Status of research reactors in Russia and prospects for their development

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ABSTRACT

Russian research reactors (RR) have a history of more than 60 years, which begins on December 26, 1946, when the first Russian RR – 24 kW uranium-graphite reactor F-1 – was started in Moscow. This reactor is still in operation and is protected by the government as a monument to Russian scientific and engineering thought. The F-1 reactor ushered in the era of nuclear power in Russia (USSR in those days) and gave rise to an important line in these activities, i.e. reactor engineering for research purposes.

Russian research reactors had an eventful and far from easy way to go in their development. Like other major nuclear states, Russia took energetic efforts to provide its own research reactors in the period of 1950s-'80s; it exported such reactors to other countries, and survived the nuclear stagnation of the end of the 20th century through beginning of the 21st century to keep its leading position in RR uses to the present day.

Reforms in the Russian nuclear industry, the extensive experience in building research reactors both at home and abroad, together with the proactive export policy of the newly established public corporation "Rosatom" form a groundwork for making Russia a more important player in the international market of research reactors. Today, Russia can offer a broad spectrum of services to foreign customers, ranging from conduct of specific experiments in its domestic reactors to building of scientific centres with research reactors at their core.

This paper discusses the current status of Russian research reactors as well as the prospects for their development in the coming years. A special note is made of the trend towards more active presence of Russia in the international RR market.

1. INTRODUCTION

Russian research reactors (RR) have a history of more than 60 years, which begins on December 26, 1946, when the first Russian RR – 24 kW uranium-graphite reactor F-1 – was started in Moscow. This reactor is still in operation and is protected by the government as a monument to Russian scientific and engineering thought. The F-1 reactor ushered in the era of nuclear power in Russia (USSR in those days) and gave rise to an important line in these activities, i.e. reactor engineering for research purposes.

Russian research reactors had an eventful and far from easy way to go in their development. Like other major nuclear states, Russia took energetic efforts to provide its own research reactors in the period of 1950s-'80s; it exported such reactors to other countries, and survived the nuclear stagnation of the end of the 20th century through beginning of the 21st century to keep its leading position in RR uses to the present day.

Expectation of the nuclear renaissance, innovative nuclear engineering, the expanding RR uses for production of isotopes and other practical purposes, the increasing number of countries seeking to use nuclear technologies in energy production, industry and science – all add up to reawaken the interest in research reactors and in the benefits they offer.

2. CURRENT STATUS OF RESEARCH REACTORS IN RUSSIA

2.1 Current status and availability of research reactors in the world

In the IAEA terminology, the RR fleet includes both research reactors proper and critical or subcritical assemblies. As of the end of 2007, 671 nuclear research facilities were built in 70 countries of the world. Table 1 describes the global RR fleet in operational and quantitative terms.

Table 2 presents data showing the RR status in the major nuclear states (Russia, USA, UK, France, China) and in the countries with nuclear power well developed or showing dynamic development (Germany, Japan, Republic of Korea, India).

Thus, as of the end of 2007, Russian operating research reactors account for almost 20% of the global operating RR fleet, which makes Russia a leader in present-day use of research reactors.

Table 3 presents relative characteristics of the operating RR fleets in the above countries.

Table 1 – Status and number of research reactors in the world (as of September 2007).[1]

RR status	Number
Operating (O)	246
Shut-down (S)	242
Decommissioned/under decommissioning (D)	170
Under Construction (C)	9
Planned (P)	4
All	**671**

Table 2 – Status and number of research reactors in some countries [2]

RR status	Number of research reactors								
	UK	Germany	India	Korea	China	Russia	USA	France	Japan
O	**3**	**12**	**5**	**2**	**14**	**49**	**41**	**14**	**13**
S	6	11	0	2	2	36	117	12	8
D	27	23	4	0	0	11	69	5	3
C	0	0	1	0	2	1	0	1	0
P	0	0	0	0	0	1	0	0	0
Total	**36**	**46**	**10**	**4**	**18**	**98**	**227**	**32**	**24**

Table 3 – Quantitative comparison of the national operating RR fleets

Country	Number of operating RRs	Percentage in the global operating RR fleet, %
UK	3	1.2
Germany	12	4.9
India	5	2.0
Korea	2	0.8
China	14	5.7
Russia	**49**	**19.9**
USA	41	16.7
France	14	5.7
Japan	13	5.3
All world	**246**	**100**

2.2 Qualitative description of the Russian RR fleet

It is necessary to be terminologically accurate in qualifying a reactor as a research facility. To be referred to as such, the reactor must have two essential attributes:

- regarding its purpose, the reactor should be specially designed for conducting investigations in dedicated experimental spaces;
- regarding its final product, such a reactor should supply neutrons of the required energy spectrum and in the required quantities to the experimental spaces.

