THE IBR-2 REACTOR – OPERATING EXPERIENCE AND DEVELOPMENT

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Introduction

The IBR-2 fast pulsed research reactor with liquid-metal coolant has become the continuation of development of pulsed neutron sources in the Frank Laboratory of Neutron Physics of the Joint Institute for Nuclear Research. Behind the construction of pulsed reactors in JINR — from the first IBR started up in 1960 to the IBR-2 commissioned 24 years later — was the idea of periodic generation of neutron pulses using a mechanical device, which had been suggested by D.I.Blokhintsev in Obninsk and successfully realized in LNP headed by I.M.Frank at that time .

The IBR-2 reactor was constructed in JINR in 1969-80 and was put into operation on February 10, 1984 after the tests and investigations during its physical (1977-78) and power startups (1980-83). Work on the construction of the IBR-2 was carried out under the scientific supervision of the JINR. The chief design organizations were the NIKIET (N.A.Dollezhal Research and Design Institute of Power Engineering), the GSPI (State Specialized Design Institute) and the VNIINM (A.A.Bochvar All-Russia Research Institute of Inorganic Materials). A large number of institutes and organizations of the USSR and JINR Member States participated in the design and construction of the equipment for the new reactor.

The IBR-2 reactor with an average power of 2 MW and neutron pulse duration of 245 μs has become one of the most effective pulsed neutron sources for beam investigations across a diverse range of science areas encompassing condensed matter physics, biology, chemistry, materials science and Earth sciences.

In recent years the number of investigations at the IBR-2 reactor, which are of interest for nuclear science and technology, has increased considerably. These investigations are concerned with the study of the structure and properties of constructions and constructional materials for reactor engineering, new superconductors, bioactive compounds with radioprotective and antitoxic properties and deal with the obtaining of nuclear data and data on heavy elements in the environment surrounding nuclear objects.

The IBR-2 reactor is operated according to the user policy program. Experiments carried out at the facility are performed not only by Russian scientists, but also by research teams from other countries: Germany, Czech Republic, France, Austria, Bulgaria, Hungary, Vietnam, Egypt, Spain, Italy, China, Netherlands, Romania, Slovakia, USA, Finland, Switzerland, CIS countries, etc.

Brief description of the IBR-2 reactor

The IBR-2 research reactor is a fast pulsed reactor of periodic operation and its main difference from other reactors consists in mechanical reactivity modulation with a movable reflector, which ensures a cyclic process of profound changes in reactivity with time.

When the movable reflector passes near the reactor core, a power pulse with a frequency of 5 Hz is generated, i.e. at this time the reactor is switched from a state of deep subcriticality to a state of supercriticality with instantaneous neutrons. The power pulse duration is of the order of 245 μs with a background between the pulses of 4-8 % of an average power. The reactivity curve is described by the parabolic dependence ***ε(t)*** (Fig. 1).

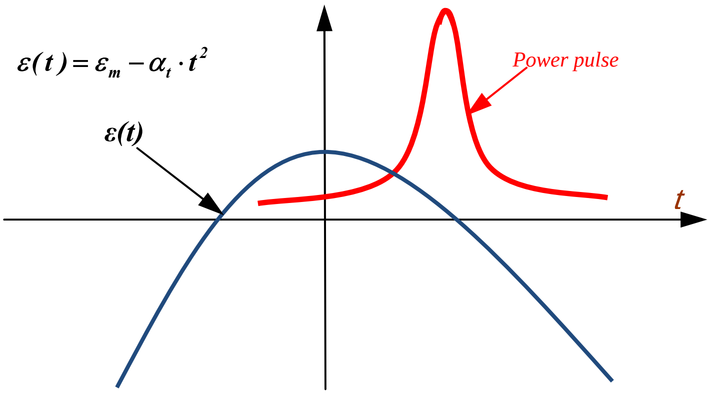

Fig. 1 Reactivity and power pulse curves.

The principal characteristics of the IBR-2 reactor are given in Table 1

Table 1.

Average rated thermal power	2 MW
Peak power in pulse	1500 MW
Half-width of power pulse	245 μs
Power pulse repetition rate	5 s^{-1}
Fuel type	Plutonium dioxide
Volume of the core	22 l
Coolant	sodium
Reflectors	tungsten, steel
Equilibrium pulsed supercriticality	$1.0 \cdot 10^{-3}$ K_{eff}
Efficiency of emergency protection	$2.1 \cdot 10^{-2}$ K_{eff}
Peak fast neutron flux density (in central channel)	$2.6 \cdot 10^{17}$ n/cm^2·s
Thermal neutron flux density from the surface of the grooved moderator: • burst maximum • time-average	 ≈ 10^{16} n/cm^2·s ≈ $0,8 \cdot 10^{13}$ n/cm^2·s

The demand for producing high neutron fluxes at short pulse duration has led to the necessity to create a compact core with short neutron lifetime. The reactor core of plutonium dioxide with sodium cooling system (Fig. 2) has been chosen.

