PHYSICAL STARTUP OF THE RBMK-REACTOR* OF THE SECOND UNIT OF THE V. I. LENIN NUCLEAR POWER STATION, LENINGRAD

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In accordance with the program for the development of nuclear power generation in the Soviet Union, in May to June 1975 the physical start-up was achieved at the reactor of the second unit of the V. I. Lenin Nuclear Power Station, Leningrad (LNPS). The physical start-up program for the reactor of the second unit of the LNPS was based on the results of the physical start-up of the first reactor [1] and provided for a number of comparative experiments during charging of the reactor. Charging of the reactor with fuel assemblies FA and with auxiliary absorbers AA was carried out with dry multiple forced circulation loops MFC and cooling of the rods of the control and safety system CSS. Although the charged reactor with dry channels, intended for the insertion of fuel assemblies and auxiliary absorbers, does not have the greatest reactivity, this charging principle allowed the multiple forced circulation loop to be prepared for a power start-up, simultaneously with charging of the fuel assemblies.

For reliable control over the core and for ensuring safety during charging, a temporary control and safety system was used together with the regular control and safety system. It effected control of the neutron flux, the reactivity and emergency shutdown, and it comprised six emergency shutdown rods (scram rods), four manual controls, and also the neutron source actuator with a control switch and a position indicator.

The physical start-up program consisted of the following main stages:

1. Composition of the minimum critical charge without auxiliary absorbers and standard control and safety rods (charge No. 1).
2. Completion of zone up to the maximum number of identical polycells, the so-called periodicity cells (loading No. 2, Fig. 1).
3. Additional charging of the reactor up to 1437 fuel assemblies and 239 auxiliary absorbers.
4. Shaping of the initial charge of the core, taking account of the operating experience from the reactor of the first unit.
5. Estimation of the reserve of reactivity of the initial charge, and ensuring the required duration of operation before the first fuel recharging.
6. Determination of the reactivity effects with dry multiple forced circulation loops and with cooling of the control and safety rods.

*Water-cooled/water-moderated channel-type reactor (high-powered).

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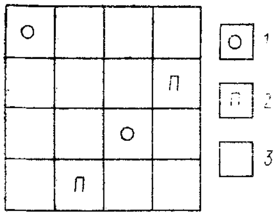

Fig. 1. Periodicity cell: 1, 2, 3) cells with control and safety rods; auxiliary absorbers; and fuel assemblies, respectively.

7. Measurement of the energy-release fields in the cold unpoisoned reactor.
8. Bringing of the reactor to the minimum level of power, controlled by the standard control and safety system.

The necessity for experiments (in comparison with the reactor of the first unit) originates by the difference in the number of technological parameters affecting the physics of the reactor. In particular, to these parameters may be referred the density of the graphite (1.67 g/cm^3 in comparison with 1.73 g/cm^3 in the first unit), the average charge with respect to ^{235}U in the fuel assemblies and the difference in the boron content in the auxiliary absorbers, etc. Comparative experiments during loading, even at the initial stage of the physical startup, permitted those changes to be forceast which must be carried out in the total reactor charge, in order to ensure the required reserve of reactivity and distribution of the energy-release field.

Preparation of the Reactor for Start-up

Before starting to charge the fuel assemblies and auxiliary absorbers, the following operations were carried out:

The multiple forced circulation loops and the control and safety rods were flushed and pressurized.

Running-in of all main circulatory pumps (MCP) and the pumps of the control and safety rod loop.

During operation of all the main circulatory pumps, the multiple forced circulation loops and the graphite brickwork of the reactor were heated up to 150°C over two days, and after heating up the graphite brickwork was cooled to room temperature.

The monitoring system for the integrity of the technological channel (MITC) was put into operation.

The regular and temporary control and safety rods were put into operation.

The through-channel water-flooding system was prepared.

The loudspeaker connection between the central hall and the modular control panel (MCP) was made operational.

