2. NEUTRON SOURCES

2.1. THE PULSED IBR-2 REACTOR

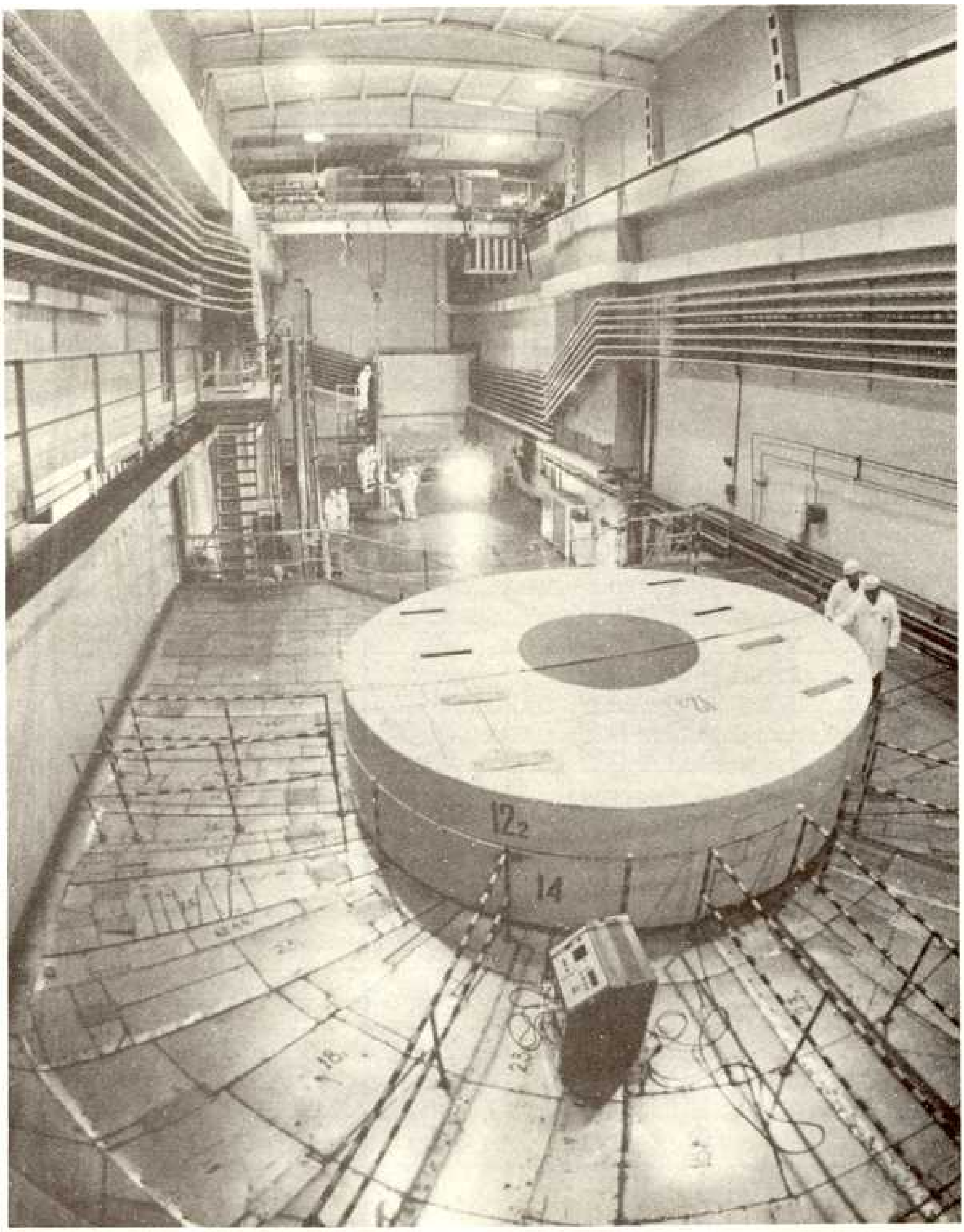
In 1992-93 the high-flux pulsed reactor IBR-2 was in operation for 4910 hours, as compared with the scheduled 5000 hours, which provided for completion of the program of physics experiments on 12 neutron beams. More detailed information on the operation of the reactor is presented in Table 4.