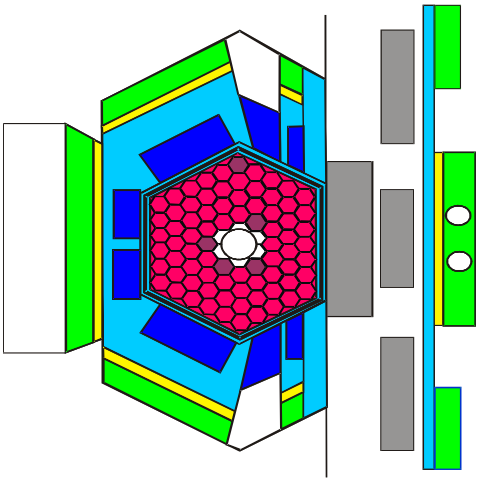

Fig. 2. A sectional view of the IBR-2 reactor core

The reactor employs a three-circuit two-loop technological scheme (Fig. 3). The core cooling system of the BR-5 reactor, which has successful operating experience, was taken as a basis for creation of a sodium cooling system for the IBR-2 reactor. Each loop is rated at 50% of power removal. Sodium circulation in the loops of circuits 1 and 2 is maintained by electromagnetic pumps. Sodium temperature at the inlet of the core is 290° C, sodium temperature at the outlet of the core is 360° C. The heat of sodium in the loops of circuit 1 is transmitted to the intermediate sodium circuit 2 through sodium-sodium heat exchangers. The heat of circuit 2 is removed in air-to-air heat exchangers (AHE) due to self-draught in AHE and pipes over them.

The sodium cooling system had been functioning successfully and uninterruptedly (both during the reactor cycles and in the shutdown periods) since its startup in 1981 to the beginning of 2007 when the sodium heat exchanger was drained.

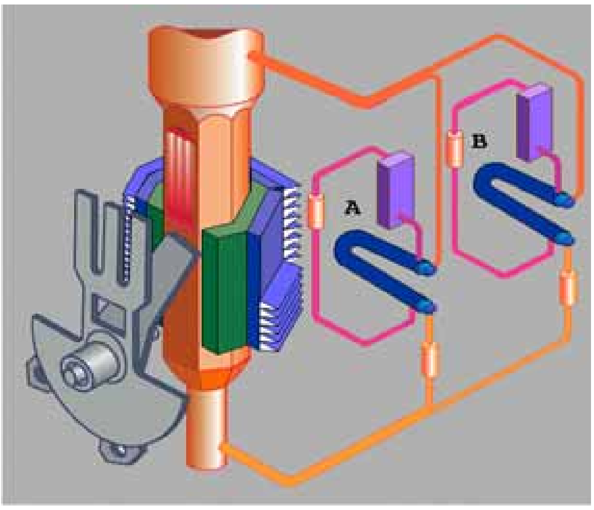

Fig. 3. A principal technological scheme of the IBR-2 reactor

On five sides (out of six) the reactor core is surrounded by a stationary reflector (SR) composed of two parts. Each part is a stainless steel device where the elements of the control and safety system and the units of boron steel are positioned and move. The boron steel units are intended to reduce the leakage of thermal neutrons to the core from the water moderators surrounding SR.

The movable reflector, which is one of the most crucial and technically most original units of IBR-2, is used for periodic modulation of reactivity and generation of power pulses. The reactivity modulator is adjacent to the largest wall of the hexahedral core. The movable reflectors (there are two of them – the main moveable reflector (MMR) and the auxiliary moveable reflector (AMR)) are coaxially positioned. It is the long blade of the rotor that serves as a reflector. The auxiliary reflector (AMR) is intended for slow reactivity modulation with a frequency of 5 Hz. Both reflectors are set in motion by one electric motor using the transmission and gear-boxes.

From the reactor start-up to 2003 three modulators of reactivity with AMR in the form of a trident and with a rotation rate of MMR of 1500 rev/min operated at the IBR-2 for 6-7 years each. Then a grating reflector of nickel alloy (Fig. 4) with rotors rotating in opposite directions and with a rotation rate of MMR of 600 rev/min was constructed.

Fig. 4. Blades of grating-type MMR and AMR.

The use of this configuration allowed us to reduce the rotation rate of MMR by a factor of 2.5 but to retain the same pulse duration. Figure 5 shows a change in the reactivity for different types of reflectors as the blades of MMR and AMR pass the reactor core. The advantage of the new reflector over the previous machines can be clearly seen. Operation at low rotation rates makes it possible to prolong the safe service life of MR up to 20 years. The same reflector will work at the modernized reactor IBR-2M.

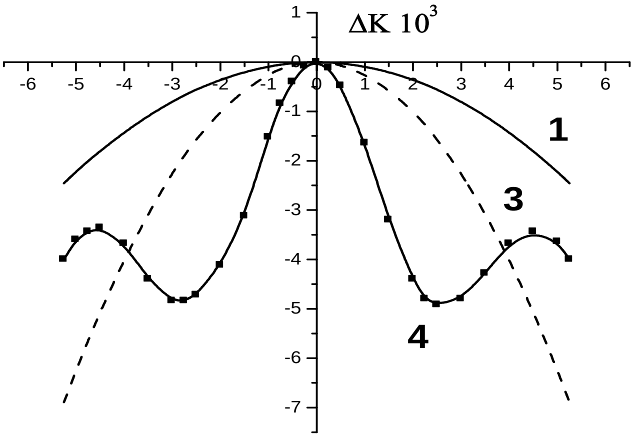

Fig.5. Reactivity curves for different types of MMR and AMR.

1 – AMR in the form of a block;

3 – AMR in the form of a trident;

4 – AMR and MMR in the form of gratings.