The system for filling the multiple forced-circulation loop with water from the emergency feed pump (EFP) tank was flushed and prepared for operation.

The drainage reservoirs were prepared for receiving water.

The general exchange and special ventilation systems were brought into operation.

The entire assembly of auxiliary absorbers was installed, with a ratio of inserts of boron steel and stainless steel of 3 : 1 in the central section, of length 500 cm and 1 : 2 at the end sections with a length of up to 100 cm.

A complete set of fuel assemblies with openings below the interzone sensors and 100 fuel assemblies were installed.

Charging of the Reactor. Comparative Experiments

During charging of the reactor, its control and safety systems were implemented, just as in the reactor of the first unit, with instruments of the temporary control and safety rods in the presence of a neutron source in the zone.

The first critical charge without auxiliary absorbers and the rods of the regular control and safety system in the absence of water in the multiple forced-circulation and the control and safety loops, contained 24 fuel assemblies (Fig. 2) and with the temporary control and safety rods withdrawn K_{eff} was 1.00096 (23 fuel assemblies and K_{eff} = 1.0050 for the reactor of the first unit). Further charging of the reactor was carried out with respect to the periodicity cells (12 fuel assemblies, two auxiliary absorbers, and two control and safety rods). After charging 77 periodicity cells (916 fuel assemblies and 154 auxiliary absorbers), charge No. 2 was brought to the critical state. Further, the critical state was recorded for charges containing 1437 fuel assemblies and 239 auxiliary absorbers, and 1452 fuel assemblies plus 239 auxiliary

TABLE 1. Some Results of Comparison Experiments during Physical Start-Up of the Reactors of the First and Second Units of the Leningrad Nuclear Power Station

charge No.	Reactor condition: FA, quantity pieces	FA, presence of water in channels	AA, quantity, pieces	AA, presence of water in channels	presence of water in the control and safety loop in both units	No. of control and safety rods inserted in core: OR	MR	AR	SRA	K_{eff}	Difference in Keff with identical compensation, %
1	23; 24 †	No.	—	No	No	—	—	—	—	1,0050; 1,00096	—1.0
2	916	»	154	»	»	8; —	56; 56	4; —	—	1,00000; 1,00064	+1,1
3	1437	Yes	239	Yes	»	13; 8	89; 89	12; 12	20; 20	1,00034; 1,00016	—0,33
4	1452	»	239	»	Yes	10; 1	89; 85	9; 12	20; 20	1.00000; 1,0032	—0.5

*OR) overcompensation rods; MR) manual control rods; AR) automatic control rods; SRA) shortened rod-absorbers.
†Here, and in future, the first and second figures are for the first and second units, respectively.

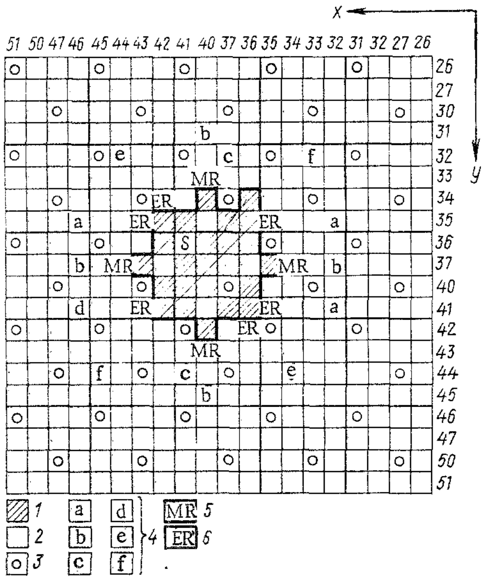

Fig. 2. No. 1 charge and diagram of the disposition of the sensors and the temporary control and safety rods: 1, 2) cells with charged fuel assemblies and uncharged channels; 3) cells with regular control and safety rods; 4) cells with sensors: a) galvanometers (G1, G2, and G3), b) reactimeters (PIR-1 and PIR-2), c) counter-trigger devices (SPU-1 and SPU-2), d) power pen recorder (ÉPPV), e) scram rod boosters (UA-9-1 and UA-9-2), f) scram-rod velocity instruments (UZS-1 and UZS-2); 5, 6) cells under temporary control and safety rods; S) neutron sources; MR) manual control rods; ER) emergency shutdown rods.