Table 4

Operation of IBR-2 reactor in 1992-93

Cycle	Cycle time	$T_{p.e.}$	$T_{m.r.}$	EPR
1	06.01-17.01.92	263	269	1
2	27.01-08.02.92	248	209	3
3	17.02-29.02.92	265	299	2
4	17.03-29.03.92	268	321	3
5	13.04-25.04.92	265	277	2
6	12.05-24.05.92	278	284	1
7	08.06-24.06.92	325	408	7
8	16.11-29.11.92	244	287	7
9	07.12-25.12.92	406	443	4
	Total for 1992	***2562***	***2797***	***30***
1	11.01-22.01.93	243	273	3
2	01.02-13.02.93	249	280	2
3	22.02-05.03.93	254	270	3
4	22.03-02.04.93	250	281	5
5	12.04-22.04.93	236	248	3
6	17.05-29.05.93	216	279	8
7	07.06-19.06.93	257	295	6
8	25.10-01.11.93	154	176	0
9	15.11-26.11.93	252	272	4
10	06.12-17.12.93	237	267	3
	Total for 1993	***2348***	***2641***	***37***
	Overall total	**4910**	**5438**	**67**

Comment: $T_{p.e.}$ is the time of operation for physical experiments; $T_{m.r.}$ is the operation time of the moving reflector; EPR is the number of emergency power shutdowns.



IBR-2 reactor hall

Short-term shutdowns of the reactor were initiated by unexpected actuation of the emergency safety system, caused by events classified as zero level events, in accordance with the international scale of events.

Since the start-up of power production by the reactor (the end of 1980) up to 01.01.1994 it has run for 26038 hours. The total number of emergency shut-downs during this period was 318, of which 307 were unexpected. The flux density of neutrons with energies > 0.1 MeV incident on the wall of the reactor casing amounts to $1.3 \cdot 10^{14}$ n/cm^2 s, when the power is 2 Mw. For the above figures the neutron fluence on the reactor casing amounted to $1.22 \cdot 10^{22}$ n/cm^2 by 01.01.94.

The active core. Long-term operation of the reactor resulted in a partial burn-up of the fuel and to a corresponding reduction of the operational supply of reactivity. The first renewal of the active core of the reactor was performed between July 19 and 23, 1993. The decoy cassette (without fuel) was extracted from the core and put away for long-term storage in the reactor storage pit. It was substituted by a heat-generating assembly (HGA) with fresh plutonium dioxide fuel (Fig. 29).

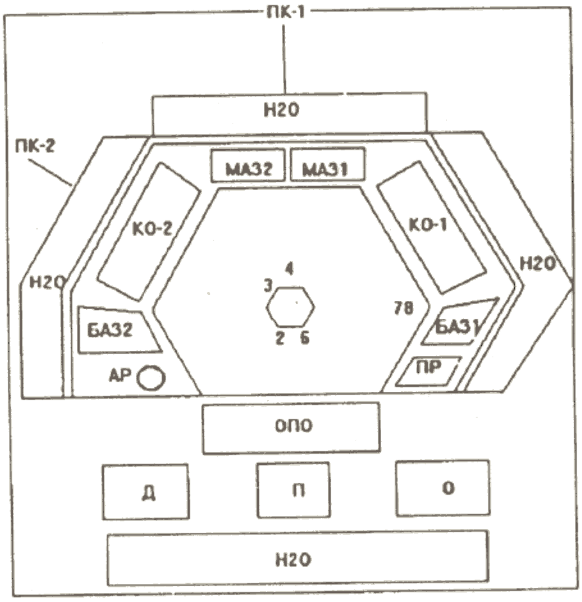
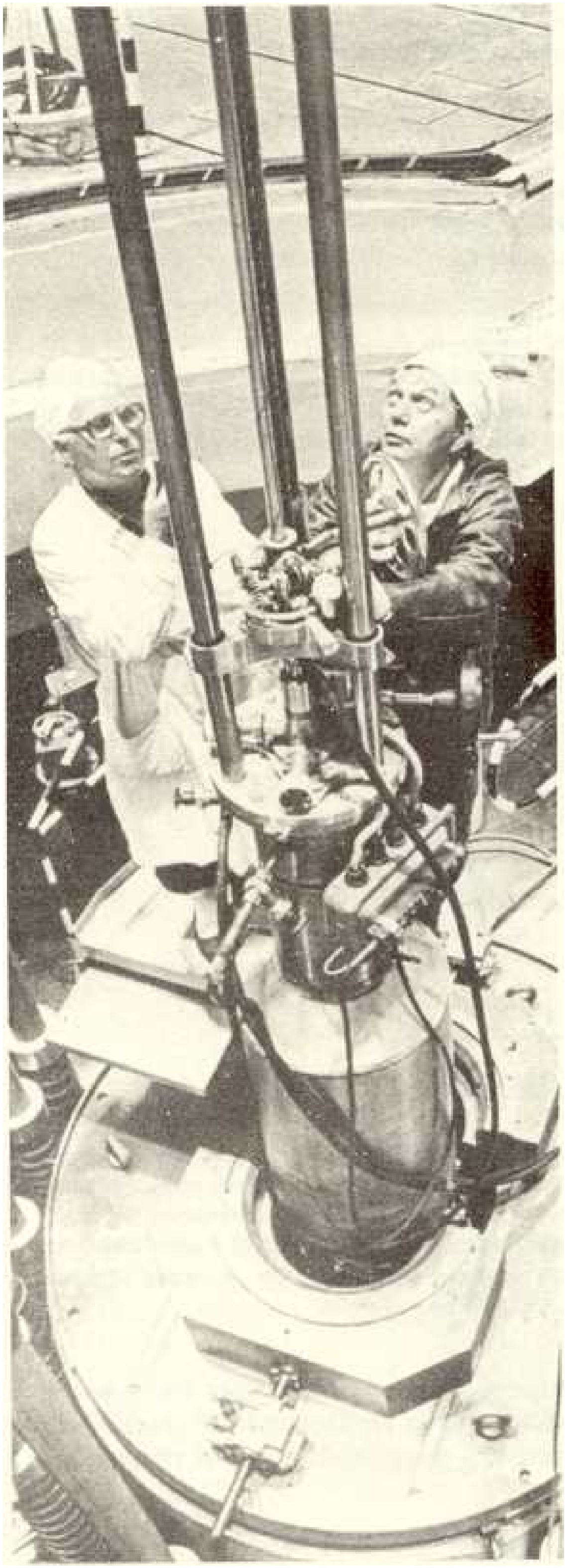