Thus, a research reactor is a facility designed for experimental studies and operating at a power level requiring forced cooling, with its composition and geometry providing for a controlled nuclear chain reaction.

The capabilities of research reactor are characterised by the neutron flux level in the experimental space. In this sense, the experimental research potential of a country depends primarily on the number and quality of medium- and high-flux research reactors, i.e. more than 15 MW and 50 MW in capacity, respectively, as generally accepted.

Table 4 presents data on such reactors in the countries under consideration.

The most general qualitative characteristic of research reactors is referred to accordingly as the “Quality” of a reactor (K_{RR}), which is defined as the ratio of the maximum neutron flux (Φ_{max}) to nominal thermal power of the reactor (Wt): $K_{RR}=\Phi_{max}/W_T$ [neutr./(cm^2·s)]/kW. The K_{RR} parameter is actually technical and economic in nature, as it indicates the number of neutrons per unit thermal power of the reactor. It goes without saying that the RR designers and operators should seek to increase this parameter.

Service time is another characteristic of importance to Russian research reactors, as many of them were brought into operation in the 1960s-'80s. Despite their sound design and engineering features, the operating research reactors face the problem of ageing, which inevitably affects the level of their operational safety and is continuously adding to the costs of maintaining the required safety level.

Table 4 – Comparison of medium- and high-flux RR fleets existing in some countries

Country	Operating RR	RR of W≥1MW	RR of W≥15MW	RR of W≥50MW
UK	3	0	0	0
Germany	12	4	2	0
India	5	4	3	1
Korea	2	1	1	0
China	14	9	2	1
Russia	**49**	**13**	**7**	**4**
USA	41	20	3	2
France	14	7	6	4
Japan	13	5	4	2
All world	**246**			

Table 5 is a list of the main Russian research reactors with their qualitative characteristics.

3. PROSPECTS FOR DEVELOPMENT OF RUSSIAN RESEARCH REACTORS

It should be noted, however, that Russian scientists and engineers feel concerned about the fact that the research reactors in greatest demand have been in operation for more than 30 – or even 40 – years, while the estimated time of their final shutdown is not very far off, as may be seen from Table 7.
Unless radical steps are taken, the Russian RR fleet will shrink to one-third of its present size, with mostly high- and medium-flux reactors to go.

It is obvious that Russia has not escaped the global trend towards reduction of the RR numbers (see Fig. 1).
In this regard, it appears imperative to optimise the Russian RR fleet. Today, the Russian nuclear industry is undergoing structural reforms: the public corporation "Rosatom" is instituted already; many research centres and institutes have been consolidated into the Joint Stock Company "Atomenergoprom" and are being restructured. Optimisation of the Russian RR mix is high on the agenda. Some operating research reactors are being upgraded and plans are being discussed for building one or, perhaps, two advanced high-flux fast reactors for research purposes.

The characteristics of some research reactors, i.e. SM-3, MIR-M1 and PIK, presented below can give an idea of the Russian experimental capabilities.

High-flux reactor SM-3 [3]

The SM-3 reactor is designed for studies of reactor core materials for nuclear power and research facilities, as well as for production of radionuclides.

The main technical characteristics of the reactor are given in Table 8, and its configuration is shown in Figs. 2 and 3.

Material testing loop reactor MIR-M1 [4]

The research reactor facility "MIR" serves for loop-testing of fuel assemblies and other core components and materials under in-pile radiation, for developing reactor coolant technologies, and for solving other engineering problems. This is a heterogeneous thermal neutron channel-type reactor, with its core immersed in a water pool.

The core-housing pool ensures the safety of handling operations, which proceed underwater, provides an additional safety barrier to release of radioactivity into the environment, and is part of the circuit for cooling the beryllium blocks of the core and reflector, the CPS rods and the structural components of the reactor. The main characteristics of the MIR-M1 reactor are listed in Table 10, and its general configuration is shown in Figs. 4 and 5.
The characteristics of loops, which are the main experimental components of the reactor, are presented in Table 11.