absorbers. Similar charges were brought to the critical state in the reactor of the first unit. For the charges containing 1437 fuel assemblies and 239 auxiliary absorbers, the effect of reactivity on the filling with water of the multiple forced-circulation loop was measured by means of a reactimeter; as in the reactor of the first unit, this was found to be +1.9β.* The results of the comparative experiments obtained during the physical startup of the reactors of the first and second units are shown in Table 1. The difference in the effective multiplication factor K_{eff} was determined in the following way. An identical sequence for withdrawing the control and safety rods was adopted for both reactors on reaching the critical state. By measuring the efficiency of the control and safety rods, amounting to the difference in the compensation position, the difference in K_{eff} was determined.

It follows from Table 1 that all the charges investigated for the reactor of the second unit have a lower reactivity. The difference in K_{eff} varies from 0.33 to 1.1%.

Effect of Various Parameters on the Reactivity

The core structure of the reactor of the second unit, in accordance with the physical start-up program, was specified by the identical core of the first unit. The differences which appeared during the physical start-up of the second reactor necessitated calculations to be carried out in order to assess the effect of deviations of the various parameters on the multiplication properties. The results of the calculations are shown in Table 2.

Analysis of the deviations from the nominal values of the mass characteristics of the fuel in the fuel assemblies, the graphite purity, and the content of boron in the auxiliary absorbers, showed that all these factors can be eliminated from those significantly affecting the multiplication properties. On the contrary, a change of graphite density affects not only the multiplication properties but also the diffusion length L and the lifetime τ of the neutrons, which define both the neutron leakage from the reactor and

*Effective fraction of delayed neutrons.

TABLE 2. Effect of Deviations of Various Parameters on the Multiplication Properties of the RBMK Reactor Core

Parameter	Nominal value of parameter	Devia. from nominal value assumed in calculation	$\Delta K_\infty/K_\infty$, %*
Uranium enrichment	1.787%	+0.01%	+0.18
Fuel density	9.30 g/cm³	+0.1 g/cm³	+1.32
Graphite density	1.67 g/cm³	+0.1 g/cm³	−0.31 (−7.1 for $\Delta M^2/M^2$)†
Absorption cross section of graphite	4.2 mbar	+0.1 mbar	−0.13
Boron content of auxiliary absorbers	2.0%	+0.1%	−0.02

*Values of $\Delta K_\infty/K_\infty$ are given for the reactor, with water in the multiple forced-circulation loop.
†$M^2 = L^2 + \tau$.

also their overflow to the control and safety rods and the auxiliary absorber rods.

Calculations by the QUAM-2 program showed that a reduction of the graphite density led to the following losses of reactivity for the charges being compared (see Table 1):

Charge No. 1 – 0.96% (– 1.0%);
Charge No. 2 – 0.91% (– 1.1%);
Charge No. 3 – 0.33% (– 0.33%);
Charge No. 4 – 0.31% (– 0.50%).

The experimental data are shown in the brackets. Thus, the calculations confirm that a reduction of reactivity in the reactor of the second unit is mainly due to the reduction of the graphite density. However, according to the calculations, this does not lead to a noticeable change of the depth of burnup in view of the increased plutonium production.

Formation of the Initial Reactor Charge

The reduction of reactivity which appears in the reactor of the second unit is compensated mainly by substituting 9 auxiliary absorbers by fuel assemblies. Moreover, the interchange of several peripheral auxiliary absorbers was effected, which gave rise to certain difficulties in the case of rechargings during operation of the reactor of the first unit. In contrast from the first unit, auxiliary absorbers were installed on the periphery in the lattice of the control and safety rods which, in this region are disposed approximately twice as sparsely as at the center of the core. It was decided not to load eight channels on the periphery of the reactor as, according to calculations, the installation of fuel assemblies in them leads to an increase of nonuniformity of the power release.