Status of the IBR-2 reactor (as of 01.01.2007)

In December, 2006 the reactor has been according to plan stopped to start works on updating of time-worn equipment within the frames of the developed program of modernization. The IBR-2 reactor operated trouble free for more than 22 years and provided neutron beams for about 200 experiments annually. The IBR-2 reactor operates in a cyclic mode, with the reactor working continuously at a rated power for 250÷270 hours (two-week cycles). Breaks between cycles are no less than 1 week. Starting from 1997, the reactor operated at a power of 1.5 MW.

Many years of uninterrupted, long-term service of the reactor have demonstrated its high operational reliability.

Table 2 presents the main operation parameters of the IBR-2 reactor as of 01.01.2007.

Table 2.

№	**Parameter (from the start of the reactor operation)**	**As of 01.01.07**	**Design value**
1	Total operation time for physical experiments, h.	49121	
2	Total energy production, MW·h.	87400	
3	Maximum fluence at the reactor vessel at the centre of the core, (, 10^{22} n/cm^2):		
	– for En > 0,1 MeV	3.74	3.72
	– for En > 0,8 MeV	1.61	1.62
4	Maximum fuel burn-up, (%):		
	▪ for solid-pellet fuel elements	6.61	6.6
	▪ for fuel elements with pellets having central holes	7.09	8.2
5	Total number of emergency shutdowns	471	550

The correctness of the technical solutions and operation organization, as well as the reliability of equipment are confirmed by the results of long-term environment radioactivity monitoring in the IBR-2 reactor location area, which show that the radioactivity is caused only by natural radioactivity and global fall-out. The existing shielding, technical and organizational measures aimed at reducing the harmful impact of radiation factors at work places of the personnel and the radiation monitoring system ensure safe conditions at operation and experiments at the IBR-2 reactor.

The data on the operation time for physical experiments for each year during the whole service time of the IBR-2 reactor (Fig. 6) give a pictorial estimate of the reactor operation stability. Certain «downfalls» refer to the reactor shutdowns to perform works on replacing the movable reflectors and refueling of the reactor core.

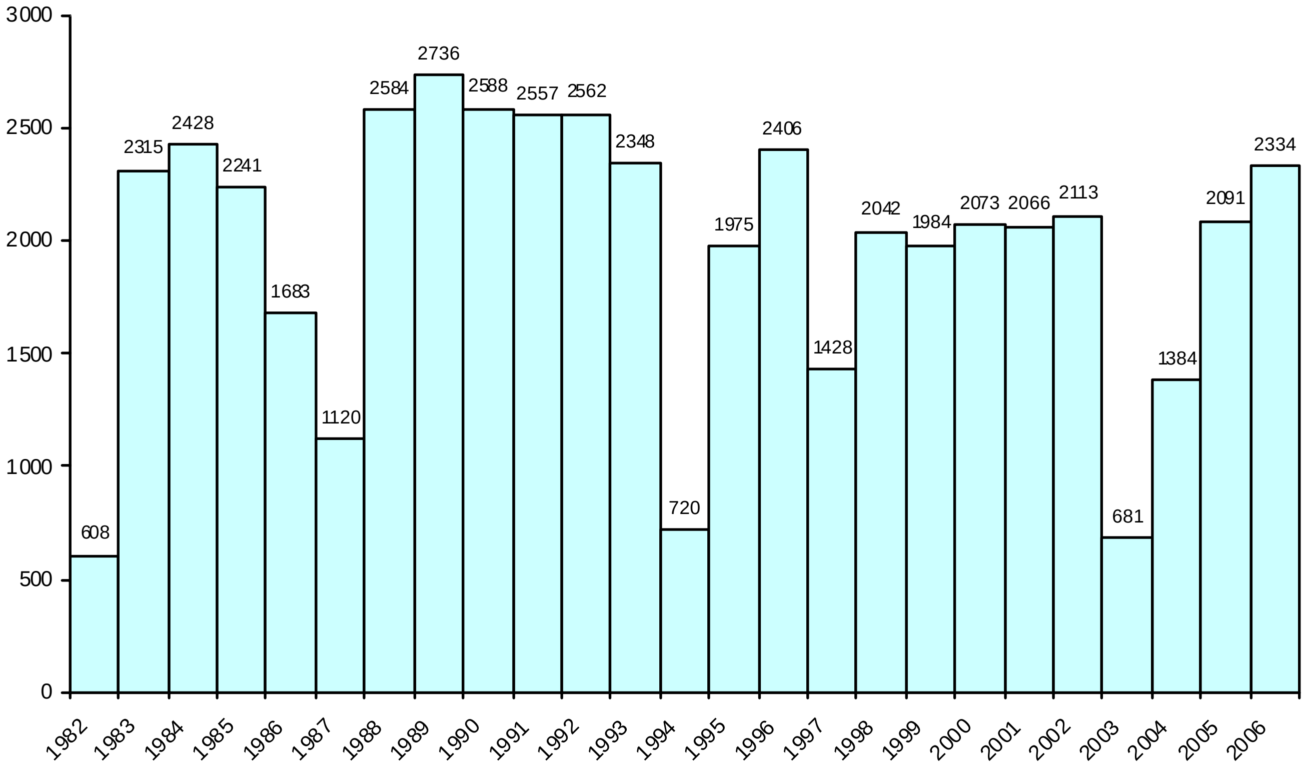

Fig.6. Operation time of the reactor for physical experiments $\tau_{phys\ exp}$*, hour*

Information on unscheduled reactor shutdowns triggered by the emergency system (ES)

Figure 7 shows the number of unscheduled ES-triggered shutdowns per year during the whole reactor service period. The distribution of ES-triggered shutdowns can be conventionally divided into two reactor operation periods: the increase in the number of shutdowns during the initial period after the reactor start-up due to the revealing of hidden defects of the equipment and the lack of sufficient operation experience and skills of the reactor personnel, and the decrease in the number of shutdowns in succeeding years.

