It is not only ample experimental capabilities that is offered by vertical holes but also the capacity for generation of commercial isotopes and doped silicon.

For off-core neutron beam activities, including for medical purpose, the reactors will include 4 horizontal holes each.

Structurally, the reactor design permits the number of holes to be great enough. The list of the experimental facilities and devices for the reactor will be subject to update as the user desires.

The following engineering and design concepts are developed as part of the technical proposals for the reactor facilities with small and medium-size water-cooled water-moderated research reactors:

- Circuitry designs;
- Estimates of neutronic and thermal-hydraulic parameters;
- Core and reflector layouts;
- Core and reflector cooling systems;
- Systems for handling of irradiated items;
- RF circuit diagrams;
- Also the cost of the design documentation development, equipment fabrication and RF construction and commissioning support activities will be determined.

6. EVOLUTION PROSPECTS OF THE NRC PROJECTS

Further activities will have the purpose of creating RR designs as part of the nuclear research centers to be assigned to a set of tasks defined with regard for specific user demands.

The available materials form the basis for the following herein listed evolution phases of the NRC baseline designs:

- Selection of components for experimental facilities and laboratories the NRC includes;
- Determination of the composition and the scientific, production, engineering and infrastructural support for the isotope generation and production of doped silicon, and the materials research support;
- Cost estimation for scientific, production, engineering and infrastructural support of the NRC in accordance with its designated function;
- Development of the NRC design materials.

NIKIET is ready to offer to those countries interested in the development of nuclear technologies its turnkey RR designs meeting all international design standards for such facilities.

On the one hand, as typical designs, these are attractive in terms of the price and quality ratio. On the other hands, these designs give the potential customer a kind of a choice with respect to the NRC components depending on the RR application planned and the specific customer needs.

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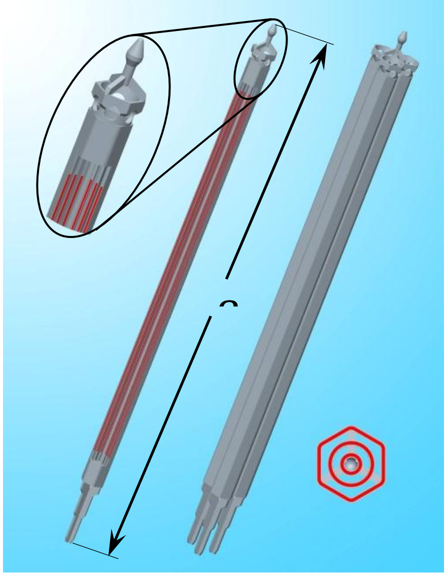