As a result of rearrangements and transfers, the initial charge for the reactor of the second unit was defined: 1455 fuel assemblies, 230 auxiliary absorbers, and 8 uncharged channels. The critical state of the initial charge (the multiple forced-circulation loop and the control and safety loop filled with water) was achieved by the insertion in the reactor of 89 manual control rods, 12 automatic control rods, 21 shortened rod-absorbers, and 10 overcompensation rods. 21 emergency shutdown rods and 26 overcompensation rods were withdrawn. With this situation of the control and safety rods, $K_{eff} = 1.00077$, the temperature of all core elements was ~20°C and the reactor power was ~1.4 kW.

Experiments on the Initial Reactor Charge

One of the problems of the physical start-up is to determine the basic physical characteristics of the reactor, necessary for its future operation. For this purpose, in the initial charging of the reactor the effects of reactivity were measured with dry cooling loops of the control and safety rods, fuel assembly channels (estimation of the "steam" effect of reactivity in the cold state), the multiple forced-circulation loop, and with installation of the interzone monitoring sensors.

At the same time, the total efficiences of the inserted control and safety rods (estimation of the reserve of reactivity of the cold unpoisoned reactor) and of the withdrawn control and safety rods were determined.

All negative reactivity effects were measured with a reactimeter during the introduction of reactivity into the critical reactor. The efficiency of the inserted control and safety rods was measured by their successive withdrawal from the critical reactor. If the efficiency of a single rod exceeded 0.3β, then the

TABLE 3. Experimental and Calculated Data for the Initial Reactor Charge

Quantity determined	Experiment	Calculation
Effect of reactivity with:		
dry channels with fuel assemblies	−0.42%	−0.43%
dry channels with auxiliary absorbers	−1.60%	−1.19%
dry multiple forced-circulation loop	−2.02%	−1.62%
dry control and safety loop	Compensated by the insertion of 13 control and safety rods	−
installation of 117 sensors for monitoring the radial neutron field	−0.006%	
Total efficiency:		
of inserted control and safety rods	8.9%	7.3%
of withdrawn control and safety rods	1.9%	1.6%
Nonuniformity factor:		
of radial neutron field	2.04*	1.94*
of neutron height field	1.37	2.45%

*Obtained on fuel assemblies in which measurements were carried out by fission chambers.
†For all fuel assemblies of the reactor.

measurements were carried out by the overcompensation method. Dehydration of the control and safety loop was carried out in the subcritical state.

The relative power release field in the initial reactor charge was measured with small-sized fission chambers. At the same time, five independent measurement channels, in the corresponding way to the commuted channels, participated in the measurements. The measurements were made at eight points with respect to height in 144 fuel assemblies, having at the center dry channels for the fission chambers. The quality of the relative measurements, carried out twice at several points, has a mean-square error of 1.6%. The absolute thermal neutron flux Φ_T was determined by the activation of gold foils in and without cadmium. The absolute power of the fuel assemblies, in which the absolute thermal neutron flux was measured, was determined from the relation

$$W_T = \frac{\Phi_T \sqrt{T_0/T}\sqrt{\pi/4}\,\sigma_{0f}^5 N^5 k_r k_1}{3.1\cdot 10^{10} k_T},$$

where T is the neutron temperature at the point of location of the indicator; T_0 = 293°K; σ_{0f}^5 is the fission cross section of ^{235}U when $T = T_0$; N^5 is the number of ^{235}U nuclei in the fuel assemblies; k_r is a factor which takes into account fission by resonance neutrons; k_1 is the deviation of the neutron flux measured by the fission chambers and averaged over the height, from the neutron flux at the site of irradiation of the indicator; and k_T is the ratio of the neutron flux at the point of measurement to the average neutron flux in the fuel.