A considerable contribution to the general distribution of ES-triggered shutdowns was made by unscheduled ES operations due to power supply system failures (Fig. 8). This category of malfunctions does not directly characterize the reactor condition, because these failures are caused by external reasons.

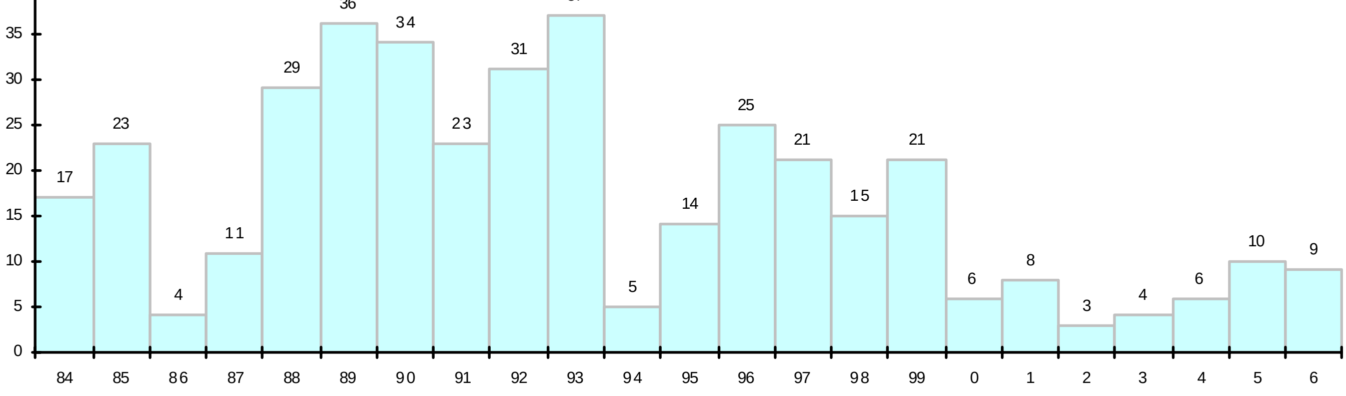

Fig. 7. The number of ES-triggered shutdowns per year over the whole period of service.

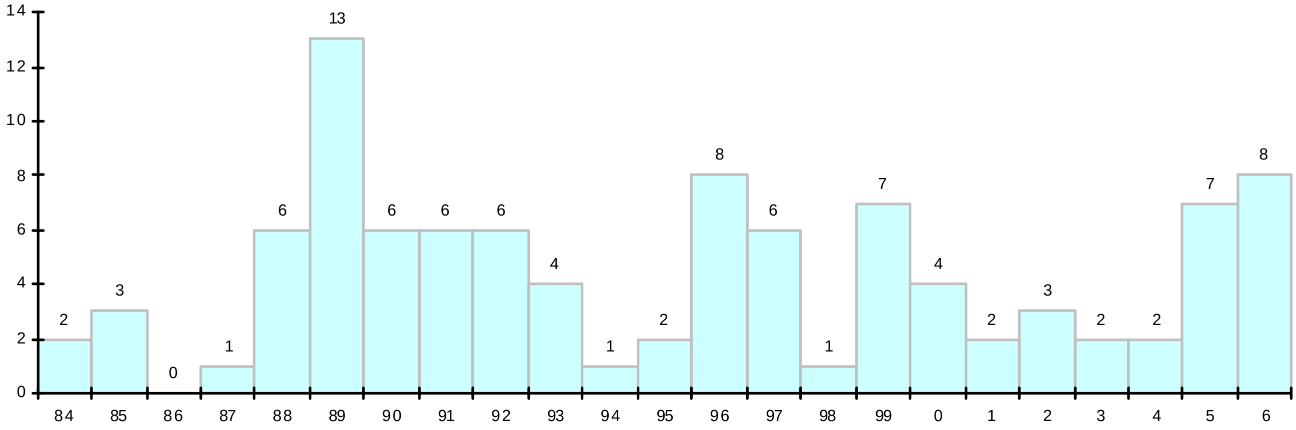

Fig. 8. The number of ES-triggered shutdowns due to power supply failures.

Modernization of the IBR-2 reactor

Due to the end of service life of the main reactor units and in order to improve and upgrade the reactor, a concept of the IBR-2 modernization has been developed. The concept of the IBR-2 reactor modernization involves the development, manufacturing and installation of the reactor equipment. At the same time, taking into account the experience of reactor operation and physical experiments, the concept includes a number of new technical solutions, which make it possible to significantly improve operational and physical characteristics of the reactor thus allowing us to say about the creation of a practically new reactor IBR-2M in the process of modernization.