High-flux research reactor PIK [5]

The high-flux beam-type reactor PIK, with the thermal neutron flux of 10^{15} n/cm^{2}s in the heavy-water reflector, is being built at Gatchina near St. Petersburg for research in various fields of fundamental science as well as for tackling a broad range of practical problems.
The experimental capabilities of PIK result not only from the high intensity of neutron beams but also from the availability of hot, cold and ultracold neutron sources.

Table 5 – Qualitative characteristics of the main Russian research reactors

Reactor	**Power, kW**	**Neutron flux, 1/cm^2 s, thermal/fast**	**Quality, К$_{RR}$**
BOR-60	60 000	/$3.7 \cdot 10^{15}$	$6.17 \cdot 10^{10}$
SM-3	100 000	$5.0 \cdot 10^{15}/2.0 \cdot 10^{15}$	$5.0 \cdot 10^{10}$
PIK (under construction)	100 000	$5.0 \cdot 10^{15}/2.0 \cdot 10^{15}$	$5.0 \cdot 10^{10}$
IR-50	50	$1.7 \cdot 10^{12}/1.7 \cdot 10^{11}$	$3.4 \cdot 10^{10}$
IVV-2M	15 000	$5.0 \cdot 10^{14}/1.5 \cdot 10^{14}$	$3.3 \cdot 10^{10}$
IR-8	8 000	$2.5 \cdot 10^{14}/5.8 \cdot 10^{13}$	$3.13 \cdot 10^{10}$
RBT-6	6 000	$1.5 \cdot 10^{14}/5.9 \cdot 10^{13}$	$2.5 \cdot 10^{10}$
Argus	20	$5.0 \cdot 10^{11}/1.1 \cdot 10^{11}$	$2.5 \cdot 10^{10}$
VVR-M	18 000	$4.0 \cdot 10^{14}/1.5 \cdot 10^{14}$	$2.2 \cdot 10^{10}$
RBT-10/2	7 000	$1.5 \cdot 10^{14}/6.9 \cdot ^{13}$	$2.14 \cdot 10^{10}$
IRT-2500	2 500	$5.2 \cdot 10^{13}/1.0 \cdot 10^{13}$	$2.08 \cdot 10^{10}$
IRT-T	6 000	$1.1 \cdot 10^{14}/1.2 \cdot 10^{13}$	$1.83 \cdot 10^{10}$
IBR-2*	2 000 (1500 MW, pulsed)	$3.0 \cdot 10^{13}/1.5 \cdot 10^{14}$ ($1.0 \cdot 10^{16}/1.3 \cdot 10^{17}$, pulsed)	$1.5 \cdot 10^{10}$
MIR-M1	up to 100 000 (40 000)	$5.0 \cdot 10^{14}/3.0 \cdot 10^{14}$	$1.25 \cdot 10^{10}$
VVR-C	15 000	$1.8 \cdot 10^{14}/0.3 \cdot 10^{14}$	$1.2 \cdot 10^{10}$
Gidra	10	$1.0 \cdot 10^{11}/1.0 \cdot 10^{12}$ ($5.0 \cdot 10^{16}/5.0 \cdot 10^{17}$, pulsed).	$1.0 \cdot 10^{10}$
OP	300	$3.0 \cdot 10^{12}$/	$1.0 \cdot 10^{10}$
IRV-M2 (under upgrades)	4 000	$1.4 \cdot 10^{13}$/	$0.35 \cdot 10^{10}$
VK-50	200 000	$5.0 \cdot 10^{13}/1.5 \cdot 10^{14}$	$2.5 \cdot 10^{08}$
F-1	24	$5.9 \cdot 10^{09}$	$2.46 \cdot 10^{08}$

*- IBR-2 is the world's only pulsed reactor with mechanical reactivity modulation.