Fig. 29. Active core of the IBR-2 reactor. The figures indicate the numbers of cells filled with simulators of fuel element assemblies. Renewal of the active core consisted in substitution of a fresh energy releasing assembly (ERA) for the simulator of cell 3. The total number of ERAs in the active core became 74. KO-1, KO-2 are reactivity compensaters, MA31, MA32 are emergency safety blocks, БА31, БА32 - rapid emergency safety blocks, ПР - intermediate regulator, AP - automatic regulator, ОПО and ДПО - main and additional reflectors, respectively, H2O - neutron moderators, ПК-1, ПК-2 - trigger channels.

Measurements carried out after the renewal showed the supply of reactivity was enhanced by a quantity sufficient for implementation of the scheduled energy production for 6 years of reactor operation in the previous mode. The resource parameters of the core after renewal are presented in Table 5.

The renewal of the core, being a task classified as nuclear-dangerous, was carried out together with all necessary organizational and technical measures required for nuclear and radiation safety. A routine test of the state of nuclear, radiation, and technical safety was made by a Gosatomhadzor (Russian State Atomic Inspection) commission upon completion of the renewal

New movable reflector
of the IBR-2 reactor



Renewal of the IBR-2 reactor core

activities at the reactor, and no deviations from or violations of the established safety restrictions of the reactor operation were observed.

Table 5

Service characteristics of the IBR-2 core after renewal

Characteristic	For 01.01.94	By the end of the scheduled service time (May 2003)
Burn-out of plutonium	2050 MW·day	4000 MW·day
- average	2.7%	5.2%
- maximum	4.1%	7.8%
Reserve of reactivity	1.55±0.05%	0±0.05%
Fluence of fast neutrons (n/cm^2)		
- at the centre of the core	$2.05\cdot10^{22}$	$4.0\cdot10^{22}$
- at the reactor vessel (maximum)	$1.17\cdot10^{22}$	$2.28\cdot10^{22}$
Volume coefficient of inhomogeneous energy release	1.53	1.50
Number of loaded fuel element assemblies	74	74

Comment: The burn-out of plutonium due to fission is assumed to be equal to 1.1 g/MW·day, which corresponds to an energy release of 192 MeV/fis. The reactivity coefficient with respect to the burn-out of fuel is $dK/dQ = -8\cdot10^{-6}$ k/MW·day. The specific fluence of fast neutrons ($E > 0.1$ MeV) was used at values of $d\Phi/dQ = 1.0\cdot10^{19}$ neutr./cm^2·MW·day in the central channel and $0.57\cdot10^{19}$ at the reactor vessel in a median cross section of the core.

The moveable reflector. A second moveable reflector, PO-2, has been in operation at the reactor since October 1987, having been substituted for the first moveable reflector, PO-1, the first reflector had been in operation for 13211 hours from the reactor startup. The permitted service time for PO-2 is 19000 hours. By 01.01.94 the running time of PO-2 amounted to 18791 hours. When the resources of PO-2 are exhausted in 1994, it will be replaced by a new moveable reflector, PO-2R. The new PO-2R reflector is fully analogous to the existing one, except that the control system for positioning the rotators is more developed. The construction of PO-2R was mainly completed in 1993, and now part-by-part assembly is under way together with some additional machining. Balancing of the rotors was completed. The tempo of work on PO-2R has been hindered both in 1992 and 1993 by insufficient financial support.

The control system for fuel elements. Work has been completed on the construction of an automated control system for the hermetic cases of the fuel elements in the core zone. The system controls the activity of the gas in the argon cavity of the expansion tank of contour I with a Ge(Li) detector. When leakage of gaseous fission products occurs, relevant information will appear automatically on the control panel of the reactor.