Since January 2007, after the termination of reactor operation for physical experiments, the IBR-2 modernization in accordance with the «Program of works on the modernization of the IBR-2 reactor in the temporary shutdown mode (2007 – 2010) » is under way.

The IBR-2 reactor development and upgrade program assumes three directions of work:

- Improvement of principal reactor parameters:
  Increase of thermal neutron flux by a factor of 1.7,
  Increase of cold neutron flux by a factor of 25;
- Enhancement of safety and operation reliability of the reactor,
- Renewal of the main reactor equipment.

Fundamental peculiarities of the new IBR-2M reactor

The IBR-2M reactor as compared to the IBR-2 reactor has the following novelties:

1. A compact core (Fig. 9) composed of 69 fuel assemblies (FA) instead of 78 FA of the IBR-2 reactor and as a consequence the reduction of fuel mass to be loaded (PuO_2).

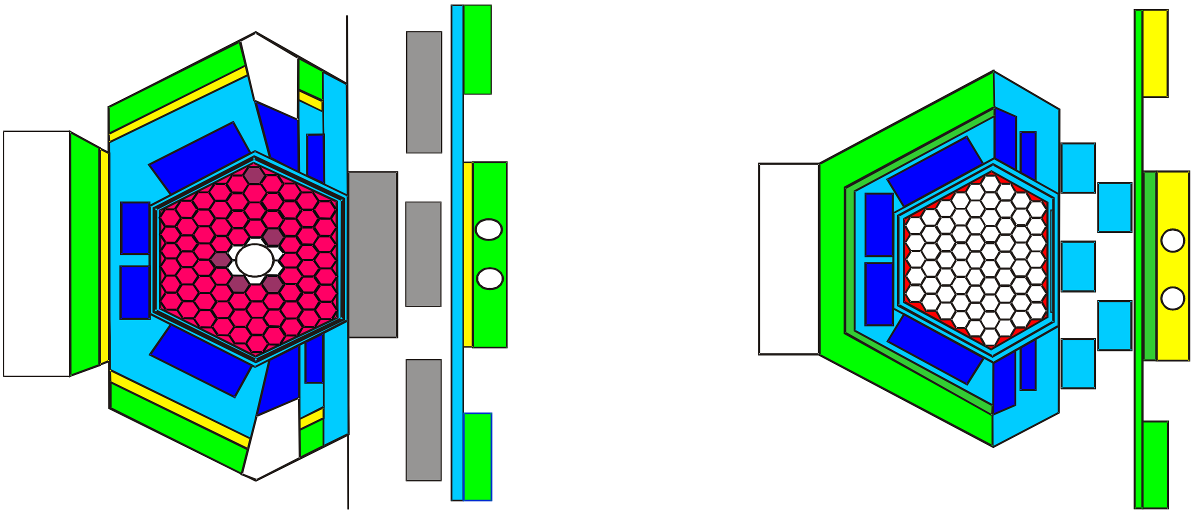

Fig. 9 A sectional view of the cores of the IBR-2 and IBR-2M reactors.

2. Use of fuel pellets with central holes (Fig. 10), which will allow an increase in feasible burn-up depth up to 9 %, i.e. almost by a factor of 1.5 as compared to the IBR-2 reactor.

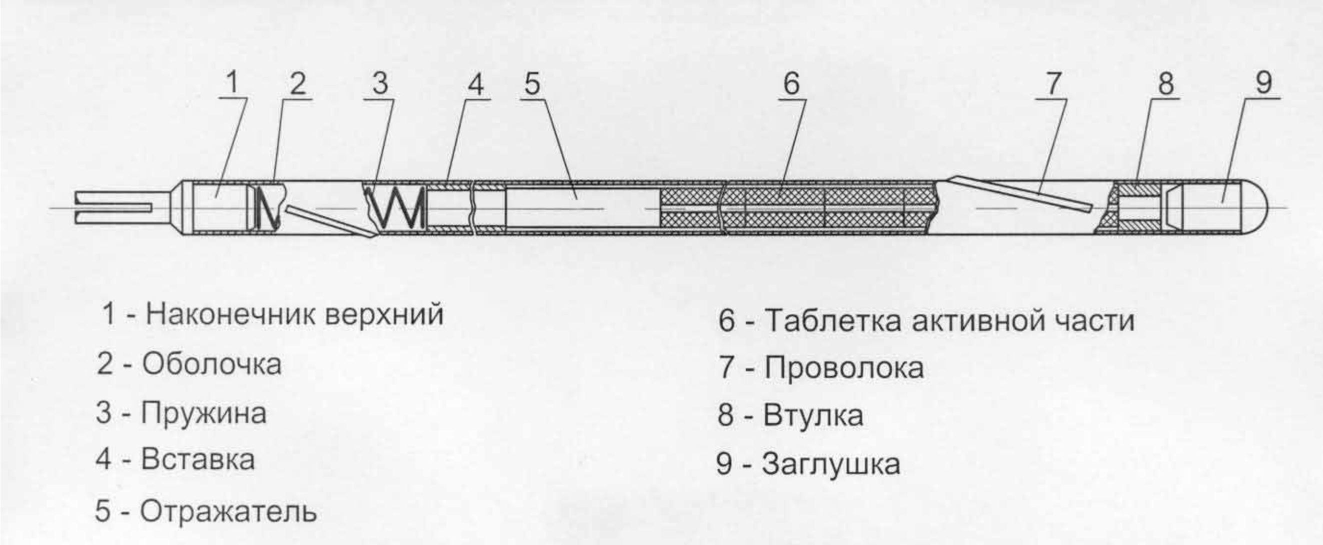

Fig. 10. Fuel rod of the IBR-2M reactor. (1 -upper end cap, 2 - cladding, 3 - spring, 4 - insert, 5 - reflector, 6 - active part pellet, 7 - wire, 8 - bushing, 9 - plug)