Table 6 – "Quality" of some research reactors

RR, country	**Power, kW**	**Maximum neutron flux, 1/(cm^2·s)**	**Quality, К$_{RR}$**
BOR-60, Russia	60 000	$3.7 \cdot 10^{15}$	$6.17 \cdot 10^{10}$
CM-3, Russia	100 000	$5.0 \cdot 10^{15}$	$5.0 \cdot 10^{10}$
PIK, Russia (under constr.)	100 000	$5.0 \cdot 10^{15}$	$5.0 \cdot 10^{10}$
FRM-II, Germany	20 000	$8.0 \cdot 10^{14}$	$4.0 \cdot 10^{10}$
IVV-2M, Russia	15 000	$5.0 \cdot 10^{14}$	$3.3 \cdot 10^{10}$
IR-8, Russia	8 000	$2.5 \cdot 10^{14}$	$3.13 \cdot 10^{10}$
JOYO, Japan	140 000	$4.5 \cdot 10^{15}$	$2.85 \cdot 10^{10}$
HFR (ILL), France	58 300	$1.5 \cdot 10^{15}$	$2.56 \cdot 10^{10}$
HFIR, USA	85 000	$2.1 \cdot 10^{15}$	$2.47 \cdot 10^{10}$
NBSR, USA	20 000	$4.0 \cdot 10^{14}$	$2.00 \cdot 10^{10}$
OPAL, Australia	20 000	$3.0 \cdot 10^{14}$	$1.5 \cdot 10^{10}$
HONARO, Korea	30 000	$4.5 \cdot 10^{14}$	$1.5 \cdot 10^{10}$
HFR, Netherlands	45 000	$4.6 \cdot 10^{14}$	$1.02 \cdot 10^{10}$
BR-2, Belgium	100 000	$1.0 \cdot 10^{15}$	$1.0 \cdot 10^{10}$
OSIRIS, France	70 000	$2.7 \cdot 10^{14}$	$0.38 \cdot 10^{10}$

Table 7 – Estimated time of final shutdown of the main Russian research reactors

Research reactor	Power, kW	Commissioning year	Current status	Estimated time of final shutdown
SM-3	100 000	1961	in operation	2017
VK-50	200 000	1965	in operation	2012
MIR-M1	100 000	1966	in operation	2017
BOR-60	60 000	1969	in operation	2009
RBT-6	6 000	1975	in operation	2009
RBT-10/2	7 000	1984	in operation	2012
IVV-2M	15 000	1982	in operation	2025
IR-8	8 000	1981	in operation	2020
IRT-2500	2 500	1967	in operation	2012
IRT-T	6 000	1967	in operation	2017
IBR-2	2 000	1984	under upgrades till 2010	2035
VVR-C	15 000	1964	in operation	2012
VVR-M	18 000	1959	in operation	2012
IRV-2M	4 000	2008	under upgrades	2040
PIK	100 000	2012	under construction	2062

Table 8 – Main characteristics of the SM-3 reactor.

Characteristics	*1.1.1 Value*
Maximum thermal power, MW	100
Working pressure in the primary circuit, MPa	5.0
Primary water flow rate, m^3/h	2400
Maximum water velocity in the core, m/s	13.5
Pressure difference in the core, MPa	0.59
Water temperature in the core, inlet/outlet, °C	60/95
Core volume, l	51.9
Uranium-235 mass, kg	23
Thermal load:	
- average over the core volume, kW/l	1930
- maximum on the fuel rod surface, kW/m^2	~15000
Maximum thermal neutron flux density, $1/cm^2 \cdot s$	5×10^{15}

Table 9 – Main characteristics of the SM-3 reactor loops.

Characteristics	*Value*	
	Loop VP1	**Loop VP3**
Maximum power, kW	2000	100
Pressure in the primary circuit, MPa	4.9	19.6
Inlet water temperature at experimental channels, °C	20-60	up to 300

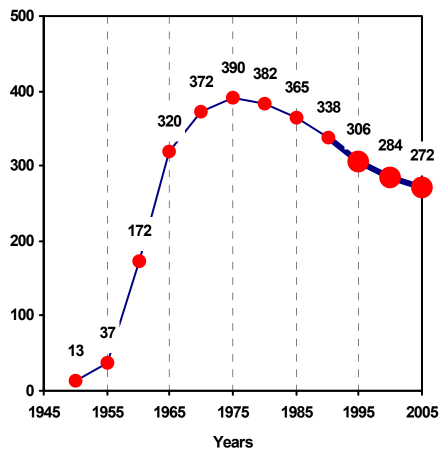

Fig. 1 – Changes in the number of the world's operating research reactors between 1950 and 2005 [1]

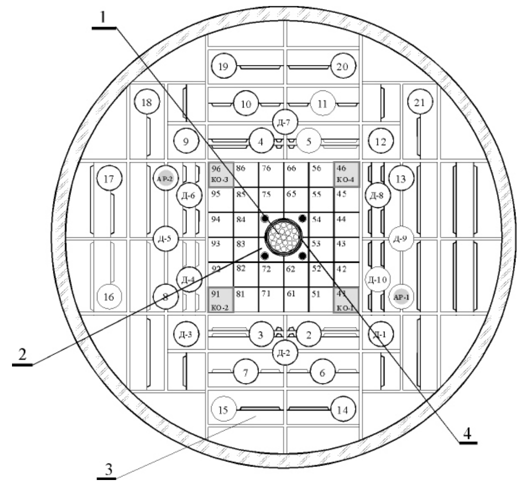

Fig. 3 – SM core

1 – central block of transuranium targets; 2 – beryllium inserts;

3 – beryllium reflector blocks; 4 – central CPS rod.