The IBR-2 automated measurement and monitoring system (AMMS). During the period covered by the report work continued on developing the reactor AMMS. Detailed information on the system is presented in the 1991 report. The AMMS consists of three subsystems: 1) technical control (T); 2) control of the reactor and of the reflector (R); and 3) the logical system for processing and forming control and emergency signals (L).

The measuring equipment for subsystem T was provided and assembled in 1991. The subsystem has been in service for two years. Periodic control of its characteristics revealed its operation to be stable. The equipment for subsystem R was obtained and installed at its working place in 1992 and tested with real signals. In 1993 improvement of the software was performed for reducing the time delays in the formation of signals for resetting the emergency safety control system. At present the parameters of the system correspond to the technical assignment. The measurement channels of subsystem R are to be tested, when the new moving reflector is put in operation in 1994. As to subsystem L, development work and the construction of equipment was to be completed in 1993. Adjustment work should be completed in 1994. To a significant degree all the necessary work was delayed by insufficient financial support.

The cryogenic moderator. In 1992 work was completed on the construction of a cryogenic moderator (CM) based on solid methane. A detailed description of the design was presented in the report for 1991. The moderator was established at its regular place near the core, transport operations for its installation and removal from the active zone were worked out, and the control and diagnostics systems were assembled and adjusted. Complex technological tests of the CM, involving cooling the methane down to 12 K, were carried out in October 1992. A CM test program was worked out for the reactor in operation, the safety of these tests was substantiated for certain restrictions (for powers not exceeding 5 MW·hour).

30.10.92-5.11.92 the CM was put in physical operation while the IBR-2 was operating at a power up to 1 MW. Measurements of the thermal and neutron-physical parameters were performed. The following results were obtained at 1 MW: temperature of solid methane was 20 K; power consumed by the moderator was 490 W as compared with 300 W at zero power; the admissible rise of reactor power cannot be greater than 0.3 MW/hour; and enhancement of the cold neutron flux ($\lambda > 4$ Å) was by a factor of 4.2-5.2 as compared with the regular comb-like water moderator.

In Fig. 30 the variation of the moderator parameters is presented for cooling without power, when the reactor is operating with power and when the moderator being heated. Fig. 31 presents experimental spectra of neutrons from the comb-like and from the cryogenic moderators, and in Fig. 32 the respective gain factor for the CM is shown. On the whole, the assignment parameters of the moderator were achieved.