The reactor power was determined from the formula

$$W_p = \frac{W_T}{Q_T^e} \frac{\sum_{i=1}^{n} Q_i^e}{\sum_{i=1}^{n} Q_i^p} \sum_{i=1}^{m} Q_i^p,$$

where Q_T^e is the relative power of a fuel assembly, measured by the fission chamber, the absolute power of which was determined by gold activation; $\sum_{i=1}^{n} Q_i^e$ is the summed relative power of the fuel assemblies, measured by the fission chambers; $\sum_{i=1}^{n} Q_i^p$ and $\sum_{i=1}^{m} Q_i^p$ are the total relative powers, calculated for the fuel assemblies n in which the fission chamber measurements were made, and all fuel assemblies m respectively.

All critical charges, and also the measured power release fields, were computed by the BOKR-COB and QUAM-2 programs, which describe channel-wise the structure of the core. Moreover, the experimental efficiency of the control and safety rods was computed by the BOKR-COB program.

The BOKR-COB program is a development of a program [2, 3] based on the solution of the diffusion equations of a reactor by a finite-difference method in x−y geometry (for the cross section of the reactor). In the program, the two-group diffusion equations of a reactor consisting of heterogeneous square cells are solved. The nodes of the reference mesh coincide with the centers of the channels. It was shown by the calculations of the experiments carried out on critical assemblies, and also on the reactor of the first unit of the Leningrad Nuclear Power Station, that such an arrangement of the reference nodes is more preferable than in the angles of elementary cells. The nonuniform poisoning of the fuel by xenon, as a function of the designed distribution of the power-release field and the fuel burnup, are taken into account in the program. The presence in the core of the control rods and other breeder channels is taken into account by assigning the appropriate homogenized properties of the cells in which these absorbers and channels are located. Partially inserted rods are replaced by completely inserted rods of equivalent efficiency. For the operational calculations, a modification of the program is used – the BOKR-COBZ program in which, in order to take account of the partially inserted control and safety rods, experimental measurements are used of the height neutron field by the sensors of the physical control system.

The QUAM-2 program achieves a new method of calculating heterogeneous reactors [4]. The reactor is represented in the form of a finite lattice of channels (in x−y geometry) in an infinite moderator. The transport of neutrons in the moderator is described by two-group diffusion equations of the Galanin–Feinberg type [5, 6], which are transformed to the so-called quasialbedo form similar to the finite difference form, and which are solved by an iterration method. As a result, computer time in solving the equations is shortened by a factor of 15-20 in comparison with the traditional heterogeneous method and amounts to ~1.5 min for the calculation of a single reactor state. The QUAM-2 program enables K_{eff} to be calculated and also the power distribution over the reactor channels with a specified position of the completely or partially inserted control and safety rods. The possibility is provided for taking into account the steady-state poisoning by xenon in the uranium burnup, individually for each channel. In calculating K_{eff}, a correction is made for the axial leakage of neutrons and the nonuniformity of properties over the height of the reactor, and also a correction which takes account of the processes caused by moderated neutrons and due to the presence of nonbreeding channels.

By means of the QUAM-2 program and a system of supporting programs, calculations of about 70 critical states (cold and hot poisonings and with uranium burnup) have been carried out for the reactors of the first and second units of the Leningrad Nuclear Power Station. The mean-square error in determining K_{eff} amounts to 0.5% and the maximum deviation does not exceed 1%.