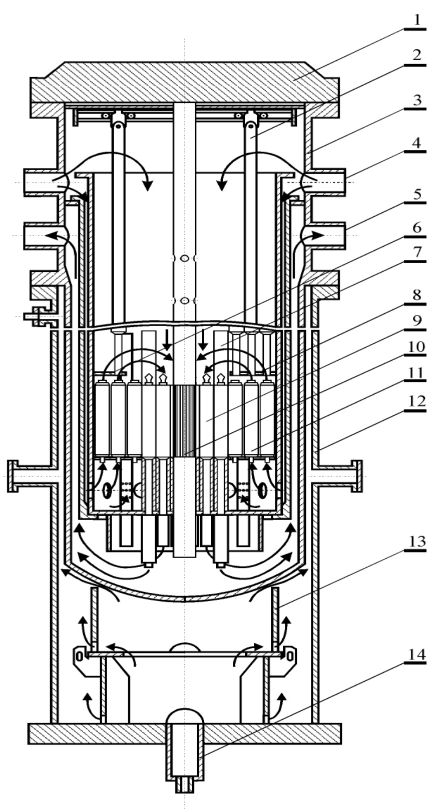

Fig. 2 – SM-3 reactor

1 – lid; 2 – reloading mechanism; 3 – vessel; 4 – inlet nozzle; 5 – outlet nozzle; 6 – smaller handling pad; 7 – pressuriser tube; 8 – larger handling pad; 9 – fuel assembly; 10 – central high-flux channel; 11 – beryllium reflector; 12 – safeguard vessel; 13 – thermal insulation; 14 – inlet nozzle of the vessel cooling system.

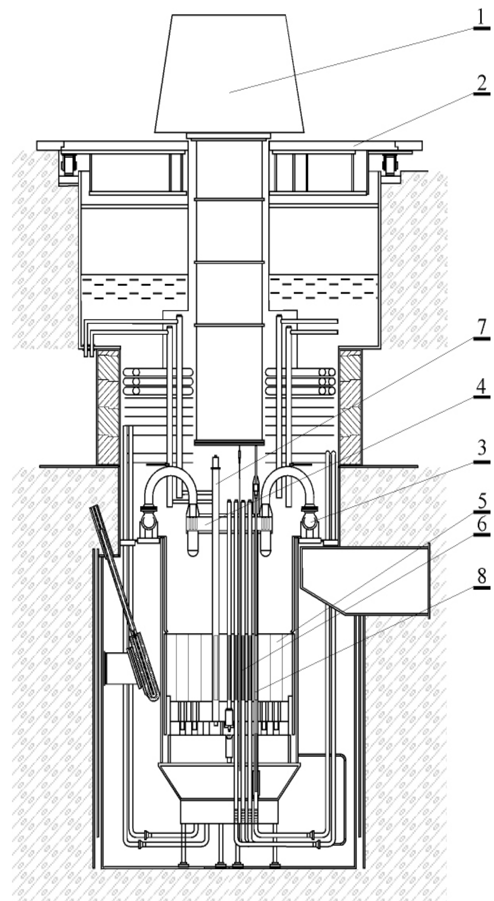

Fig. 4 – MIR-M1 configuration

1 – platform of CPS rod drives; 2 – shielding turnplate; 3 – annular header;

4 – feeding header; 5 – core; 6 – fuel channel; 7 – loop channel;

8 – movable fuel assembly channel.