The columns of the reactor fuel rods are composed of plutonium-239 dioxide pellets and are enclosed in cylindrical steel cladding 0.45 mm thick, 8.6 mm in diameter and 780 mm long. The height of a fuel rod active part is 444 mm. Above the fuel column there is a tungsten insert 60 mm long, which serves as a butt reflector, the remaining space is used to collect gaseous fission products. Fuel rods are welded to the grid in the upper part of the cassette and are spaced with wound wire.

A significant peculiarity in the operation of the IBR-2 core is the occurrence of nonstationary thermal impact on fuel rods, i.e. thermal shock. To prevent the pellet expansion in the IBR-2 fuel rods induced by thermal shock, the pellets are pressed down with a force by springs.

In 2002, in the Federal State Unitary Enterprise «Institute of Reactor Materials» (Zarechnyi), experimental investigations of two standard fuel assemblies with the burn-up of 4.8 % h. a. were carried out after their operation in the IBR-2 reactor from 1980 to 1996. Fuel composition was in the form of pellets having central holes and solid pellets. Fuel rod cladding was irradiated under fast pulsed reactor conditions up to the fluence of $1.5 \cdot 10^{22}$ n/cm^2 ($E \geq 0.5$ MeV). No material swelling was observed. It has been found that the cladding material has high strength and plastic properties. The fuel in the IBR-2 rods was found to be in a satisfactory state. Fuel composition of all core sections had a fine-grained structure characteristic for the initial state.

A typical sectional view of fuel assembly rods is presented in Fig. 11. It can be seen that the fuel composition remains in a sintered state but underwent cracking. The prevailing location of cracks in the fuel pellets is mainly in the radial direction. All cross-sections under investigation had a gap between fuel and cladding.

The cladding and fuel rod composition of the IBR-2 fuel assemblies were found to retain their serviceability.

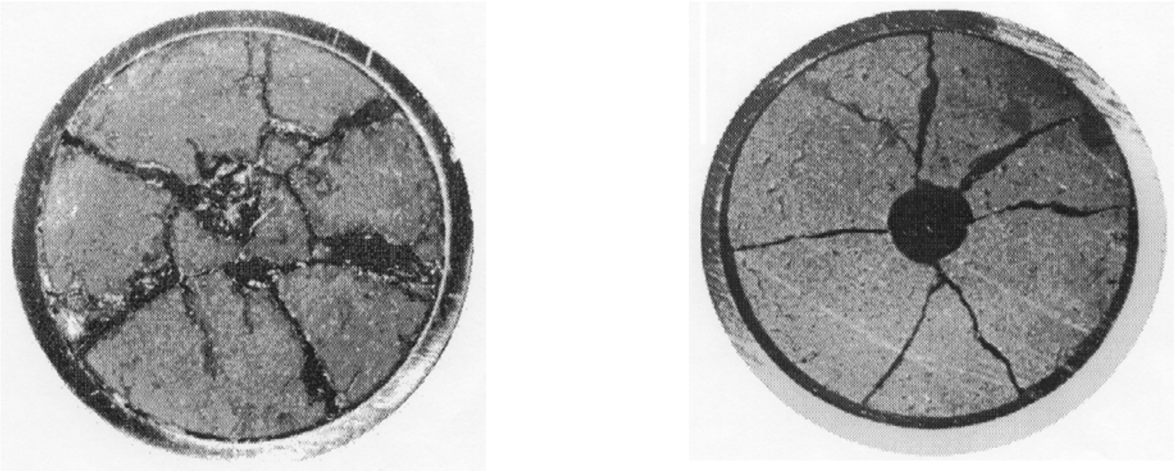

Fig.6. A sectional view of irradiated pellets of the IBR-2 reactor.

3. Use of two safety blocks in combination with a step motor drive realizing the function of fast and slow emergency protection systems. Thus, the design of a stationary reflector becomes much simpler and the reliability of the emergency protection mechanism increases.

4. Development and construction of rolling moderators, which will allow a prompt change of moderators without dismantling stationary reflectors and working elements of the safety control system.

5. Creation of a complex of cryogenic moderators.

Owing to the use of the moderator complex, it becomes possible to ensure high efficiency of research in solid state physics using cold neutrons with a wavelength of more than 0.4 nm. Hard balls made of a mixture of aromatic hydrocarbons - mesitylene, which are periodically changed in the moderator chamber, are used as a working material for cryogenic moderators. Such a moderator has been constructed for the first time in the world. A principal scheme of feeding of the balls and cooling the moderators is given in Fig. 12.

One of the most important advantages of using cryogenic moderators made on the basis of aromatic hydrocarbons is their long operation time without changing the temperature mode and loading – no less than three days.