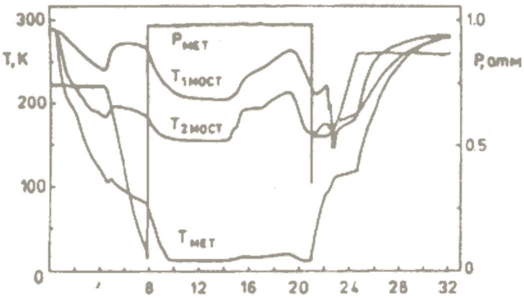
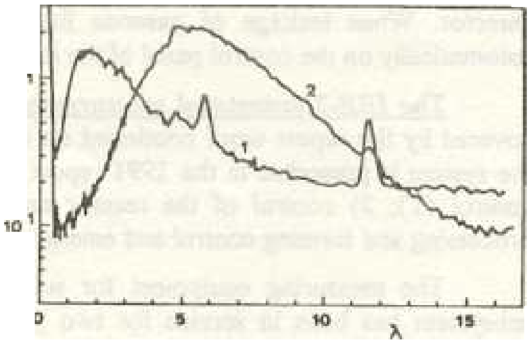
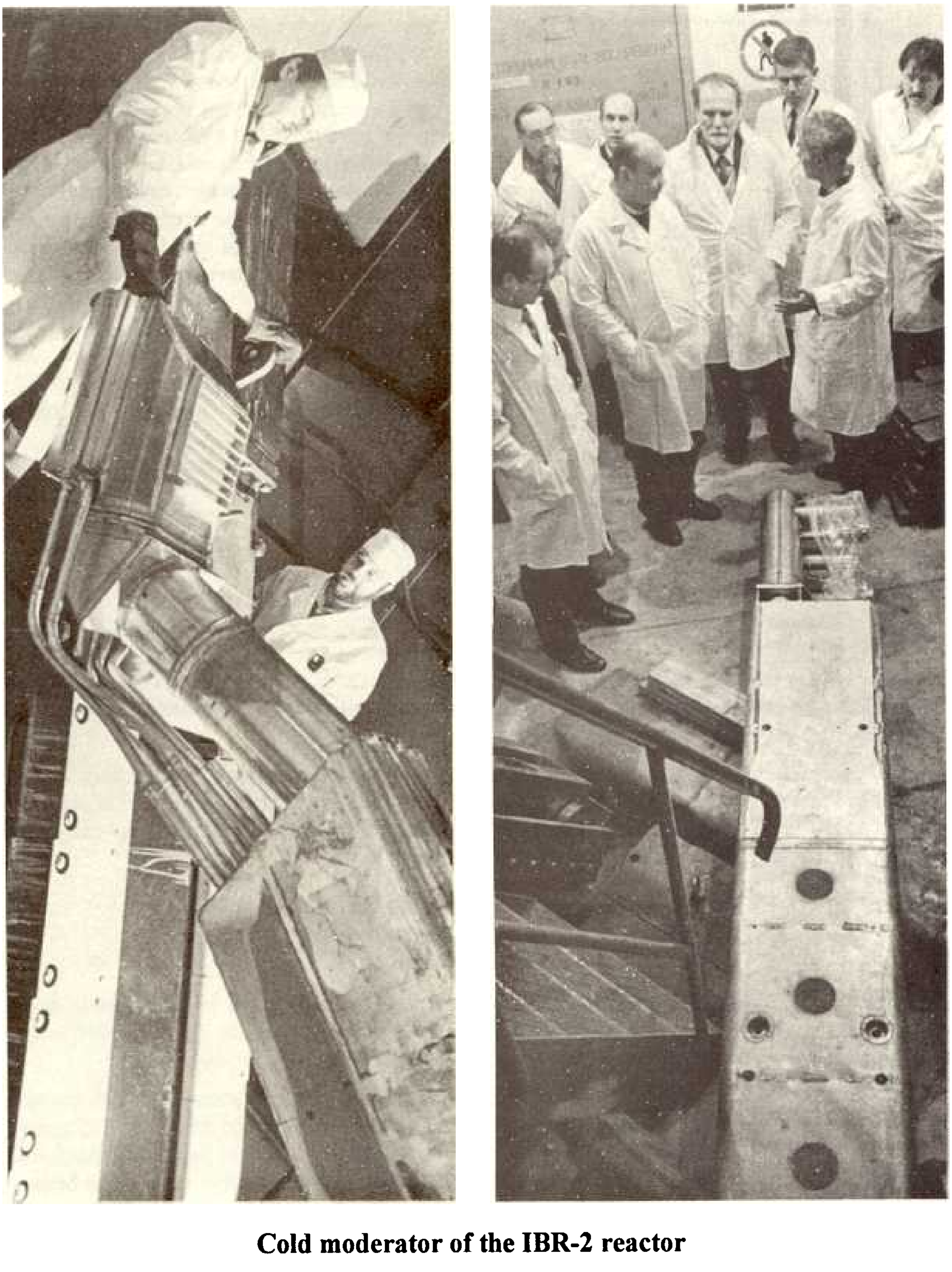


Fig. 30. Change in pressure $P_{met.}$ and temperature $T_{met.}$ in the moderator and temperatures $T_{1bridge}$ and $T_{2bridge}$ at two points of the thermal bridge of the moderator: t ~ 8 h - the moderator is filled with helium up to 1 atm; t ~ 14 h - the IBR-2 power is enhanced up to 1 MW; t ~ 19.5 h - the reactor is shut down; t ~ 21 h - the moderator is connected to the receiver, the cooling is switched off.

Fig. 31. Neutron spectra measured in beam N 4 of IBR-2 reactor: 1 - comblike moderator, 2 - cryogenic moderator. The x-axis - λ(Å), the y-axis represents the count intensities in arbitrary units for each spectrum.





Cold moderator of the IBR-2 reactor

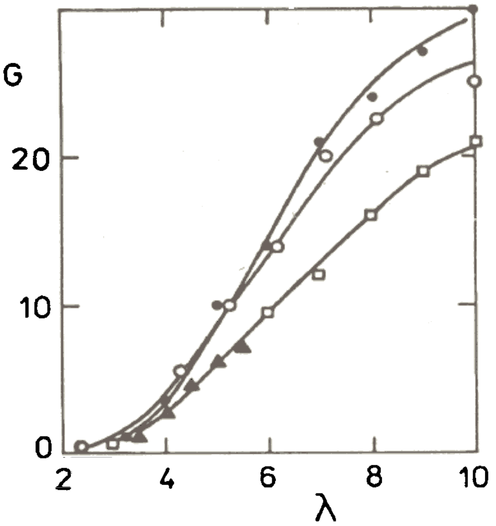


Fig. 32. Dependence of gain factor G on the neutron wave length λ (Å): • - measurement of spectra with a semiconductor Si(Li) detector in beam N 4 with a flight base L = 18 m; O - measurement on small-angular scattering diffractometer SANS with carbon, L = 18 m; □ - current ^{235}U fission chamber in beam N 6, L = 5.5 m; Δ - measurements on DN-2 diffractometer with zirconium dioxide ZrO_2, L = 25 m.

In 1993 work continued for mastering the moderator. The main work was the investigation of solid methane irradiated in conditions close to the operating conditions of the cryogenic methane moderator at a power of 2 MW over a prolonged period of time. The purpose of the work was to obtain the following quantitative characteristics: the degree of swelling of methane exposed to radiation, the rate of accumulation and disposal of radiolytic hydrogen, and the reaction rates for radicals.