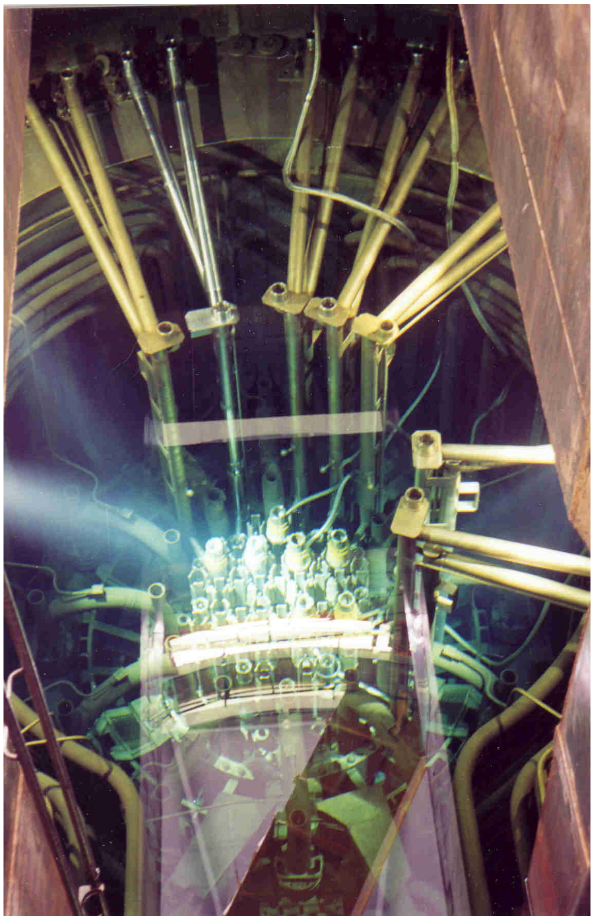

Fig. 5 – MIR-M1 view

The PIK parameters are presented in Table 12, and its experimental capabilities are described in Table 13.

Figures 6 and 7 are the general view of the PIK reactor and the view of the core in its central cross-section. As seen from these pictures, the reactor is configured to include a large number of experimental devices.

According to the latest decisions of 2007, the PIK reactor is to be commissioned in 2012. Figure 8 presents photographs of the PIK reactor.

3. RUSSIAN EXPERIENCE IN BUILDING RESEARCH REACTORS IN OTHER COUNTRIES AND THE CURRENT EXPORT POLICY

More than 20 nuclear research facilities were built abroad to Russian designs with the country's participation, the greater part of which are still in operation. Table 14 presents some of these reactors.