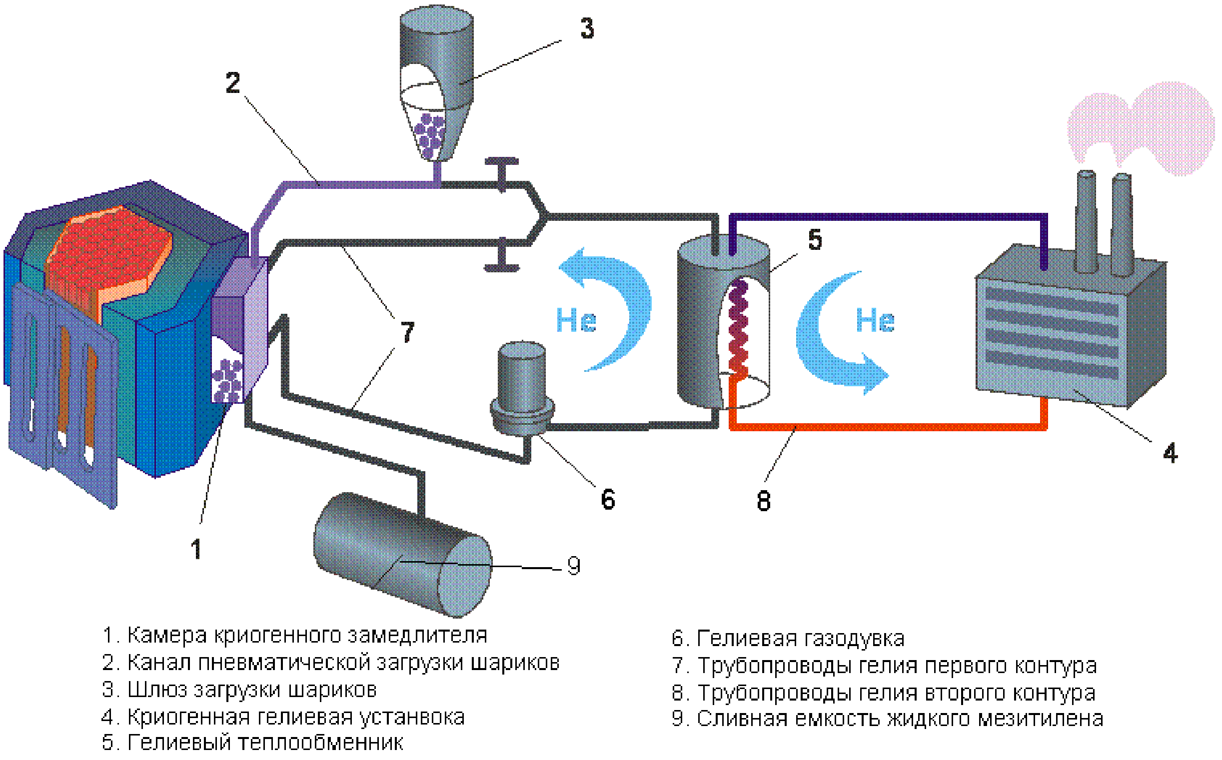

Fig. 12. A principal scheme of the IBR-2 cryogenic complex. (1 – cold moderator chamber; 2 – ball charging pneumatic pipeline; 3 – ball-charging device; 4 – helium refrigerator; 5 – helium heat exchanger; 6 – helium blower; 7 – helium pipelines of 1st circuit; 8 – helium pipelines of 2nd circuit; 9 – collecting tank for liquid mesitylene)

The moderator complex at the IBR-2M modernized reactor will allow an increase in the efficiency of using neutrons in experiments on extracted beams by a factor of 25. In its turn, this will open up possibilities for creating a powerful spectrometric basis for the performance of investigations in the field of condensed matter physics and retaining leading positions by Russia in the world science in the twenty-first century.

For comparison, Table 3 presents the parameters of the IBR-2 reactor and modernized IBR-2M reactor.

Table 3.

Parameter	**IBR-2**	**IBR-2M**
Average power, MW	2	2
Fuel type	PuO_2	PuO_2
Number of FA	78	69
Peak burn-up, %	6.5	9
Pulse frequency, Hz	5; 25	5; 10
Half-width of the pulse, µs	215	200
Rotation rate, rev/min:		
MMR	1500	600
AMR	300	300
MMR and AMR material	steel	nickel+steel
MR service life, hours	20000	55000
Background, %	6	7
Number of satellites at 5 Hz	4	1

Realization of the IBR-2M project

In the course of the IBR-2 modernization the following units and systems of the reactor are to be replaced:

- reactor vessel;
- fuel elements;
- stationary reflectors with rolling shielding;
- safety and control system (SCS) including executive mechanisms of control and emergency protection units, reactor control equipment, technological parameters control system and reactor control room;
- radiation monitoring system;
- moderators;
- cooling system for cryogenic moderators.

This will make it possible not only to improve the main reactor parameters but to enhance safety and operational reliability of the reactor. It is also planned to upgrade the external power supply system of the reactor building.

In the realization of the IBR-2 modernization project the following organizations were involved: NIKIET (chief reactor designer), GSPI (general civil engineering designer), VNIINM, NIKIMT, "Mayak Plant" (manufacturer of fuel rods for IBR-2M), SNIIP-SYSTEMATOM, INEUM, GELIYMASH, JINR Experimental Workshops and other specialized organizations.