Comparison of the calculations by the BOKR-COB and BOKR-COBZ programs with the experimental data, shows that the calculations predict satisfactorily the criticality of the various states of the reactor. For the system of neutron-physical constants assumed, the discrepancy in K_{eff} does not exceed 0.9%. For a complete charge, it does not exceed 0.5% and, taking into account the height field of the neutrons (the BOKR-COBZ program), it amounts in all to 0.2%. It is shown that the height distribution of the neutrons has a marked effect on the calculated value of K_{eff}. In the calculations with sinusoidal and measured neutron distributions, the difference in K_{eff} amounted to 0.3%. Therefore, for a more accurate calculation of K_{eff} by the BOKR-COBZ program, it is necessary to take account of the actual height distribution of the neutrons. The efficiencies of different groups of control and safety rods, calculated for different charges, mainly coincide well with the experimental data. The results of the experiments and calculations of certain effects of reactivity and neutron distributions over the core, carried out for the initial reactor charge, are shown in Table 3.

Comparison of the experimental and calculated power-release fields along the radius of the reactor, obtained by the BOKR-COBZ and QUAM-2 programs, showed agreement at the location of the field maximum; the mean-square error in determining the power of the fuel assemblies by both programs is identical and amounts to 9.7%.

After completion of the experiments on the initial charge, the power start-up of the second unit of the Leningrad Nuclear Power Station was effected in July-August 1975. The power of the unit was built up gradually in accordance with the readiness of the turbogenerators. Initially, at a total power of 500 MW, the third turbogenerator was cut-in and then the fourth turbogenerator was brought into operation. On September 30, 1975 the State Commission authorized the handover of the second unit of the V. I. Lenin Nuclear Power Station, Leningrad to commercial operation. On October 10, 1975 in accordance with the start-up program, the electric power output of the second unit amounted to 750 MW.

During the power start-up, the basic decisions taken according to the results of the physical start-up were checked and confirmed. In particular, according to the results of measurements of the power-release fields, the rate of decrease of reactivity as a result of poisoning and burnup of the uranium, the validity of the specification for the initial charge, and the creation of the necessary reserve of reactivity were confirmed.

CONCLUSIONS

During the physical start-up of the reactor of the second unit of the Leningrad Nuclear Power Station, the initial reactor charge was specified, experiments and calculations were carried out which permitted a comparison to be made with the results obtained during the start-up of the reactor of the first unit:

1. The initial reactor charge consists of 1455 fuel assemblies and 230 auxiliary absorbers (eight channels remain uncharged).

2. There are certain differences between the reactors of the first and second units, in that similar charges in the reactor of the second unit have a lower reactivity. The decrease of reactivity of the total reactor charge (charge No. 4) amounted to 0.5%. This difference is explained mainly by the lower density of the graphite in the reactor of the second unit.

3. Dehydration of the 1455 channels with fuel assemblies and the 230 channels with auxiliary absorbers reduces the reactivity by 2%.

4. The effect of reactivity during dehydration of the control and safety loop is positive and is compensated by the insertion of 13 shutdown rods.

5. The reactor has the greatest reactivity when the circulation loop is filled with water and the control and safety loop is dry.

6. Dehydration of the channels with 1455 fuel assemblies leads to a reduction of the reactivity by 0.42%, which exceeds by 0.3% the similar effect in the reactor of the first unit and confirms the more negative steam effect of reactivity on the initial stage of operation of the reactor.

7. The total efficiency of the inserted control and safety rods amounts to 8.9%.

8. In order to bring the cold, unpoisoned reactor with water in the multiple forced-circulation and the control and safety loops to the critical state, 47 shutdown rods must be withdrawn, the total efficiency of which amounts to 1.9%.

9. A comparison of the experimental and calculated power-release fields along the radius of the reactor, obtained by the BOKR-COBZ and QUAM-2 programs, showed that the mean-square deviation between the measured and the calculated powers of the fuel assemblies by both programs is identical and amounts to 9.7%.

The physical startup of the reactors of the first and second units of the Leningrad Nuclear Power Station permitted considerable experimental data to be accumulated concerning the startup of RBMK-type reactors. By taking into account the possibility of variation of certain technological parameters of the core materials, it will be advantageous during startup of the next units to carry out comparative experiments in order to correct the initial charge and to refine the operating characteristics of the reactor.

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