The following results were obtained with the specially made URAM installation:

1. No radiation swelling of the methane in the 20-60 K temperature interval was observed under irradiation during periods up to 4 days.

2. A strong temperature dependence has been observed for kinetics of the hydrogen yield from methane. At T > 50 K, hydrogen diffusion was insignificant. At T > 55 K the diffusion rate was so high, that when the methane was submitted to heating for periods of about 10 min, the radiolytic hydrogen had time to leave the methane before the methane started to melt.

3. No spontaneous fast recombination reaction of radicals (RRR) was observed in the conditions of the URAM experiment. RRR were initiated in the case of sufficiently rapid heating of the cooling helium by 3-5 K, if the preceding irradiation continued for at least 4 hours.

A CM test program for reactor powers up to 2 MW has been elaborated on the basis of data analysis of the physical startup and studies at the URAM installation. The results of the CM tests will be used in choosing its optimum operation modes. Implementation of the program is scheduled for the first half of 1994.

2.2. THE IBR-30 + LUE-40 BOOSTER

In 1992-93 the IBR-30 pulsed fast booster, with its injector based on the LUE-40 linear electron accelerator, was in regular operation for 20 cycles of total duration equal to 5030 hours, which provided for implementation of the nuclear physics program on 6 neutron beams.

In the 1991 report, the development of a new tantalum target was announced. The purpose of this project was an enhancement of the efficiency using photo-neutrons and the creation of a more uniform thermal field about the target channel. To the latter end the target has been surrounded with a tantalum screen. The target was installed at its regular place inside the active zone of the booster and prepared for working tests in October 1992. During tests at nominal power the temperature of the fuel elements around the target was two times lower than when the target was without a screen. However, week-long tests of the target turned out to be unsuccessful, on the whole. The tantalum target, cooled by liquid helium, started to disintegrate under the influence of the electron beam, which resulted in pieces of tantalum jamming the target channel, in a drop of helium consumption and in a corresponding increase in the target temperature. The tests were stopped. The target was replaced by the regular tungsten target, with which the 1992-93 campaign continued. A new target has been improved taking into account the results of the tests; for instance, tungsten has been substituted for tantalum, while the tantalum screen of the target has been retained.

At the end of 1992 control of IBR-30 installation became the responsibility of Gosatomnadzor (State Atomic Supervision) of Russia. In connection with the introduction of new documentation regulating technical standards, much work was performed in 1993 to bring the booster into accordance with the new requirements for safe operation.

Financial support of IBR-30 is based on non-budgetary funds allocated to the scientific self-supporting section "The IBR-30 reactor".

2.3. THE SOURCE OF RESONANCE NEUTRON (IREN)

The 1991 report announced the start of work on the design of a new high resolution neutron source (the old name of the project was HRNS), which is to replace the source actually in service, the IBR-30 booster. In the course of work on the project in 1992 it became clear that it was possible to create a relatively cheap pulsed source of resonance neutrons with parameters at a world level in its class. In March 1993 the JINR Plenipotentiaries, upon completion of a large preparatory work for choosing the most promising source, made the decision to create a new pulsed source of resonance neutrons (IREN) at FLNP.

The rated parameters were defined for the two main systems of the installation: for the electron accelerator and the multiplying target. The principal part of the installation is the powerful linear electron accelerator LUE-200. The parameters of the IREN setup and of the LUE-100 accelerator are presented in Table 6, while the location of IREN in the building where the IBR-30 is situated, is shown in Fig. 33.

Table 6

Rated parameters of the IREN installation

Electron energy, MeV	200
Peak current, A	1.5
Pulse frequency, Hz	150
Pulse duration, mcs	0.2
Average power of electron beam, kW	10
Duration of neutron pulse, mcs	0.4
Average fission power, kW	30
Peak fission power, MW	540
Average flux n/s	$1{,}5\cdot10^{15}$
Peak flux, n/s	$2{,}7\cdot10^{19}$
The background in between pulses, %	5.6
Multiplication	28
Average lifetime of prompt neutrons, mcs	0.01
Volume of active zone, dm^3	2.5

Comment: The neutron yield is calculated for e-γ-n-converter made from stainless steel, uranium-235 and uranium-235 mononitride, and for an active zone of plutonium.