FIG. 1. VVR-M2 FA

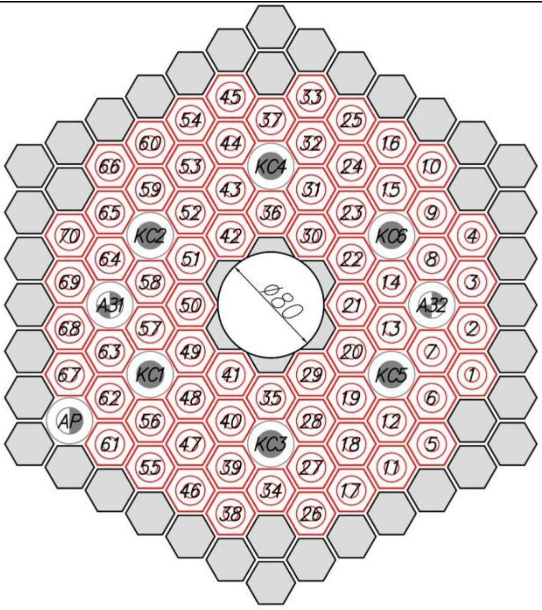


FIG. 4. Core map of the 0.5MW RR

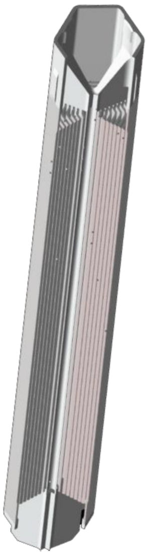


FIG. 2. VVR-KN FA

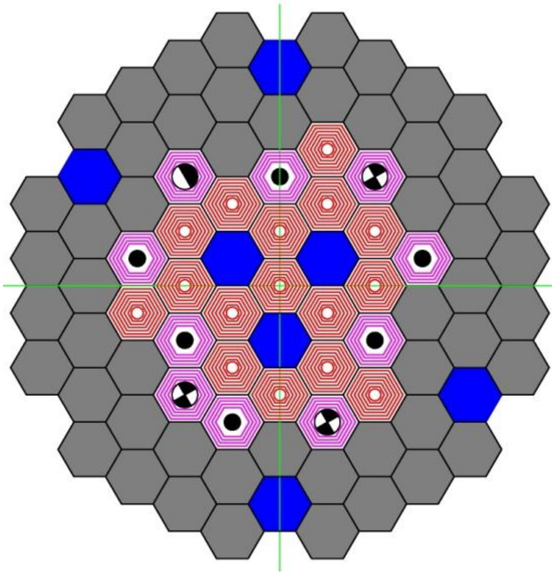


FIG. 5. Core map of 10MW RR with VVR-KN FAs

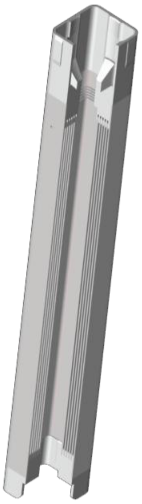


FIG. 3. IRT-4M FA

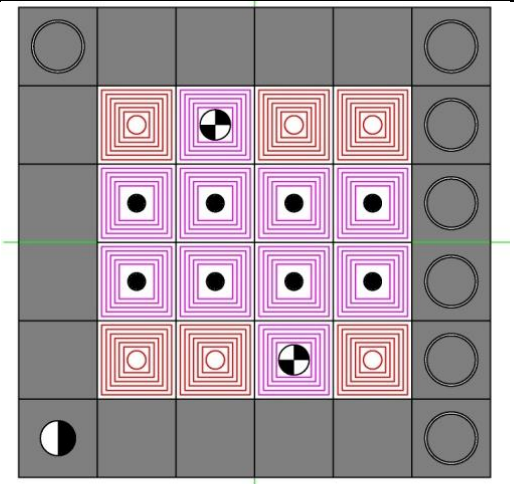
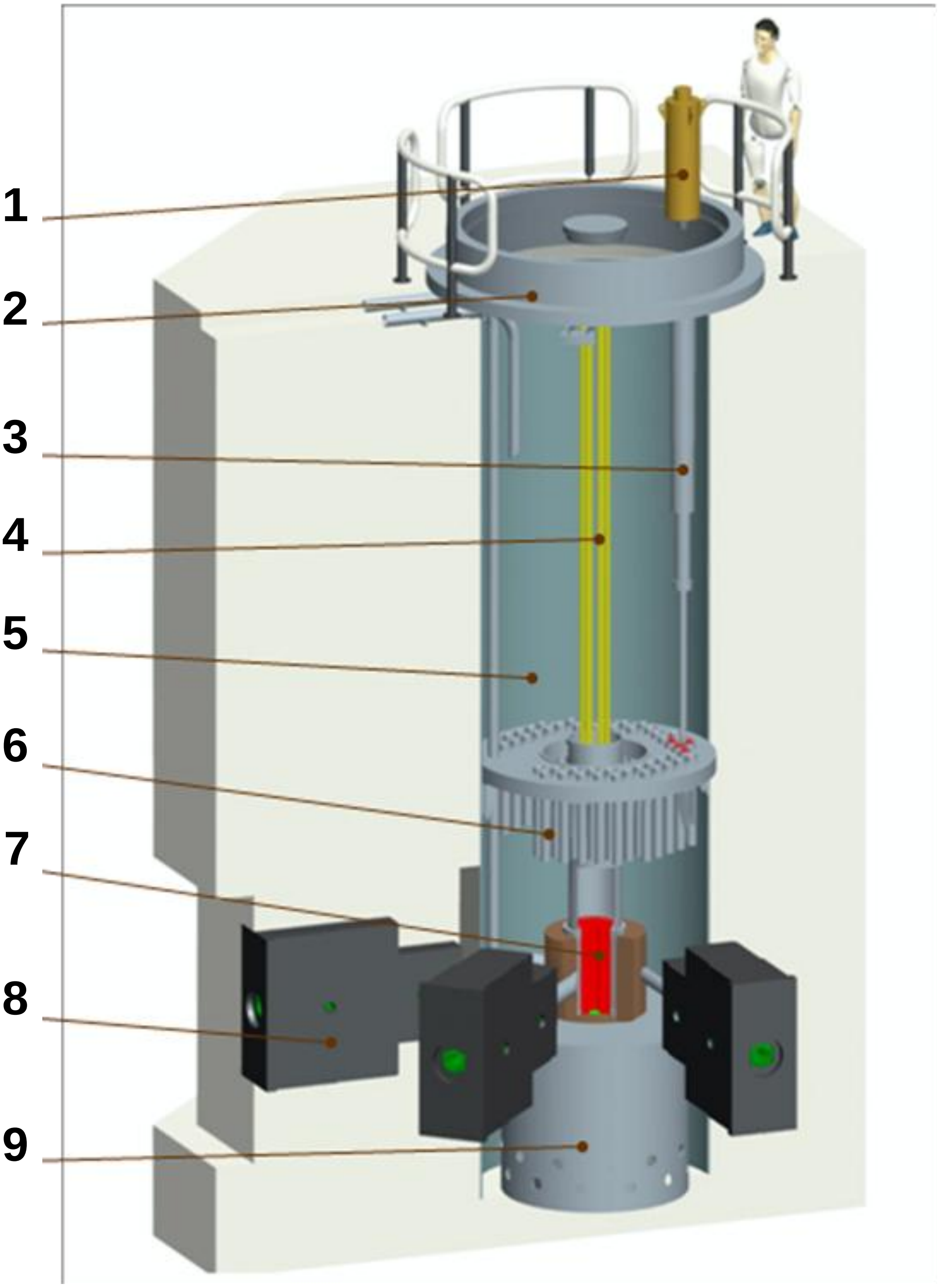
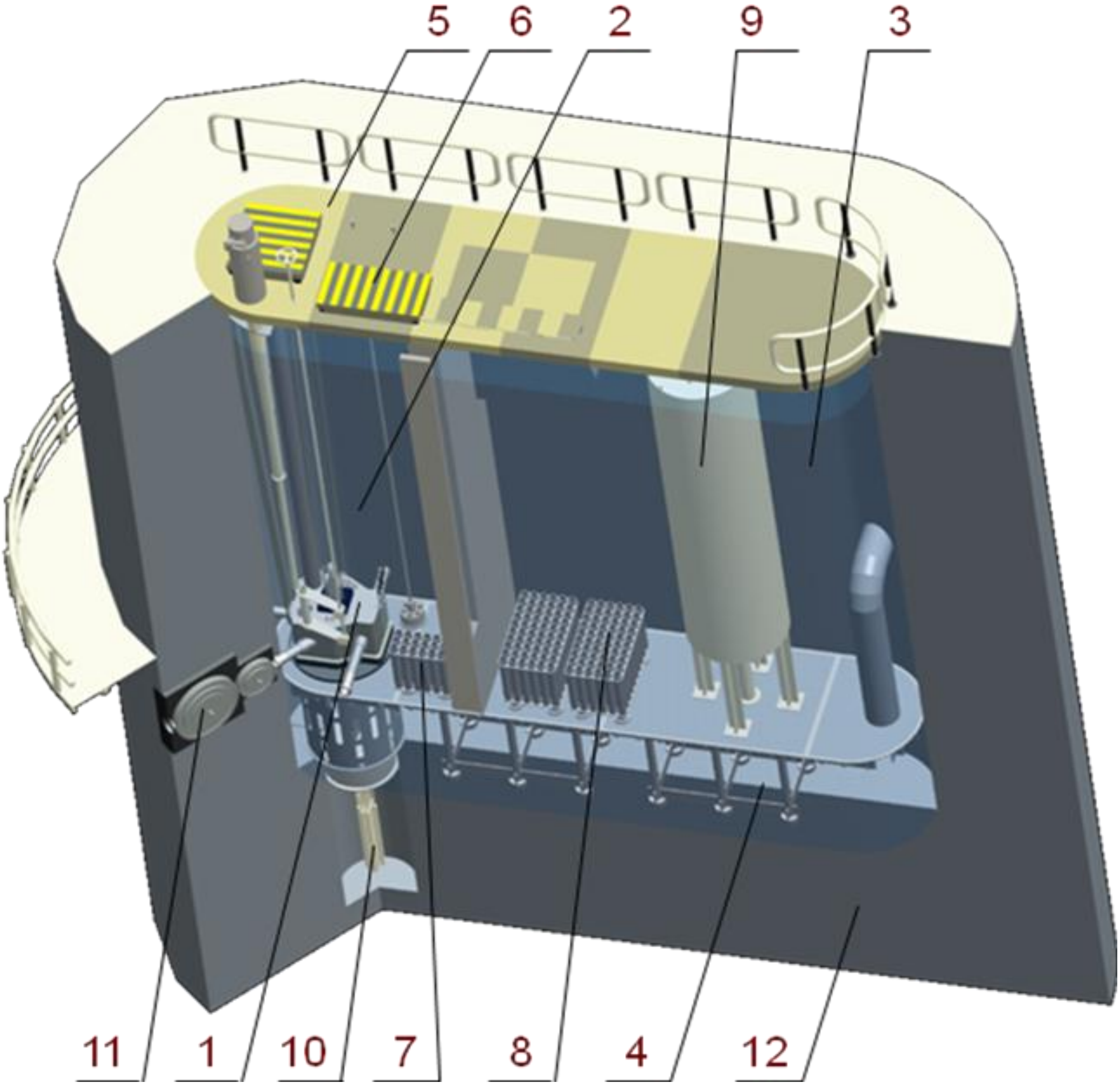


FIG. 6. Core map of the 10MW RR with IRT-4M FAs



1 – transfer cask; 2 – shielding plate; 3 – shielded transfer channel; 4 – CPS channels; 5 – reactor pool; 6 – FA storage; 7 – core and reflector; 8 – HEH gate valve; 9 – retainer tank

FIG. 7. 3D model of the small RR



1 – reactor core and reflector; 2 – reactor pool; 3 – storage pool; 4 – retainer tank; 5 – upper plate; 6 – sliding plate; 7 – intermediate storage; 8 – SFA storage; 9 – ECCS tank; 10 – CPS drives; 11 – HEH gate valve; 12 – biological shield body

FIG 8. 3D model of the 10 MW RR