In 2006, fuel elements for loading into the IBR-2M reactor core were manufactured at the JINR.

Unloading of the IBR-2 reactor core, which was carried out in the first half of 2007, became the first stage of works to dismantle the worn-out IBR-2 equipment.

After unloading the IBR-2 core, sodium coolant was drained from the cooling circuits, the sodium circuits were filled with Ar, and the equipment of the safety control system with expired service life was disassembled. The movable reflector was moved away from the vessel into an intermediate state. The reactor vessel was disassembled and placed in the used vessels storage.

The next stage of equipment dismantling was the removal of rolling biological shieldings with stationary reflectors. To perform the task, technical and organizational measures were implemented to protect the personnel from ionizing radiation due to high induced activity of the stationary reflectors.

The NIKIET experimental workshops have manufactured and delivered to JINR the IBR-2M reactor vessel. The new vessel was installed by the PKU-2 erection crew of the JSC «Energospetsmontazh» (Obninsk) in collaboration with the specialists of FLNP JINR.

The JINR experimental workshops manufactured new rolling biological shieldings with stationary reflectors. A special feature of new rolling shielding are rolling moderators installed into the body of each shielding, which can be moved on the rail track along the longitudinal axis. This allows a prompt change of moderators without dismantling stationary reflectors and working elements of the safety control system.

JSC «SNIIP-SYSTEMATOM» developed and manufactured the hardware complex for the safety control system of the IBR-2M reactor. The ASCS hardware complex represents an electronic part of the safety control system designed to control, maintain and terminate in an emergency the chain fission reaction, and combines functions of the safety system and normal operation of the IBR-2M reactor. The hardware is manufactured on the basis of state-of-the-art elements and complies with the modern level of information technologies.

In 2008, the «INEUM» completed the development, manufacture and delivery to the JINR of equipment for the technological parameters control system (TPCS) of the IBR-2M reactor. The TPCS is manufactured using modern components and is designed on unified elements, which make it possible if necessary to repair the system by quick replacement of a defect unit, thus reducing the time of repair and reactor shutdown. Industrial computers are used to process incoming signals; the current state of the systems under control is displayed on the monitors of operation personnel. At present, the installation of the equipment is being completed.

Today, works on cryogenic moderators are being carried out: dismantling of overage equipment, acquisition of equipment for the cryogenic complex, preparation of rooms for the installation of new equipment.

Final stage of modernization

In 2010 the final stage of modernization – physical start-up of the IBR-2M reactor will be realized.

The final stage scheduled for 2010 – 1012 includes:

- Physical start-up of the IBR-2M reactor with water moderators – 2010;
- Power start-up of the reactor – 2011;
- Installation of the complex of cold moderators – 2011 – 2012;
- First physical experiments with cold moderators – 2011 – 2012.

Thus, after 2010, the modernized neutron source – the IBR-2M reactor – with the record pulsed neutron flux of $2 \cdot 10^{16}$ n/cm^2 and expected service life of 30 years will resume its operation in Russia. The user capabilities will be considerably extended as a result of using cold moderators. The research pulsed reactor IBR-2M will retain leading positions among neutron sources in the world for investigations on extracted neutron beams.

References:

[1] E.P.SHABALIN / Fast Pulsed and Burst Reactor, Pergamon Press, Oxford, 1979

[2] V.D.ANANIEV, A.V.VINOGRADOV, The IBR-2 pulsed research reactor: status report. Proceedings of PANS-II Second International Seminar "Advanced Pulsed Neutron Sources: Physics of/at Advanced Pulsed Neutron Sources", June 14-17, 1994, Dubna, Russia.

[3] V.L.AKSENOV / Update on pulsed reactor IBR-2 at Dubna, Phisica B 174 (1991), North-Holland Publishing Company

[4] V.V.KHMELSHCHIKOV, I.T.TRETJAKOV, A.A.PORTNOV, A.V.VINOGRADOV Modernization and reconstruction of ageing Russian research reactors as the method to extend their operational life (IAEA-SM-360/42). Symposium “Research Reactor Utilization, Safety and Management”, 6–10 September 1999, Lisbon, Portugal

[5] ANANIEV V.D., VINOGRADOV A.V. BABAEV A.I., SOKOLOV N.B., SHKABURA I.A., GOLOVNIN I.S., IVANOV A.YU., PEREKHOZHEV V.I., SINEL’NIKOV L.P., KOZLOV A.V., SCHERBAKOV YE.N. Investigation of two fuel rods of the IBR-2 reactor. // VNIINM Preprint, 2003.

[6] ANANIEV V.D., BLOKHINZEV D.I., BULKIN YU.M., BUNIN B.N., VOROBJOV YE.D., DOLLEGAL N.A., LUSCHIKOV V.I., OSTANEVICH YU.M., SMIRNOV V.S., FRANK I.M., HRIASTOV N.A., SHABALIN YE.P., SHARAPOV E.I., YAZVITSKII YU.S. IBR-2 – pulsed reactor of periodic operation for neutron investigations // JINR Preprint, P3-10888, 1977.

[7] AKSENOV V.L., ANANIEV V.D., BELUSHKIN A.V., VINOGRADOV A.V. The IBR-2 Fast Pulsed Reactor: Present and Future // Report.- ICANS-XIV.- Starved Rock Lodge, Utica, Illinois.- 1998.