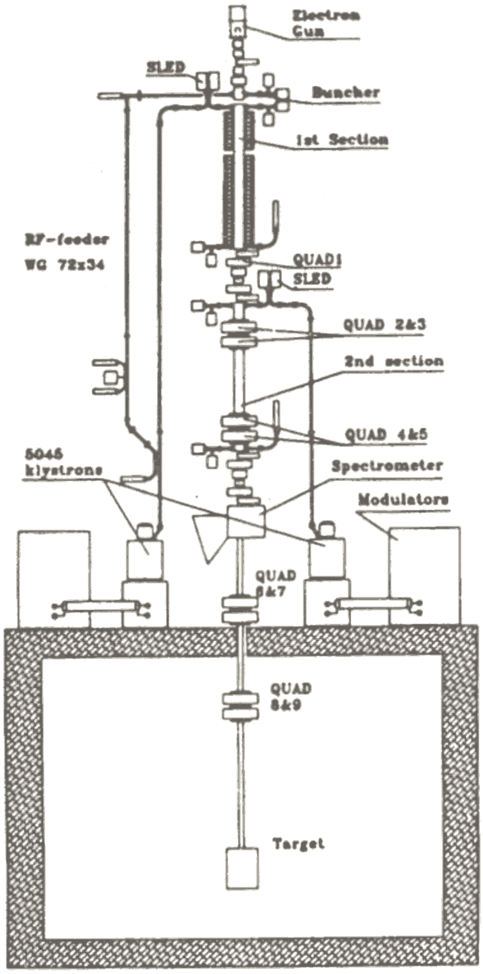


Fig. 33. Layout of IREN installation in building 43 of JINR FLNP (vertical section).

In 1992 an agreement was concluded for designing and constructing the LUE-200 at the Institute of Nuclear Physics of the RAS Siberian Branch (Novosibirsk). For two years the INP carried out a large volume of work in creating the working design of the electron accelerator. International expertise of the design was carried out. In connection with the close completion of the design work a detailed division of responsibilities for constructing the linac was performed between INP and JINR: about 20% of high technology norm-hours are to be consumed in Novosibirsk and the rest in Dubna. Preparation is under way for signing a financial Agreement for implementing the work in INP.

Close collaboration has been established with Stanford University (USA) concerning the issues of the linac construction. For the IREN project the most modern and most powerful clystrons in the world, constructed at Stanford, will be used as sources of SHF power. A corresponding agreement has been prepared and signed between the Department of Energy (USDOE) and JINR. Permission has been obtained and a program has been worked out concerning the supply and transport of the clystrons and the equipment for them. The first clystron and its equipment have been paid by JINR and will be delivered to FLNP in the summer of 1994.

A new scientific experimental department was formed in FLNP, and its task is realization of the IREN project. In order to reduce the design and construction time and realization expenses a cooperation has been established between FLNP and some other JINR laboratories. The linac focusing system and the channel for transporting the beam to the target are under development at the Laboratory of Nuclear Problems. Here, also, the general layout of the linac in the appropriate building is being worked on. The electron source is being designed together with staff members of the Laboratory of High Energies and the Laboratory of Nuclear Problems. At present a version of the vertical arrangement of the electron source and of the high-voltage supply for it has been completed. Work is under way in the new department on modulators for the American clystrons. At the same time the department has begun working on design and experimental work for a choice for elements of the linac beam diagnostics system.

An agreement has been concluded with NIKIET (Moscow) for preparation of the technical design for the target complex of the IREN installation. The project involves development of the active zone with plutonium fuel elements such as the elements for IBR-30, of an electron-neutron converter, of cooling systems, of an emergency safety system, of a biological safety system, and of neutron reflectors and moderators. The layout of the multiplying target together with the tungsten reflector (a tungsten-nickel-iron alloy) and water neutron moderator is shown in Fig. 34.

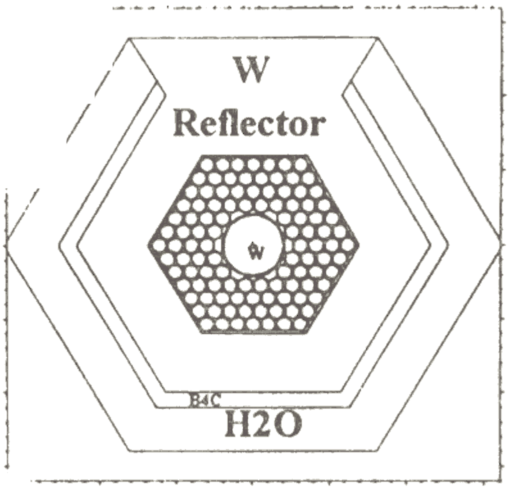


Fig. 34. Multiplying target of IREN setup.

The active zone of the target consists of 108 fuel elements 16 cm high. The amount of loaded plutonium is 17.6 kg for a neutron multiplication coefficient equal to 0.98. Utilization of plutonium, instead of uranium, as planned for the first version of the target, will permit a twofold enhancement of the neutron flux at the surface of the moderator. The spectrum of neutron leakage is presented in Fig. 35.