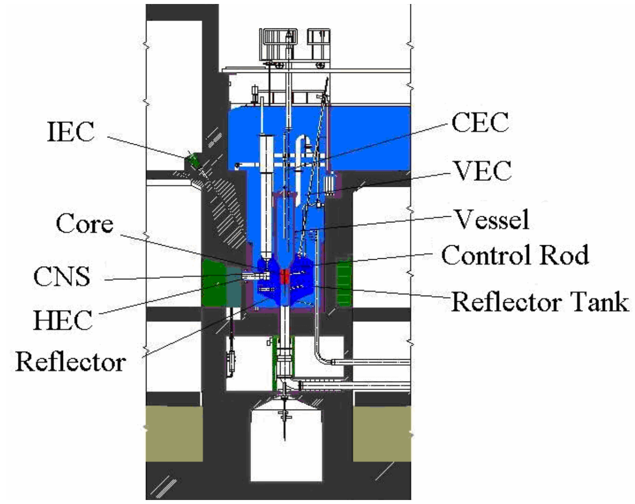

Fig. 6 – General view of the PIK reactor

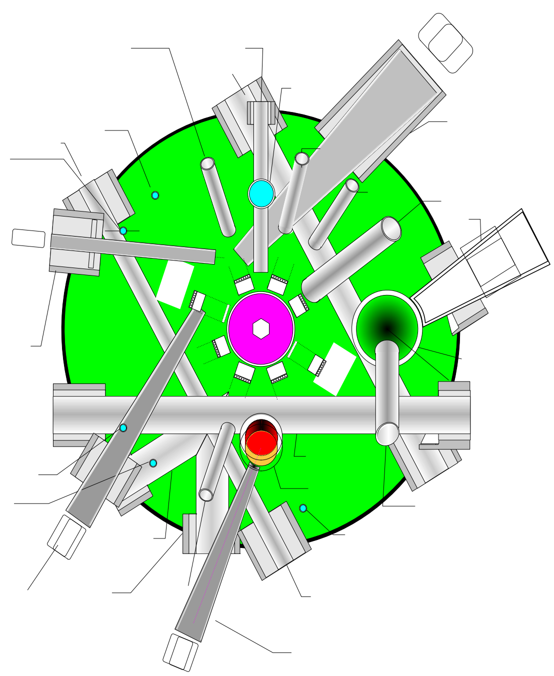

Fig. 7 – Central cross-section of the PIK core

Table 10 – Main characteristics of MIR

Characteristics	*Value*
Maximum thermal power, MW	100
Coolant	H_2O
Reflector	Be
Moderator	H_2O+Be
Pressure in the pressure header of primary pumps, MPa	1.5
Nominal pressure in a fuel channel, MPa	1.2
Primary water flow rate, m^3/h	2500
Water flow rate in the pool circuit, m^3/h	1000
Water temperature in a fuel channel, °C (inlet/outlet)	40/83
Water temperature in the pool, °C (inlet/outlet)	40/60
Water velocity in a fuel assembly, m/s	up to 10
Nominal uranium inventory, kg	17.95
Maximum undisturbed density of thermal neutron flux, $1/cm^2s$	5×10^{14}
Heat pickup surface of a fuel assembly, m^2	up to 1.37
Core height, mm	1000
Beryllium block height, mm	1100
Water column height above the core centre, m	8
Number of loop channels in the core	up to 11

Table 11 – Main characteristics of MIR loops

Loop		Power, kW	Number of experimental channels	Maximum temperature, °C	Pressure, MPa
High-temperature water	PV-1	2000	2	350	≤20
	PV-2	2500	2	350	≤17.8
Boiling water	PVK-1	2000	2	350	≤20
	PVK-2	2500	2	350	≤17.8
Steam-water	PVP-2	2000	1	500	≤20
Gas	PG-1	200	1	500	20

Table 12 – Main parameters of the PIK reactor

Power	100 MW
Maximum specific power	6 MW/l
Core volume	51 l
Core diameter	390 mm
Core height	500 mm
PIK fuel: UO_2 in a copper-beryllium matrix	
- enrichment: 90%	
- uranium density in the matrix: 2 g/ cm^3	
- cladding: stainless steel 0.15 mm in thickness	
- uranium-235 concentration in fuel: 600 g/l	

D_2O reflector: diameter of 2.5 m; height of 2 m
Cooling circuit: H_2O coolant
- pressure: 50 atm
- flow rate: 2400 m^3/h
- inlet/outlet temperature: 50/70 ^oC

Table 13 – Experimental capabilities

Central loop channel in the core	
Thermal neutron flux	$5 \cdot 10^{15}$ n/cm^2·s
Fast neutron flux (E>1.2 MeV)	$5 \cdot 10^{14}$ n/cm^2·s
Channel diameter	100 mm
Irradiation channel diameter	41 mm
Pressure range	0.15÷5.0 MPa
Power removed by cooling at 5.0 MPa	400 kW
Horizontal experimental channels – 10 in number	
Thermal neutron flux at end caps	$(0.1 \div 1.2) \cdot 10^{15}$ n/cm^2·s
Outlet thermal neutron flux	$(0.2 \div 3) \cdot 10^{11}$ n/cm^2·s
Channel diameters	100÷250 mm
Inclined experimental channels – 6 in number	
Thermal neutron flux at end caps	$(0.2 \div 1) \cdot 10^{15}$ n/cm^2·s
Fast neutron flux (E>0.7 MeV) at the end cap of channel 5	$2.5 \cdot 10^{13}$ n/cm^2·s
Outlet thermal neutron flux	$(0.4 \div 2) \cdot 10^{10}$ n/cm^2·s
Channel diameters	90–140 mm
Vertical experimental channel – 7 in number	
Thermal neutron flux at end caps	$(1 \div 3) \cdot 10^{14}$ n/cm^2·s
Channel diameters	60 mm
Cold neutron sources – 2 in number	
Flux density (undisturbed) in a vertical channel	$4 \cdot 10^{14}$ n/cm^2·s
Flux density (undisturbed) in a horizontal channel	$1.0 \cdot 10^{15}$ n/cm^2·s
Hot neutron source – 1	
Average thermal neutron flux density (undisturbed)	$3 \cdot 10^{14}$ n/cm^2·s
Wave length at the spectrum peak	0.5 Å
Outlet neutron flux	$3 \cdot 10^{9}$ n/cm^2·s
Neutron guides – 7 in number (with possible increase to 9)	
Wave length	λ=1.0÷12 À
Outlet flux	$(0.3 \div 1.5) \cdot 10^{9}$ n/cm^2·s