Practically all 10 kW of the electron beam power are released in the form of heat in the heavy material of the converter inside a volume of the order of magnitude of 1 cm^3. A beryllium beam scatterer is to be utilized in order to reduce the energy release density. The role of the scatterer is clearly demonstrated in Fig. 36, in which a comparison is made of electron-phonon showers, when a beryllium scatterer 10 cm high is present and when it is absent; 25 histories were simulated for electrons of initial energy equal to 150 MeV. The radial distribution of released power is shown in Fig. 37.

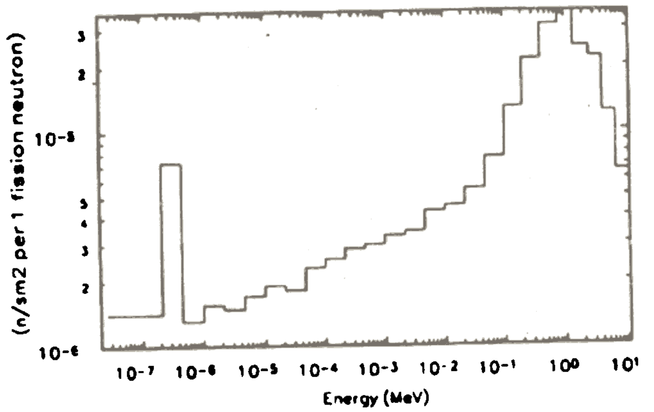


__Fig. 35.__ Group spectrum of neutrons leaking from the surface of the moderator of the multiplying target of IREN. The moderator is 3 cm thick. The spectrum of decelerated neutrons $\varphi(E) \sim 1/E^{1-\alpha}$, where $\alpha = 0.11$.

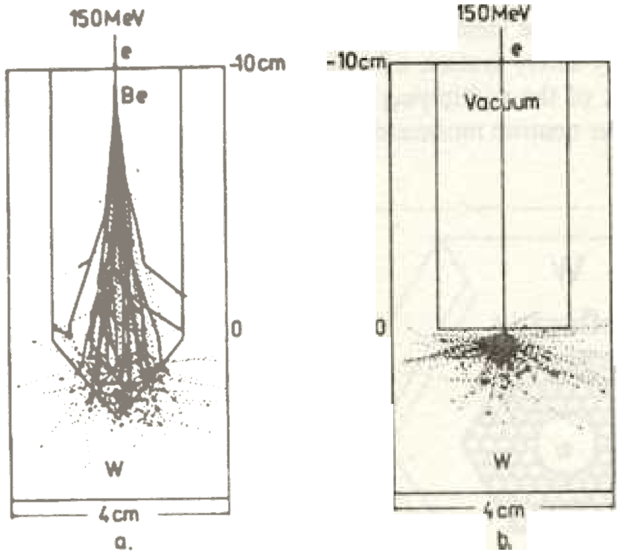


__Fig. 36.__ Electron-photon shower in tungsten target with beryllium scatterer (a) and without scatterer (b). The scatterer reduces the maximum heat release density in tungsten by a factor of 2, when the beam is 1 cm in diameter.

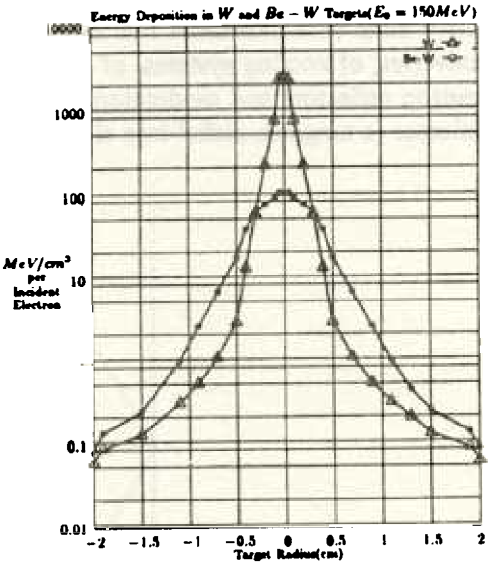


__Fig. 37.__ Radial distribution of the heat release in a tungsten target at a depth of 3 radiation lengths (maximum heat release) in presence of beryllium scatterer (1) and without scatterer (2).

An agreement has been concluded with PKNTs "Reconstruction" for a computational technical substantiation of the multiplying target. However, owing to a delay of the preliminary payment by JINR, provided for in the agreement, implementation of the agreement has been delayed by half a year. This has shifted the performance of work in NIKIET. An agreement has been concluded with GSPI (Moscow) for preparation of the working design of IREN, that is to include disassembly of the IBR-30 booster and appropriate accommodation of the parts of the new electron accelerator and of the neutron multiplying target. At present all design work is being carried out in close collaboration with FLNP.

Besides creation of the IREN installation itself in 1994-96, plans are to reconstruct the experimental base for studies in neutron nuclear physics. This will not only make possible the utilization of a first-class neutron source, but also, to actually have a neutron factory providing the broadest experimental facilities possible for specialists from JINR member states and from other countries.