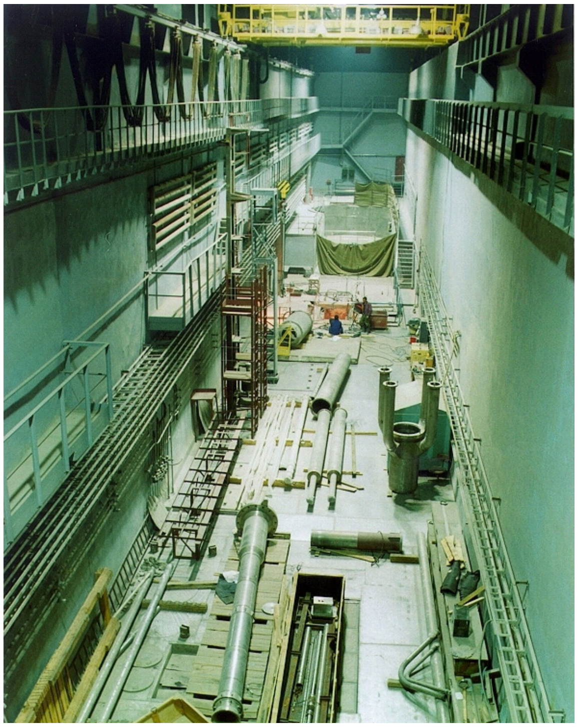

Fig. 8: (a) PIK reactor hall

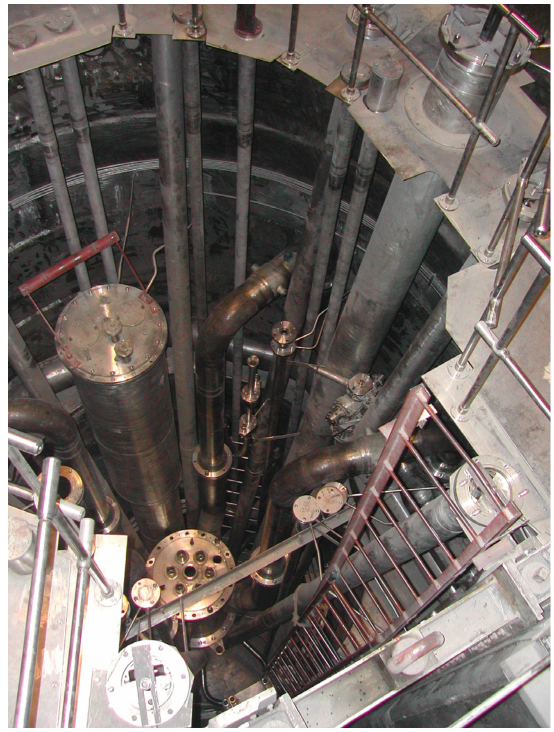

Fig. 8: (b) PIK reactor vault

Table 14 – Research reactors of Russian design built in other countries

Research reactor	Country	Power, MW	RR status
IRT-2000	Bulgaria	2.0	Shut down
IRT	North Korea	8.0	In operation (?)
IRT-5000	Iraq	5.0	In operation
IVV-7 (IRT-1)	Libya	10.0	In operation
Eva	Poland	10.0	Shut down
Maria	Poland	30.0	In operation
VVR-SM	Hungary	10.0	In operation
VVR-S	Rumania	2.0	Shut down
HWRR	China	15.0	In operation
ETRR	Egypt	2.0	In operation
RFR	Germany (former GDR)	10.0	Shut down
RA	Serbia (former Yugoslavia)	6.5	Shut down
LVR-15	Czechia	10.0	In operation
IRT-M	Georgia	8.0	Shut down
IRT-M	Latvia	5.0	Shut down
IRT-M	Belarus	4.0	Shut down
VVR-C	Uzbekistan	10.0	In operation
VVR-M	Ukraine	10.0	In operation
IR-100 (IR-200)	Ukraine	0.1	In operation
VVR-K	Kazakhstan	6.0	In operation
IVG-1	Kazakhstan	60.0	In operation
IGR	Kazakhstan	10.0	In operation

4. CONCLUSION

The present-day mix of operating research reactors is capable of meeting Russia's demands for experimental studies on the problems of nuclear science and engineering.

The fleet of Russian research reactors is in the process of optimisation, which implies its quantitative and qualitative improvement, including provision of new research reactors.
Russia has a history of active RR export, which may and will have a continuation. We are prepared to offer our services to other countries both by rendering scientific and engineering support for operation of existing reactors and in building new research reactors and whole research centres.

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